POSSIBLE WAYS TO SUPPRESS ANOMALOUS ABSORPTION AT ECRH

E.Z. Gusakov, A.Yu. Popov

Ioffe Institute, St.-Petersburg, Russia
e-mail: Evgeniy.Gusakov@mail.ioffe.ru

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ABSTRACT

Possible approaches to reduce the anomalous absorption rate associated with the low-power-threshold two-UH-plasmon parametric decay instability (PDI), which is excited by an extraordinary pump wave in X2 ECRH experiments in the vicinity of the local maximum of the plasma density profile, are analyzed. A universal case of only one trapped upper hybrid wave is considered as well as the case of two trapped UH waves leading to the strongest PDI. It is shown that because of a rather low power-threshold for this instability, its complete suppression in ECRH experiments with MW microwave beams is hardly possible. However, it is demonstrated that increasing the pump beam radius allow reducing the related anomalous absorption rate.

Motivation

Electron Cyclotron Resonance Heating

Powerful microwave generators - gyrotrons - are available on the market (invented in 60th in NIRFI, Gorkiy, USSR, 30 -170 GHz, very effective 50-70%, up to a couple of MWs, reliable generators)

According to fixed theoretical notion:

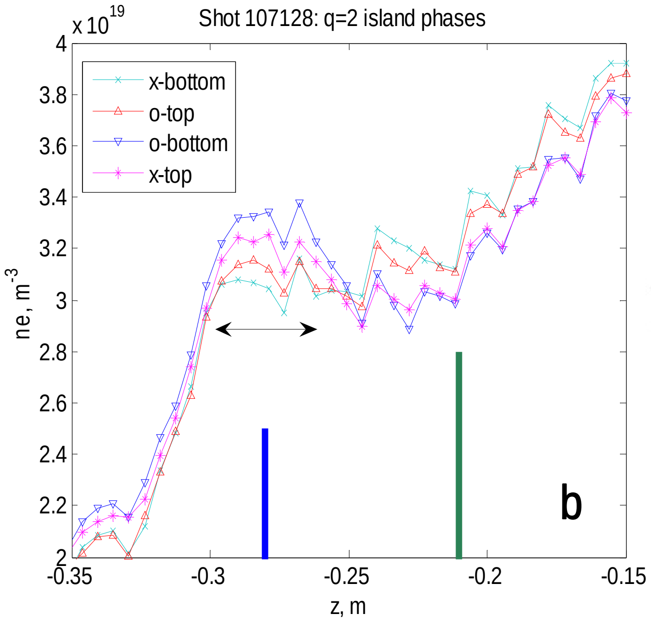
- **The power absorption should be well-localized** $\delta R \propto \frac{T_e}{m_e c^2} R$
- **The power absorption should be very effective in hot plasma of large fusion devices** $\Gamma >> 1 \text{ at } T_e \geq 1 \text{ keV and } R > 1 \text{ m}$
- **Based on the proposed three-wave interaction model (Piliya & Rosenbluth) the most dangerous scenarios of microwave decay were analayzed (Cohen et al 1991; Litvak et al. 1993). Their power thresholds were found to exceed drastically the power of current and future microwaves generators.**
- **The method is planned for application in ITER to control a neoclassical magnetic island and to heat plasma.**

Motivation

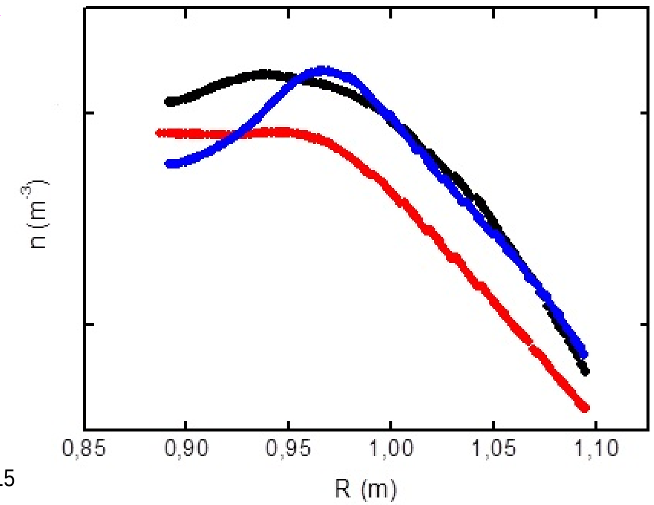
Recent unexpected observation of Anomalous phenomena during ECRH on toroidal devices

- Plasma emission with frequencies shifted with respect to the gyrotron frequency (TEXTOR, ASDEX-UG, W-7X)
- Ion acceleration (TJ-II, TCV)
- Power deposition profile broadening & non-local transport (T-10, TJ-II , L-2M, LHD)

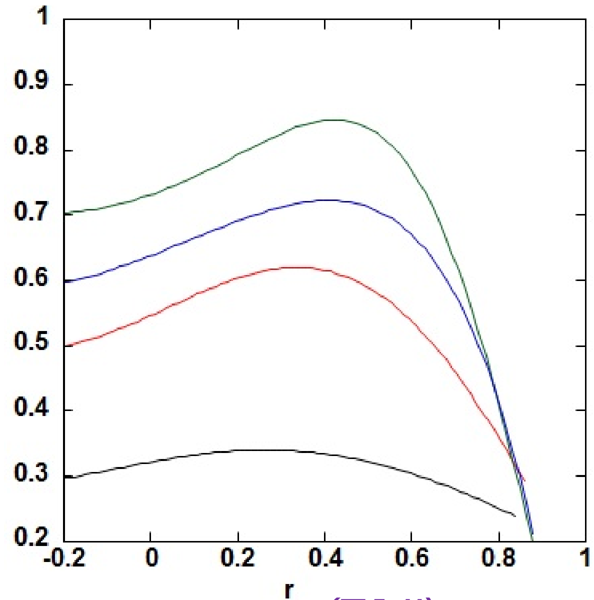
All these anomalous effects were observed in the presence of ***nonmonotonic*** density profile



Kantor *(TEXTOR)*



Coda *(TCV)*



Rapisarda *(TJ-II)*

a) presence of a magnetic island,
b) a pump-out effect

c) centre of a plasma column
d) blobs and streamers at a plasma edge

Motivation
Parametric Decay Instabilities in the regimes with Rotating Magnetic Islands, near the Plasma Center and in Connection with Edge Localized Modes at ECRH in ASDEX-Upgrade

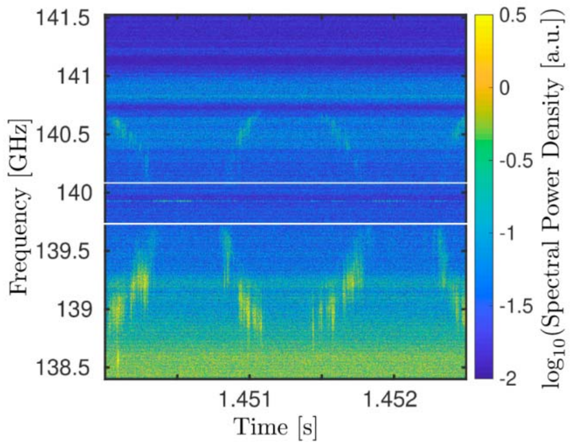


Figure 5.14 – Fast CTS signal near 140 GHz during a rotating magnetic island in ASDEX Upgrade #35186. The white lines mark the edges of the notch filter around the gyrotron line. Spikes occur with a repetition rate determined by the mode frequency.

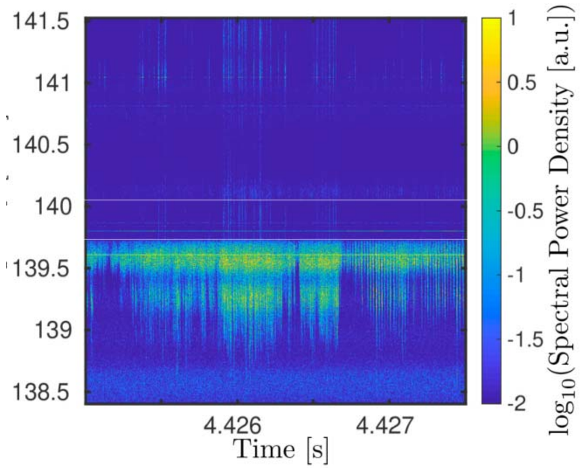


Figure 5.23 – Fast CTS signal near 140 GHz during central PDI in ASDEX Upgrade #35527. The white lines mark the edges of the notch filter around the gyrotron lines.

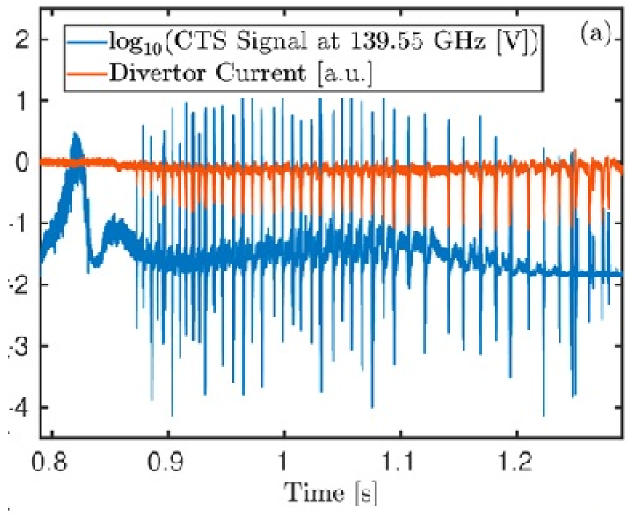


Figure 5.8 – Slow CTS signal at 139.55 GHz and divertor current versus time in ASDEX Upgrade #35376 (a) and #35588 (b). A strong correlation is visible.

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Motivation
Parametric Decay Instabilities in the regimes with the local maximum of a density profile in ASDEX-UG (Half pump frequency radiation emission)

A magnetic island

The center of a plasma column

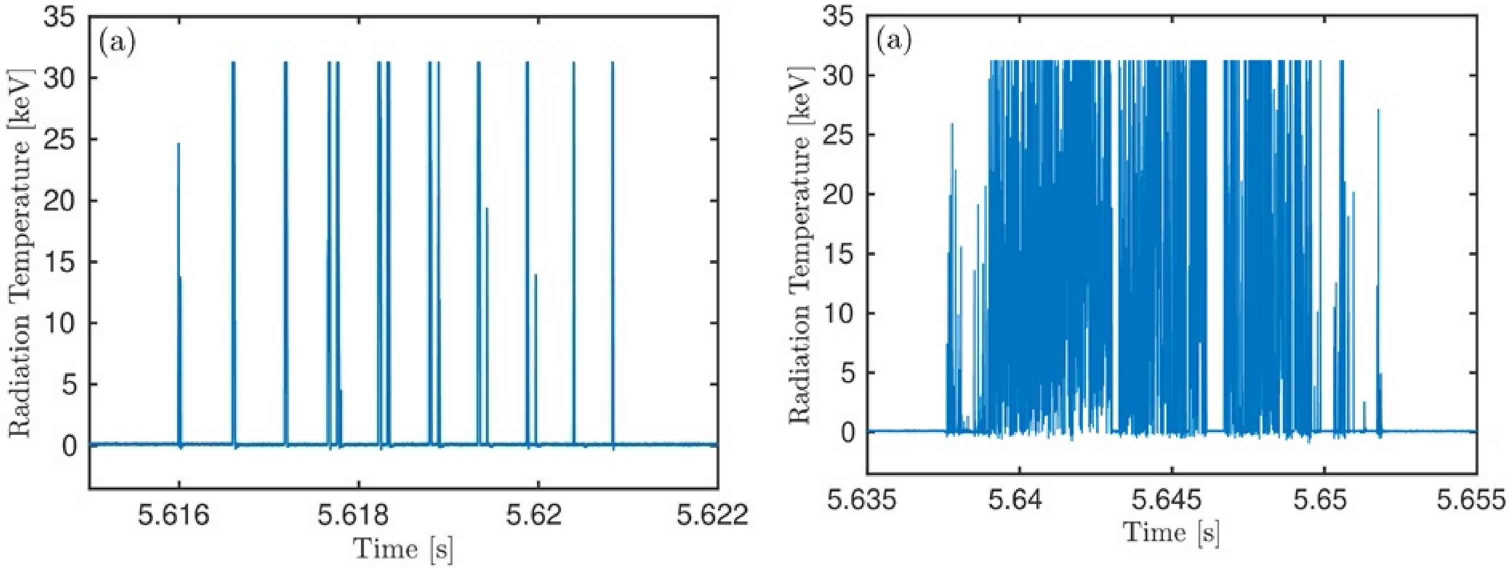

Figure 5.13 – Degradation of ECE mixer during a rotating magnetic island in ASDEX Upgrade #35939. Pane (a) shows the signal from a channel around 75.5 GHz;

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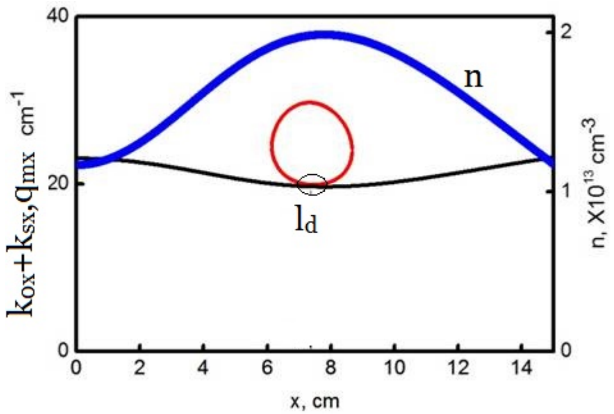
Motivation

Physical reasons and consequences of anomalous effects at a low pump power:

- Anomalous phenomena can be interpreted as a result of low power-threshold parametric excitation of trapped decay daughter waves.
- Low threshold excitation of PDI is due to the suppression of daughter wave convective losses in the direction of plasma inhomogeneity because of a non-monotonic density profile. The absolute PDI is excited due to localization of daughter waves on a magnetic surface caused by a powerful microwave beam.
- The most effective PDI scenario is related to the parametric excitation of trapped upper hybrid (UH) waves:
- A more universal PDI: $t = t + l_{UH}$ in which only one trapped UH wave is excited.
- The strongest PDI: $t = l_{UH} + l_{UH}$ in which two trapped UH waves are excited.
- Typical thresholds for different experiments: 40 kW - 300 kW
- Theoretically predicted anomalous absorption rate: 10% - 80%
- Not realistic to suppress completely in MW – range ECRH experiments, but possible to reduce the anomalous absorption rate.

Growth rate and threshold of $t = t + l_{UH}$ PDI



Dispersion curves illustrating the universal scenario of PDI:
$t = t + l_{UH}$ (q_{mx})
(TCV parameters)

$$\phi(\mathbf{r}) = C_m(y,z,t)\, f_m(x)$$

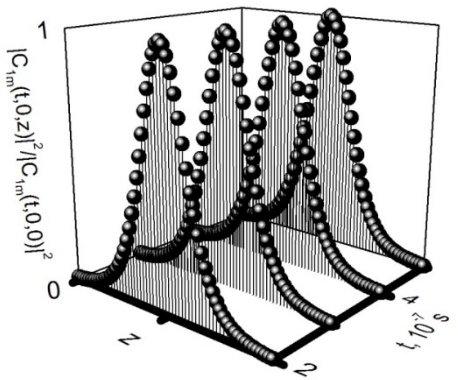
$$f_m(x) = \frac{1}{\sqrt{L_m^+}} \exp\left(i\int_{x_l^*}^{x} q_x^+(\omega_m,\xi)\, d\xi - i\frac{\pi}{4} \right) + \frac{1}{\sqrt{L_m^-}} \exp\left(i\int_{x_l^*}^{x} q_x^-(\omega_m,\xi)\, d\xi + i\frac{\pi}{4} \right)$$

$$\left(\frac{\partial}{\partial t} + i\Lambda_y \frac{\partial^2}{\partial y^2} + i\Lambda_z \frac{\partial^2}{\partial z^2} \right) C_m = \nu_0 \exp\left(-\frac{y^2+z^2}{w^2} \right) C_m$$

$$\nu_0 = \gamma_0^2 \left(E_0^2 \right) \tau_X \frac{l_d}{L_m}$$

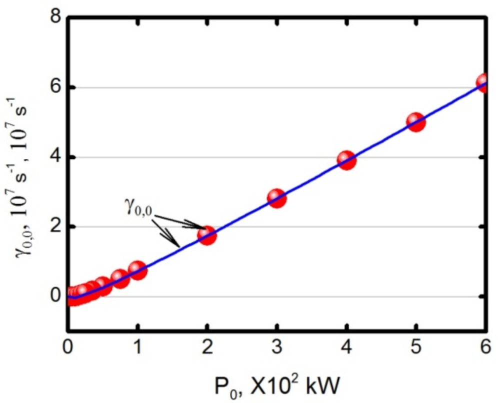
$$C_m(y,z,t) = u_n(y)\, u_l(z) \exp(\gamma_{n,l} t),$$

$$\gamma_{n,l} = |\nu_0| - \sqrt{\frac{|\nu_0|}{2w^2}} \left[(2l+1)\sqrt{\Lambda_z} + (2n+1)\sqrt{\Lambda_y} \right]$$



Excitation of the eigenmode - like structure retaining its shape conserved in time

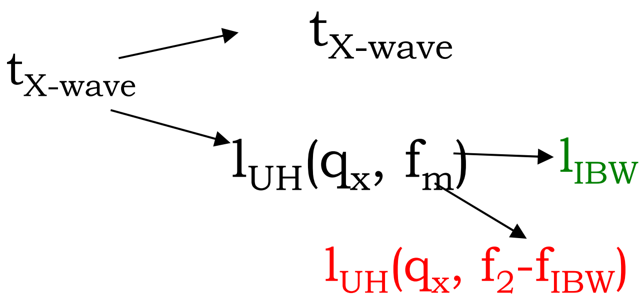
Numerical solution



Power dependence of the growth rate (analytic & numerical

$$P_0^{th} \sim 10 \div 100 \text{ kW}$$

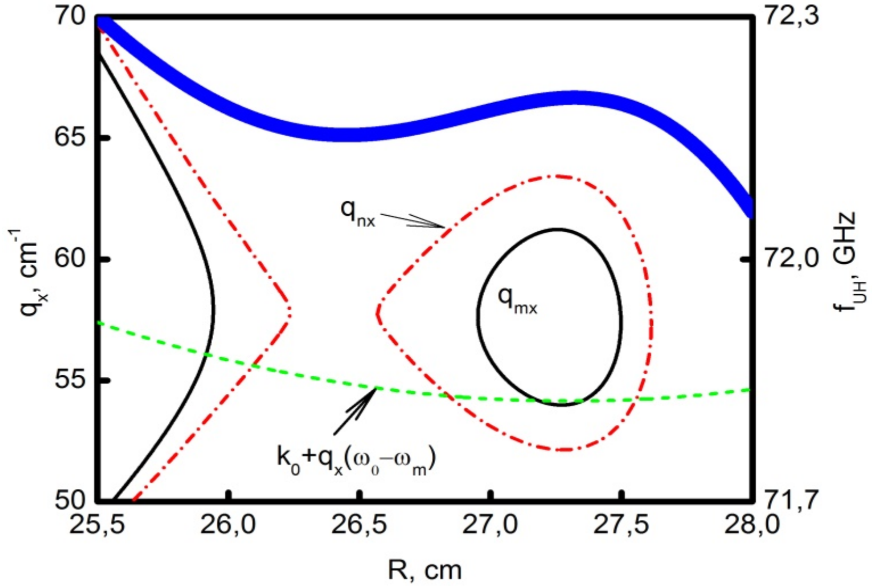
Saturation of t = t + l_{UH} PDI due to odd-step cascade of secondary decays



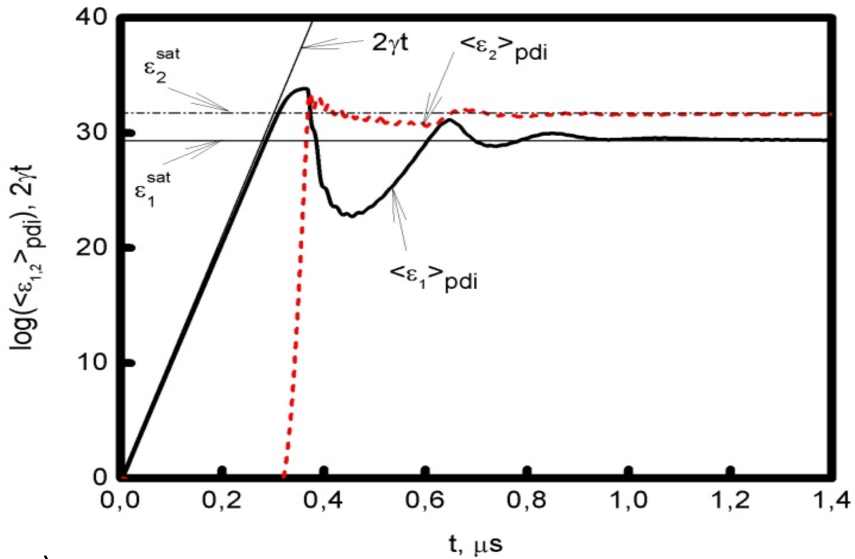
Primary decay

$$\begin{cases} \dfrac{\partial a_m}{\partial t} + i\Lambda_{my}\dfrac{\partial^2 a_m}{\partial y^2} + i\Lambda_{mz}\dfrac{\partial^2 a_m}{\partial z^2} = \nu_0(a_0)\exp\left(-\dfrac{y^2+z^2}{2w^2}\right)a_m - \nu_s\left|a_n\right|^2 a_m \\ \dfrac{\partial a_n}{\partial t} + i\Lambda_{my}\dfrac{\partial^2 a_n}{\partial y^2} + i\Lambda_{nz}\dfrac{\partial^2 a_n}{\partial z^2} = \nu_s\left|a_m\right|^2 a_n \end{cases}$$

Secondary decay



Dispersion curves of the trapped UH waves (solid line-primary), (dashed-dotted line-secondary) and the sum of wavenumbers of the pump and running primary UH wave (dashed line) .
The UHR profile is plotted by the thick solid line. At the local maximum of the density profile and. (TEXTOR parameters)



PDI saturation levels

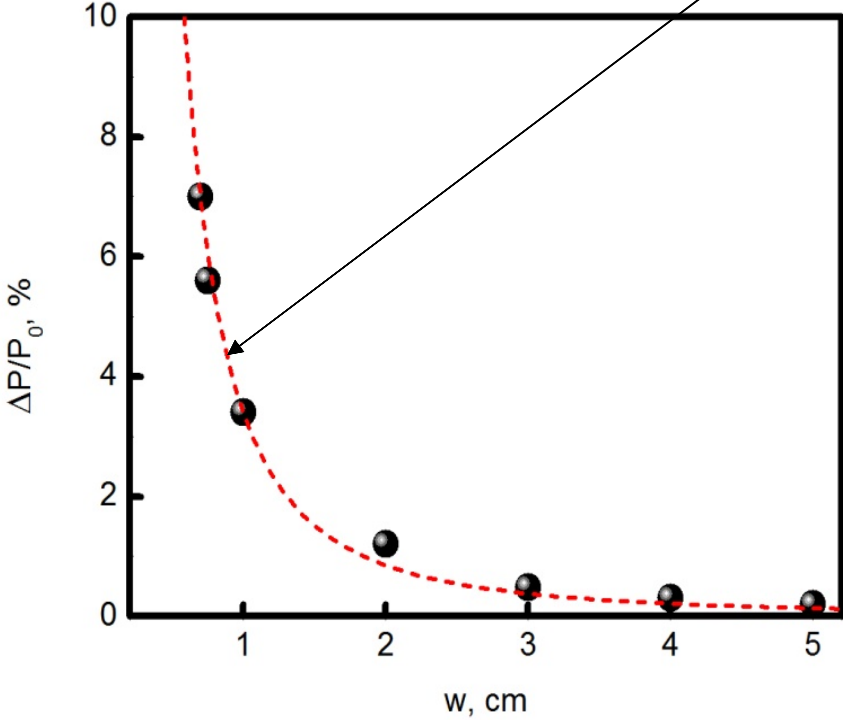
$$\varepsilon_m^s = \left|a_m^s\right|^2 \simeq \frac{1}{\left|\tau_\Lambda \nu_s\right|}, \varepsilon_n^s = \left|a_n^s\right|^2 \simeq \frac{\nu_0}{\nu_s}$$

Dependence of the anomalous absorption rate on the pump power and width

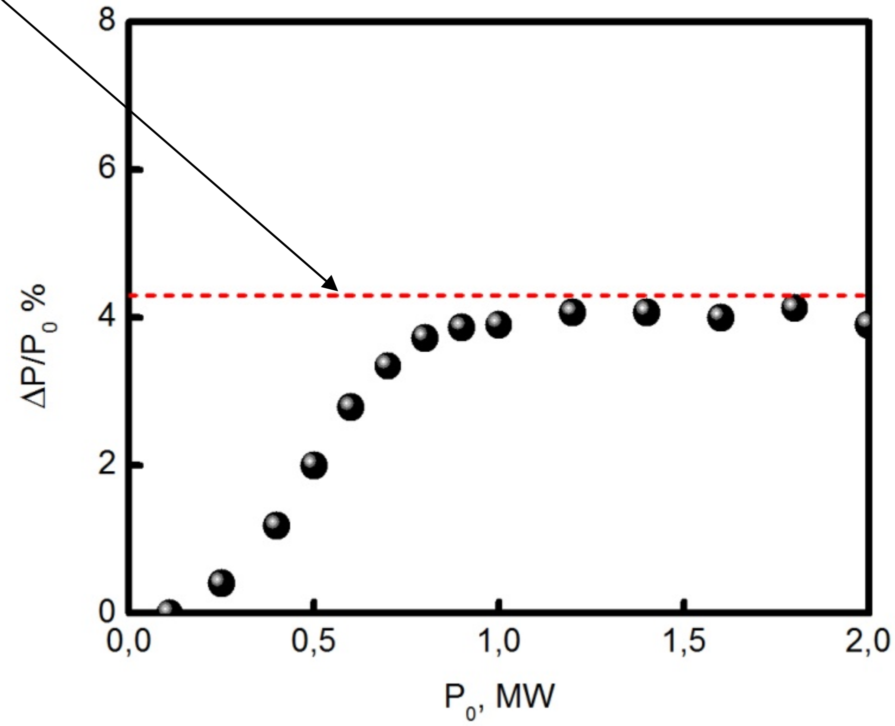
Analytical theory prediction:

$$\frac{\Delta P}{P_0} \approx \tilde{\gamma}_p \frac{8T_e}{P_0} \varepsilon_m^s \propto \frac{1}{w^2}$$

Increasing the beam width



Increasing the power of a beam



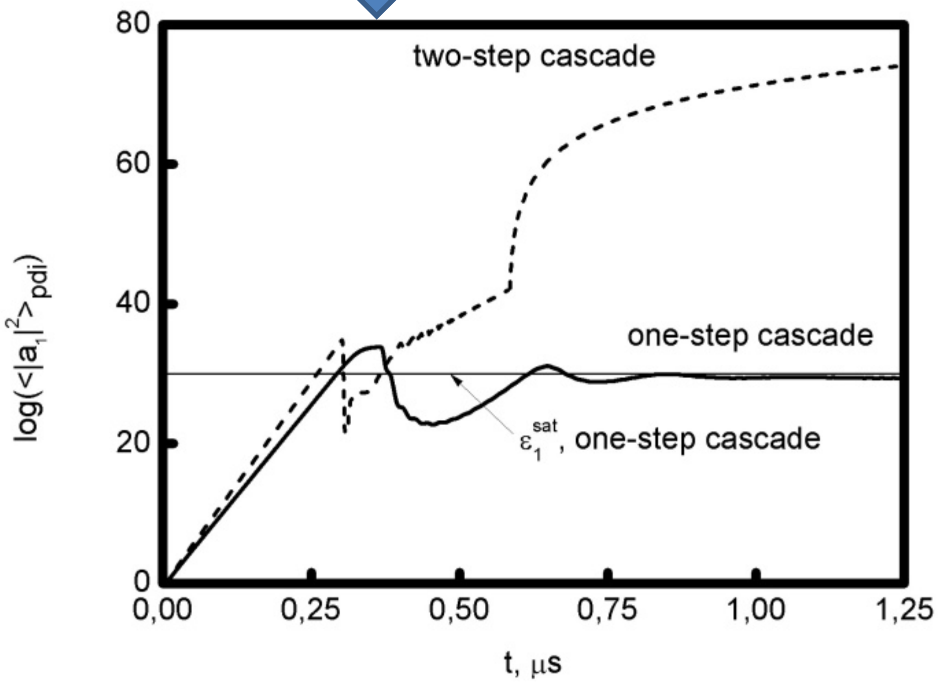
This dependence can explain the absence of the parametric phenomena in X2-mode ECRH experiments on DIII-D, in which wide pump beams were utilized

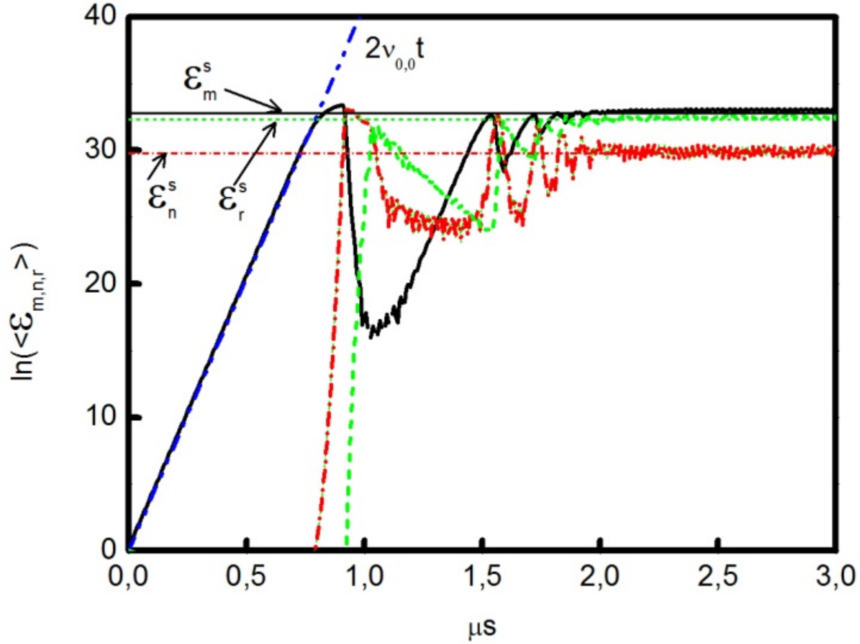
PDI saturation in the case of even-step cascade of secondary decays

$$
\begin{cases}
\dfrac{\partial a_m}{\partial t} + i\Lambda_{my}\dfrac{\partial^2 a_m}{\partial y^2} + i\Lambda_{mz}\dfrac{\partial^2 a_m}{\partial z^2} = \nu_0(a_0)\exp\left(-\dfrac{y^2+z^2}{2w^2}\right)a_m - \nu_s|a_n|^2 a_m \\
\dfrac{\partial a_n}{\partial t} + i\Lambda_{ny}\dfrac{\partial^2 a_n}{\partial y^2} + i\Lambda_{nz}\dfrac{\partial^2 a_n}{\partial z^2} = \nu_s|a_m|^2 a_n - \nu_t|a_p|^2 a_n \\
\dfrac{\partial a_p}{\partial t} + +i\Lambda_{py}\dfrac{\partial^2 a_p}{\partial y^2} + i\Lambda_{pz}\dfrac{\partial^2 a_p}{\partial z^2} = \nu_t|a_n|^2 a_p
\end{cases}
$$

+ pump depletion

$$
\left\{ \frac{\partial}{\partial \xi} a_0 = -\gamma_p \frac{T_e}{P_0}\frac{\omega_0}{\omega_m}\left|a_m(y,z)\right|^2 \int_{\xi}^{\infty} d\xi' a_0(\xi')\exp\left(i\Psi_p(\xi) - i\Psi_p(\xi')\right) \right.
$$

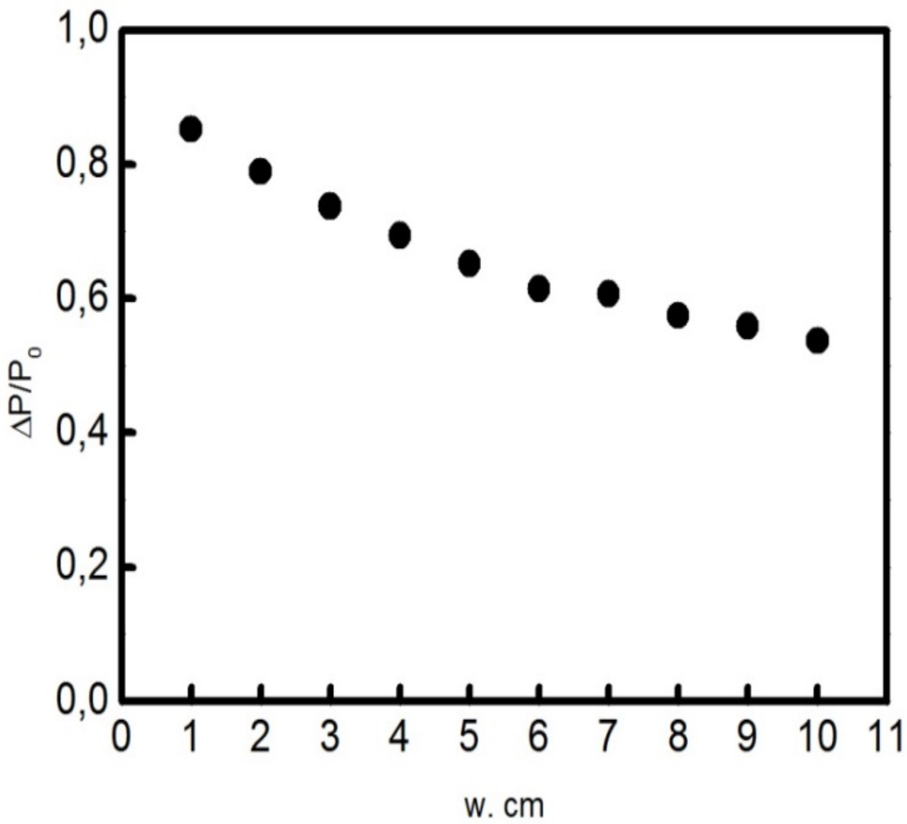




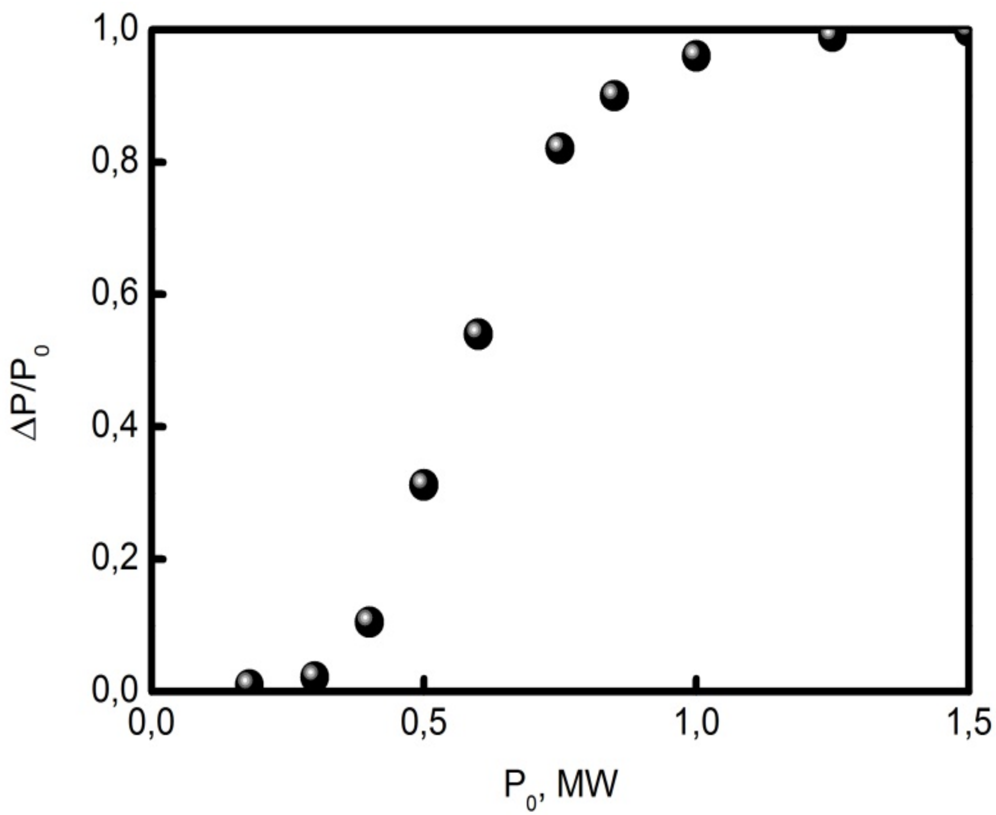
No saturation without pump depletion

Dependence of the anomalous absorption rate on the pump power and width

Increasing the beam width



Increasing the power of a beam



Some reduction of anomalous absorption rate with growing pump beam width is achieved, however not sufficient to speak of the PDI suppression.

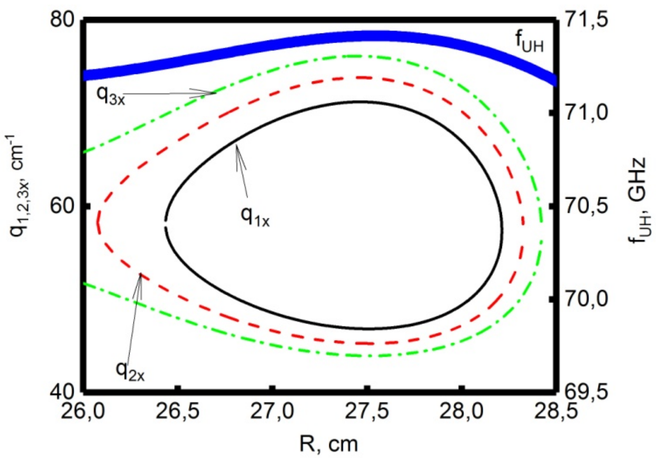
Saturation of $t = l_{UH} + l_{UH}$ PDI due to odd-step cascade of secondary decays

$$\frac{\partial a_1}{\partial t} - u_1 \frac{\partial a_1}{\partial y} + i\Lambda_{1y} \frac{\partial^2 a_1}{\partial y^2} + i\Lambda_{1z} \frac{\partial^2 a_1}{\partial z^2} = \nu_p(y,z) b_1 - \nu_d |b_1|^2 a_1 - \nu_s |a_2|^2 a_1$$

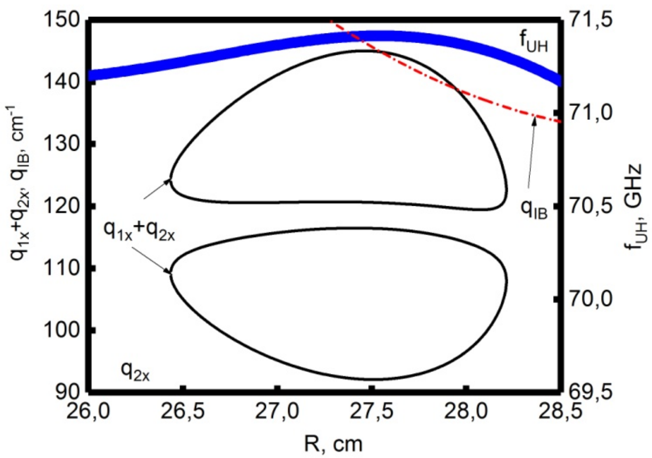
$$\frac{\partial b_1}{\partial t} + u_1 \frac{\partial b_1}{\partial y} - i\Lambda_{1y} \frac{\partial^2 b_1}{\partial y^2} - i\Lambda_{1z} \frac{\partial^2 b_1}{\partial z^2} = \nu_p^*(y,z) a_1 - \nu_d^* |a_1|^2 b_1 - \nu_s^* |b_2|^2 b_1$$

$$\frac{\partial a_2}{\partial t} - u_2 \frac{\partial a_2}{\partial y} - i\Lambda_{2y} \frac{\partial^2 a_2}{\partial y^2} - i\Lambda_{2z} \frac{\partial^2 a_2}{\partial z^2} = \nu_s^* |a_1|^2 a_2$$

$$\frac{\partial b_2}{\partial t} + u_2 \frac{\partial b_2}{\partial y} + i\Lambda_{2y} \frac{\partial^2 b_2}{\partial y^2} + i\Lambda_{2z} \frac{\partial^2 b_2}{\partial z^2} = \nu_s |b_1|^2 b_2$$



The dispersion curves of primary (the radial wavenumber , solid curve), secondary (the radial wavenumber , dashed curve) and non-trapped (dashed-dotted curve) UH waves and the UH frequency profile (thick solid curve. (TEXTOR parameters)

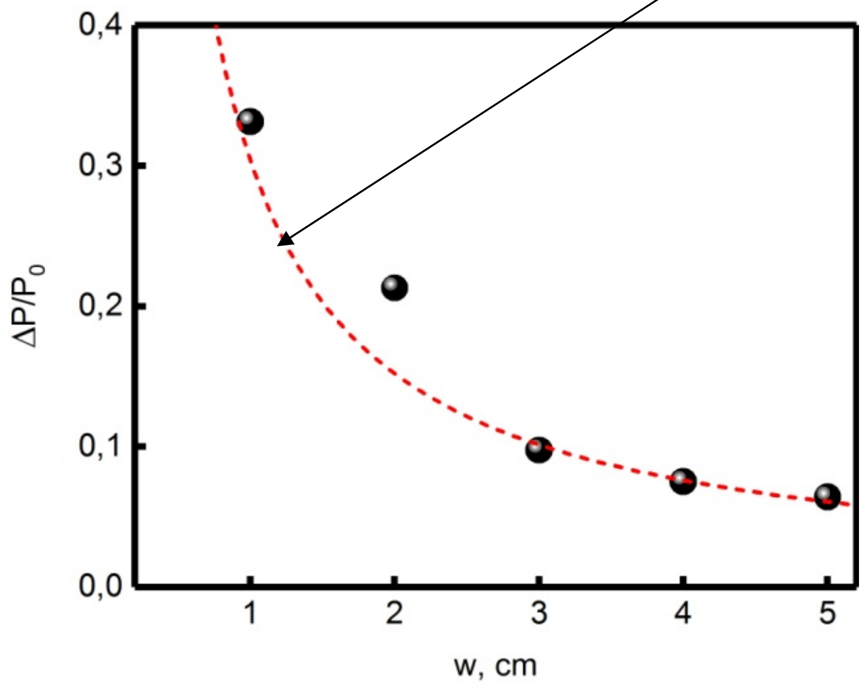


Dispersion curves for Secondary decay

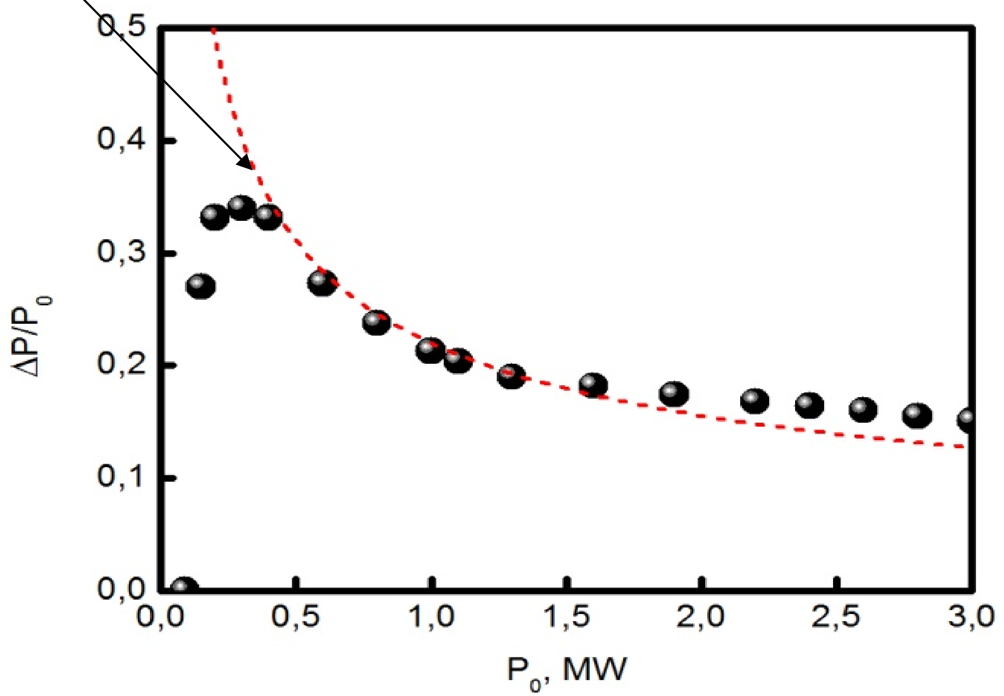
Dependence of the anomalous absorption rate on the pump power and width for the odd-step cascade

Analytical theory prediction: $$\frac{\Delta P}{P_0} \approx \frac{8\left|\nu_p\left(0,0;P_0\right)\right| T_e \varepsilon_1^s}{P_0} \propto \frac{1}{w\sqrt{P_0}}$$

Increasing the beam width



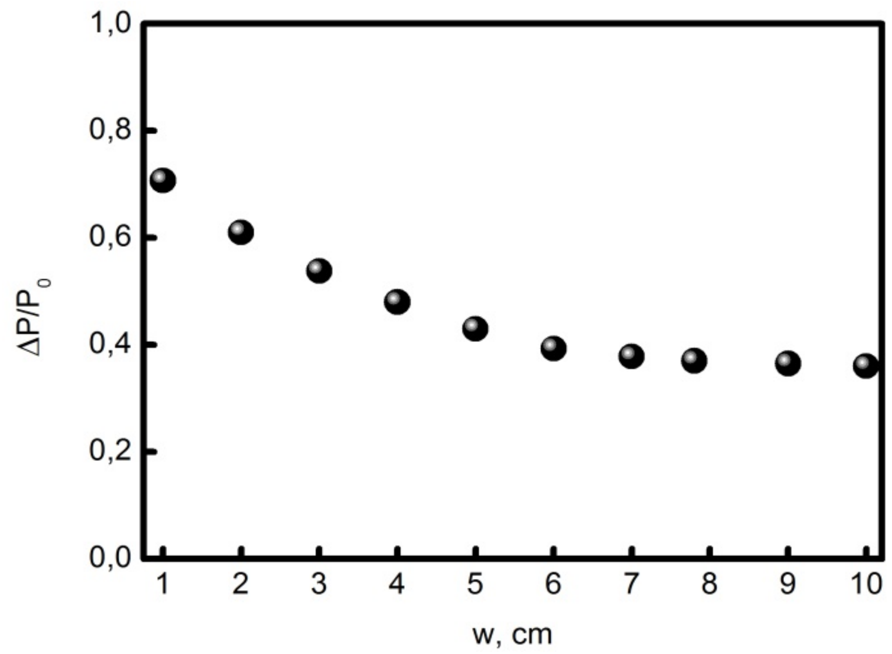
Increasing the power of a beam



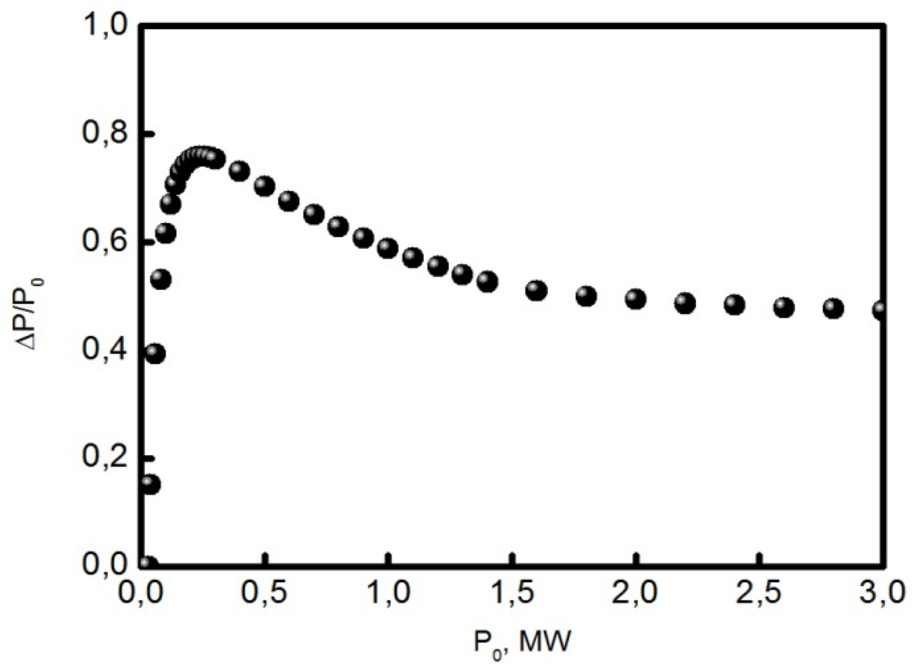
This dependence can explain the absence of the parametric phenomena in X2-mode ECRH experiments on DIII-D, in which wide pump beams were utilized

Dependence of the anomalous absorption rate on the pump power and width for the even-step cascade

Increasing the beam width



Increasing the power of a beam



Some reduction of anomalous absorption rate with growing pump beam width and power is Achieved, however not sufficient to speak of the PDI suppression.

Conclusions

- **The low-power-threshold parametric decay instabilities responsible for anomalous phenomena routinely observed in ECRH experiments at tokamaks and stellarators in the presence of non-monotonous plasma density profile are leading to substantial anomalous absorption of the microwave power (10% – 80%)**

- **The anomalous absorption in the range of 10%-80 % is possessing a potential to explain the evident broadening of pump wave power deposition profile in ECRH experiments.**

- **It is shown that the growth of the pump beam radius, leading to decrease of the two-UH plasmon parametric decay instability power-threshold, is able to reduce substantially the anomalous absorption rate caused by this instability.**