Induced microwave scattering in the ITER edge transport barrier at ECRH and possibility of its modeling at ASDEX-Upgrade

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OUTLINE

- **Introduction on low-threshold nonlinear wave phenomena at ECRH (observations and explanation)**
- **A new effect of 2D localization of lower hybrid (LH) wave in the direction of the plasma inhomogeneity in the edge transport barrier and in the toroidal direction due to the magnetic ripples.**
- **O-mode pump parametric decay instability (PDI) leading to low-power-threshold excitation of 2D trapped LH waves and forward-scattered O-mode radiation.**
- **Threshold and growth rate of the absolute PDI at O1 ECRH in ITER**
- **Threshold and growth rate of the absolute PDI at O2 ECRH and CTS in ASDEX-UPGRADE**
- **Conclusions**

INTRODUCTION

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

According to predictions of the linear theory:

- **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**

$$\Gamma >> 1 \text{ at } T_e \geq 1 \text{ keV and } R > 1 \text{ m}$$

- **The possibility of nonlinear effects in ECRH experiments was analayzed in (Cohen et al 1991, Litvak et al. 1993). Their power thresholds were found to exceed drastically the power of current and future microwaves generators (ITER, DEMO).**

Observation of anomalous phenomena in ECRH experiments

Last decade the mysterious phenomena in the X2-mode and O1-mode ECRH experiments were observed:

- **Anomalous scattering of the pump wave with the frequency downshift** (TEXTOR, AUG, W7-X, LHD, L-2M, FTU)

- **Fast ion generation in the X2-mode ECRH experiments** (TCV, TJ-II)

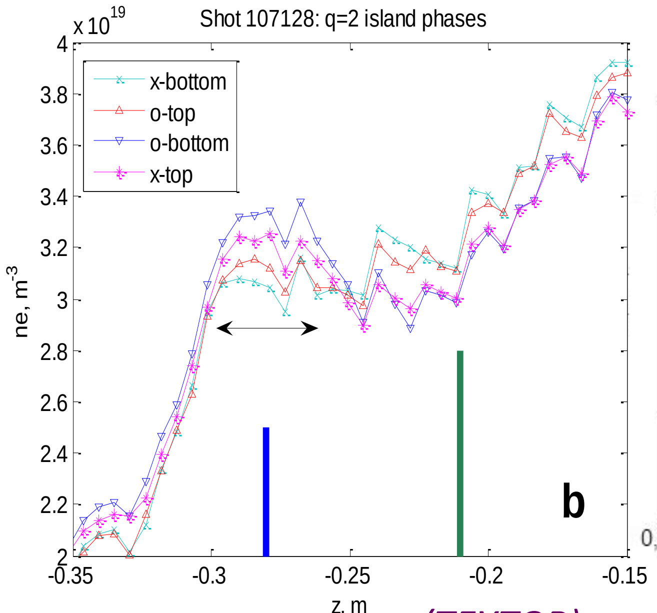
- **Broadening of the power deposition profile and/or nonlocal electron transport in the on-axis X2-mode ECRH experiments** (T-10, LHD, L-2M)

The observed effects look like associated with nonlinear phenomena, however the thresholds predicted by the standard parametric decay instability theory are far too high

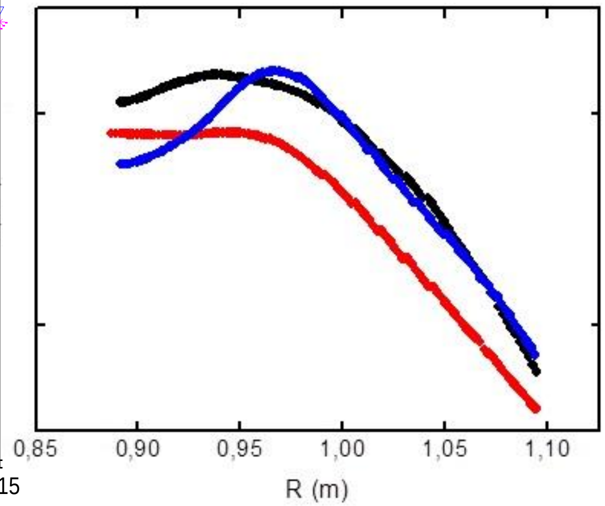
However this theory was developed for the monotonous density profile whereas in the ECRH experiment local maxima often exist associated with the discharge axis, magnetic islands, density pump-out effect or density fluctuations at the discharge edge.

Observation of anomalous phenomena in ECRH experiments

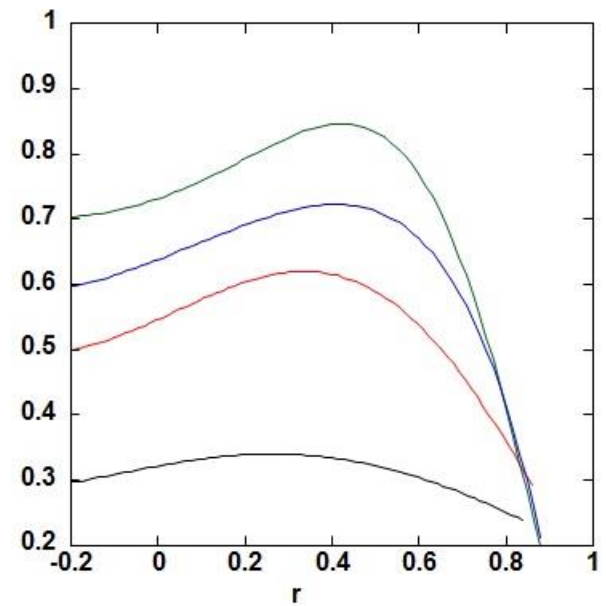
Next to all these anomalous effects were observed in the presence of a ***nonmonotonic (hollow)*** density profile*



M.Kantor et al. 2009 PPCF 51 055002 *(TEXTOR)*



Courtesy of S. Coda *(TCV)*



Rapisarda et al 2007 PPCF 49 309 (TJ-II)

which is originated due to:
a) the presence of a magnetic island,
b) the density pump-out effect
c) the centre of a plasma column

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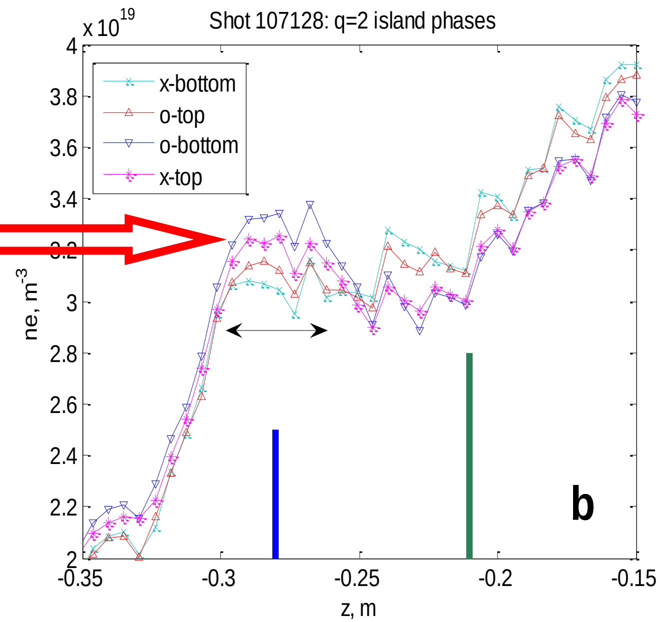
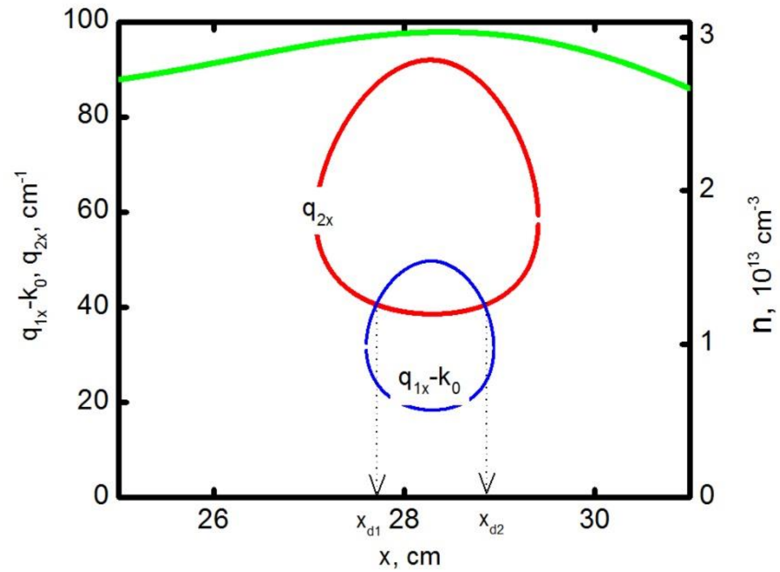
* The theory (Porkolab 1988; Cohen 1991; Litvak 1993) deals with a **monotonic** density profile

Low-threshold parametric decay excitation due to trapping of the UH waves in the density maximum vicinity

$\omega_0 \approx 2\omega_{uh}$





$$T_e = 500\text{eV}, \omega_0 = 140\text{GHz}, \; f_1 = 70.18\text{GHz} \approx \frac{f_0}{2}, \; f_2 = 68.82\text{GHz} \approx \frac{f_0}{2}$$

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

Lower hybrid (LH) waves in the Edge Transport Barrier

$$\phi(\mathbf{r}) = \frac{\psi(x,z)}{2}\exp\left(iq_y y + i\Omega t\right) + c.c.$$

The Poisson equation for the LH wave potential:

$$\hat{D}_{LHW}\psi = \left(\varepsilon(\Omega)\left(\partial_{xx} - q_y^2\right) + \partial_x\varepsilon(\Omega)\partial_x + \partial_x g(\Omega) q_y + \eta(\Omega)\partial_{zz}\right)\psi = 0$$

where $\varepsilon = 1 + \omega_{pe}^2/\omega_{ce}^2 - \omega_{pi}^2/\Omega^2;\ \eta = 1 - \omega_{pe}^2/\Omega^2;\ g = -\omega_{pe}^2/\Omega\omega_{ce}$

WKB version of this equation:

$$\varepsilon(\Omega)\left(q_x^2 + q_y^2\right) + \eta(\Omega) q_z^2 = 0$$

No transparency for $q_z = 0$

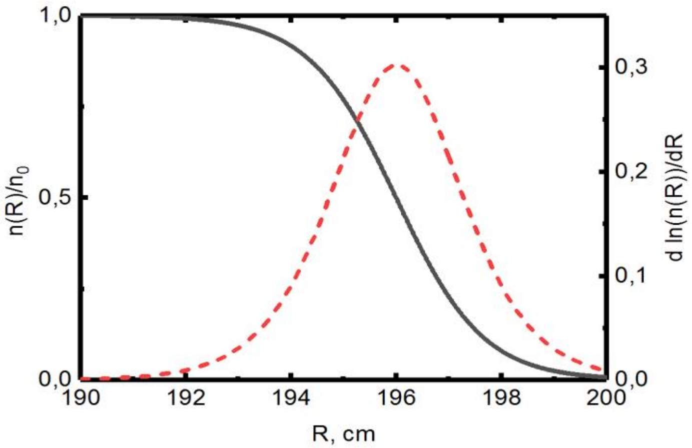
However $|g| \gg |\varepsilon|$ and therefore the Poisson equation provides transparency

for strong enough gradients $\partial_x g(\Omega) > \varepsilon(\Omega) q_y$

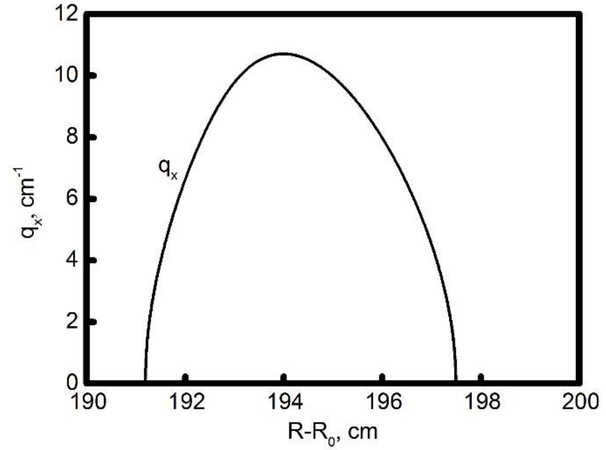
$$q_x^2 = \frac{\partial_x g(\Omega) q_y}{\varepsilon(\Omega)} - q_y^2 = Q(\Omega) q_y - q_y^2$$

E.Z. Gusakov, M.A. Irzak, A.D. Piliya, 1997 JETP Lett. 65, 25–31

Trapping of LH waves in the Edge Transport Barrier



The density profile normalized to the density at the magnetic axis (solid line), and the profile of its derivation (dashed line).



The LH wave dispersion curve

In the vicinity of the density profile inflection point and toroidal magnetic field minimum between coils the Poisson equation takes a form describing trapped LH waves:

$$\hat{D}_{LHW}\psi = \varepsilon(\Omega, x_m)\left(\partial_{xx} + Q_0 q_y - q_y^2 - K_x^4 (x - x_m)^2\right)\psi - \left|\eta(\Omega, x_m)\right|\left(\partial_{zz} - K_z^4 z^2\right)\psi = 0$$

here we introduced: $Q \approx Q_0(1-(x-x_m)^2/(2l_x^2)+z^2/(2l_z^2))$

$$K_x = (Q_0 q_y / (2l_x^2))^{1/4} \qquad K_z = K_x (l_z^2 \,|\eta(\omega_L)|\, / l_x^2)^{-1/4}$$

$$B = \overline{B}\left(1 - \delta(x, y)\cos(Nz/R)\right)$$

Remarkable property of 2D trapped LH wave

$$v_{gy} = \frac{\partial D_{LHW}}{\partial q_y} \Big/ \frac{\partial D_{LHW}}{\partial \Omega}\Bigg| = Q_0\left(\Omega\right) - 2q_y \approx 0 \quad \text{at} \quad q_y^* = Q_0\left(\Omega\right)/2$$

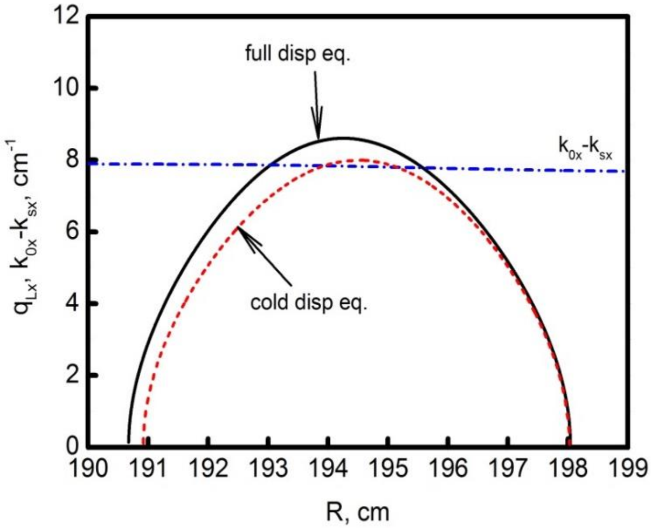
For such a LHW with the poloidal number $q_y^* = Q_0\,(\Omega)/2$ the group velocity tends to zero, and therefore the only mechanism of energy loss is diffraction, which is a slower process than convection.

Parametric decay of the O-mode pump into the 2D trapped LH wave and a forward-scattered O-mode

Equations describing daughter waves

$$\begin{cases} \left(\Delta_\perp - q_y^2\right) A_s + \omega_s^2 / c^2 \eta\left(\omega_s, x\right) A_s = -i \dfrac{\omega_{pe}^2}{\omega_0 \omega_{ce} \bar{B}} \dfrac{\omega_s}{c} \Delta_\perp E_0^* \psi \\ \hat{D}_{LHW} \psi = i \dfrac{\omega_{pe}^2}{\omega_0 \omega_{ce} \bar{B}} \dfrac{c}{\omega_s} \Delta_\perp E_0 A_s \end{cases}$$

Decay condition fulfillment



$q_y^* = 7.99\ \mathrm{cm}^{-1}$ $f_0 = 170\ \mathrm{GHz}$

$T_i = 1\ \mathrm{keV}$ $f_s = 168.88\ \mathrm{GHz}$

$$\mathbf{E}_0 = \mathbf{e}_z \sqrt{\frac{2P_0}{cw^2 n_x\left(\omega_0, x\right)}} \exp\left(-\frac{y^2+z^2}{2w^2} + i\int_0^x k_x\left(\omega_0, x'\right) dx' - i\omega_0 t\right) + c.c. \leftrightarrow \text{a beam of O-mode pump}$$

$$\mathbf{E}_s\left(\mathbf{r}\right) = \mathbf{e}_z \frac{A_s\left(x\right)}{2} \exp\left(iq_y^* y + i\omega_s t\right) + c.c. \leftrightarrow \text{a side-scattered O-mode microwave}$$

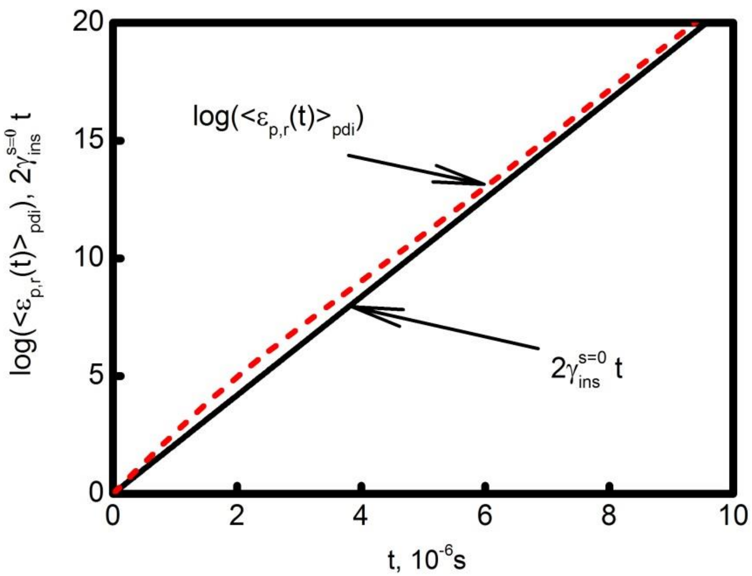
Parametric excitation of the 2D trapped LH wave by the O-mode pump

$$\left(\frac{\partial}{\partial t} + i\Lambda_y \frac{\partial^2}{\partial y^2}\right)\psi_{p,r} = \gamma \exp\left(-\frac{y^2}{w^2}\right)\psi_{p,r}$$

$$\gamma = i\frac{\omega_{pe}^4\left(k_x^2(\omega_0)+q_y^{*2}\right)^2}{\omega_0^2\omega_{ce}^2\left|<\partial_{\omega_L} D_{LHW}>\right|}\frac{2P_0}{cn_{0x}w^2\bar{B}^2}\Bigg|_{x_m}\int_{-\infty}^{\infty} dz\left|f_r(z)\right|^2 \exp\left(-\frac{z^2}{w^2}\right)\int_{-\infty}^{\infty} dx f_p(x)^* G_s\left\{\exp\left(i\int_{x'}^{x} k_x(\omega_0)dx''\right)f_p(x')\right\}$$

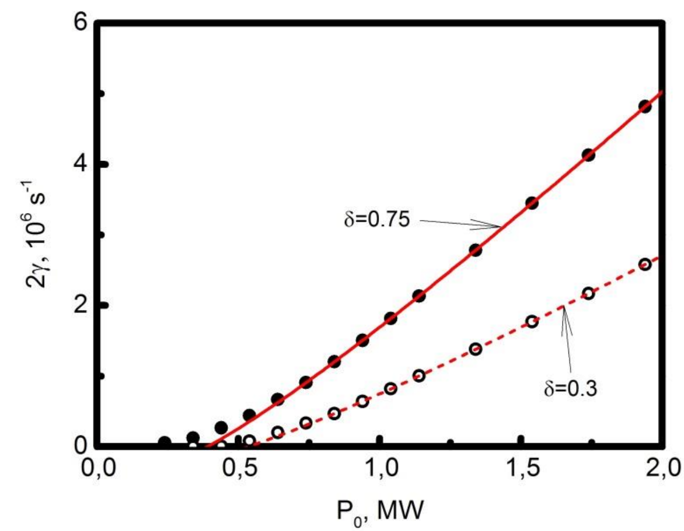
$$G_s\{\ldots\} = \frac{ic}{2\omega_s}\int_{-\infty}^{x}\frac{dx'\{\ldots\}}{\sqrt{n_{sx}(x)n_{sx}(x')}}\exp\left(-i\int_{x}^{x'}\left(k_{0x}(x'')-k_{sx}(q_\zeta^*,x'')\right)dx''\right)$$

The PDI threshold is determined by a balance of nonlinear pumping and diffractive losses



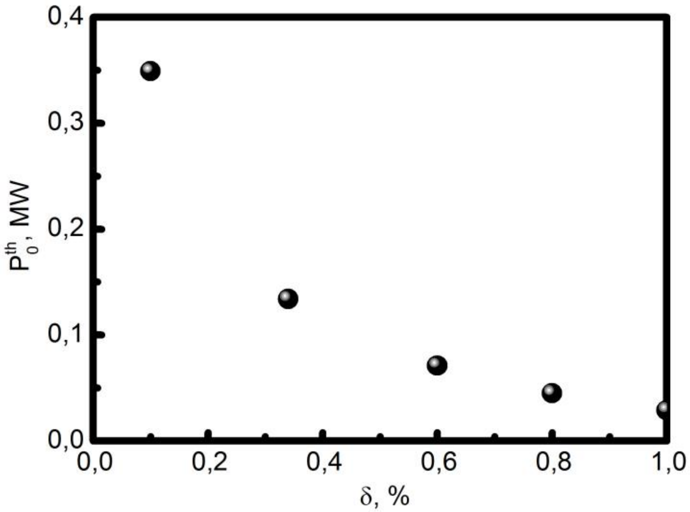
$$\gamma_{th} \sim \frac{\Lambda_y}{w^2}$$

$$P_0^{th} = 0.158\ \text{MW}$$



$s = 0, P_0 = 1\text{MW}$ **Gusakov, Popov 2022 PRL 128, 065001** $w = 2$ cm

Parametric decay threshold (ITER)



$$B_0 = 4.5\ \mathrm{T}$$

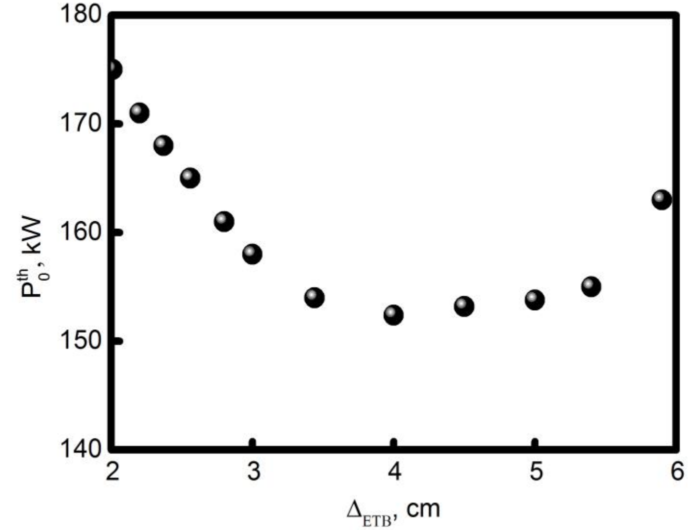
$$f_0 = 170\ \mathrm{GHz}$$

$$T_{e,i}\left(x_{\inf}\right) = 1390\ \mathrm{eV}$$

$$n\big|_{x_i} = 4.1\times 10^{13}\,\mathrm{cm}^{-3}$$

$$\Delta_{ETB} = \left|\partial \ln n / \partial x\right|_{x_i}$$

$$w = 2\ \mathrm{cm}$$

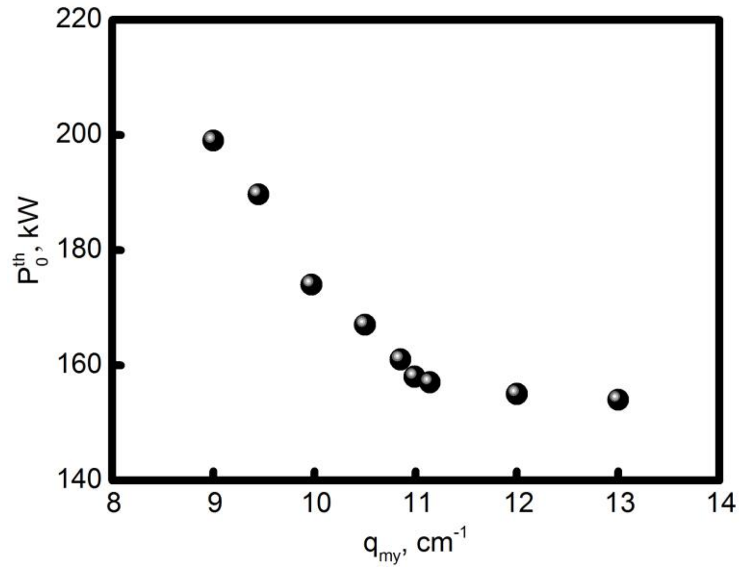


$$\Delta_{\mathrm{ETB}} = 3\ \mathrm{cm}$$

$$f_{s0} = 168.94\ \mathrm{GHz}$$

$$q_{ym} = 10.99\ \mathrm{cm}^{-1}$$

$$\vartheta_s = 17.13^0$$



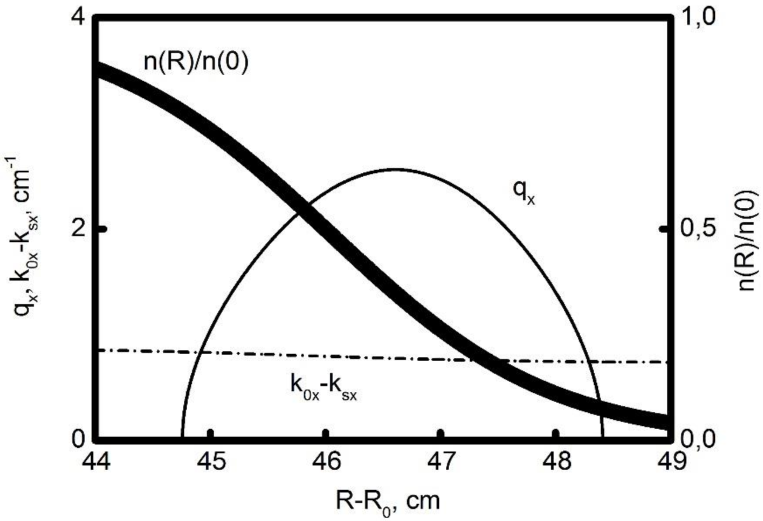
$$\delta \simeq 0.32\%$$

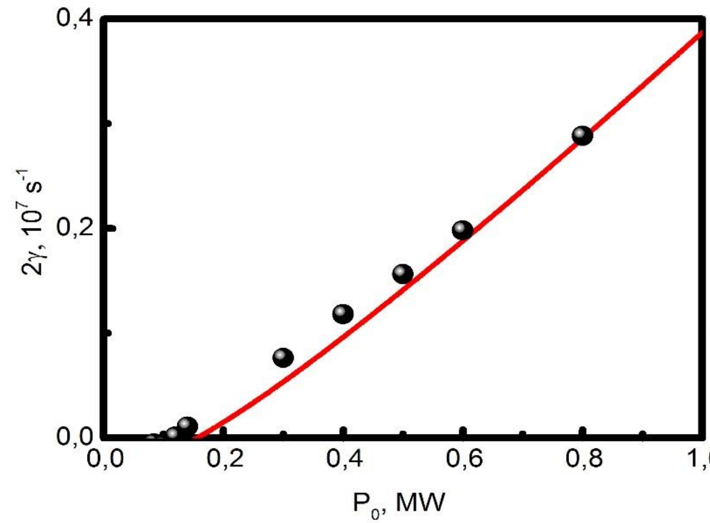
$$q_{ym} = 10.99\ \mathrm{cm}^{-1}$$

$$\vartheta_s = 17.13^0$$

The PDI threshold is three orders of magnitude lower than the standard theory prediction

Parametric decay at O2 ECRH in ASDEX-UG





$$B_0 = 2.5 \text{ T}$$

$$f_0 = 140 \text{ GHz}$$

$$w = 2 \text{ cm}$$

$$\Delta_{\text{ETB}} = 2 \text{ cm}$$

$$T_{e,i}\left(x_{\text{inf}}\right) = 200 \text{ eV}$$

$$q_{ym} = 2.4 \text{ cm}^{-1}$$

$$f_s = 137.02 \text{ GHz}$$

$$n\left(x_{\text{inf}}\right) = 0.7 \times 10^{14} \text{cm}^{-3}$$

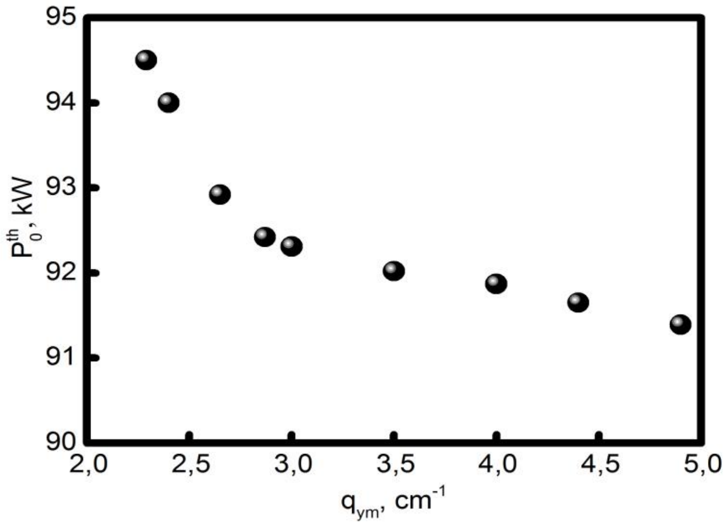
$$\vartheta = \tan\left(q_{ym} / k_{sx}\right)^{-1} = 5.3^0$$

$$\delta \simeq 0.5\%$$

$$P_0^{th} = 0.094 \text{ MW}$$

The PDI threshold is three orders of magnitude lower than the standard theory prediction

Parametric decay at O2 ECRH in ASDEX-Upgrade



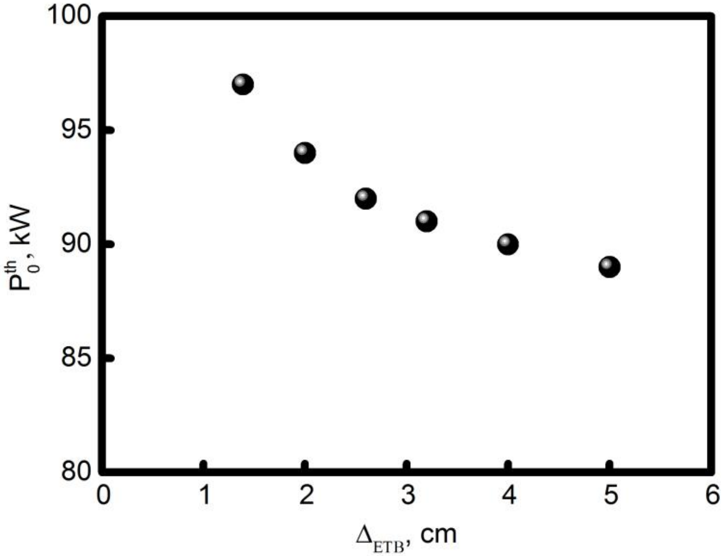
$$B_0 = 2.5 \text{ T}$$

$$f_0 = 140 \text{ GHz}$$

$$T_{e,i}\left(x_{\inf}\right) = 200 \text{ eV}$$

$$n\left(x_{\inf}\right) = 0.7 \times 10^{14} \text{cm}^{-}$$

$$w = 2 \text{ cm}$$



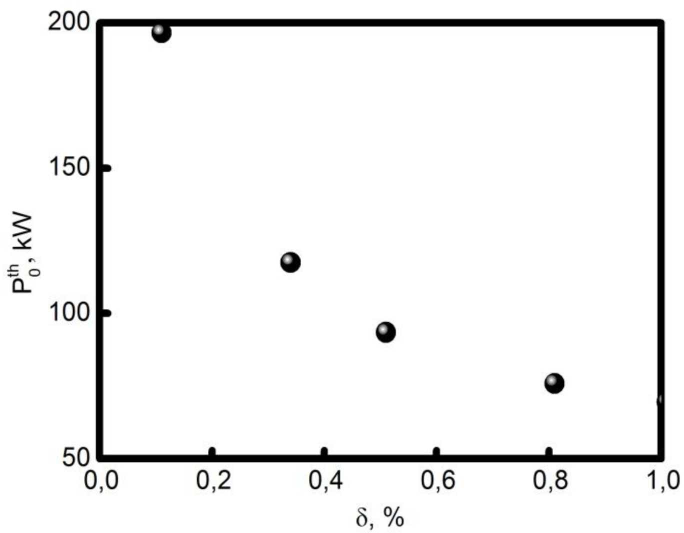
$$\Delta_{\text{ETB}} = 2 \text{ cm}$$

$$f_s = 137.02 \text{ GHz}$$

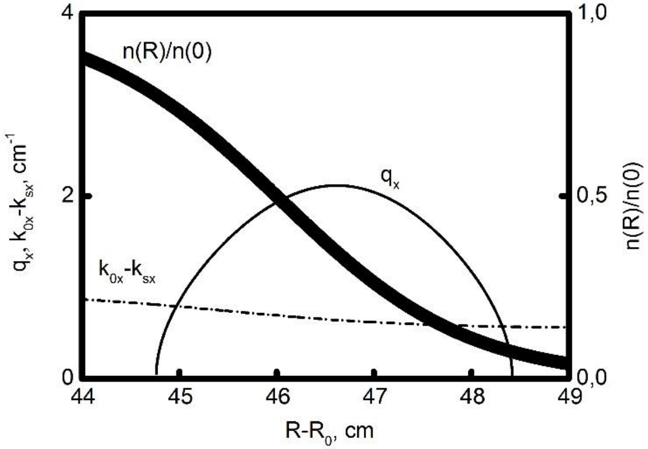
$$\delta \simeq 0.5\%$$

$$q_{ym} = 2.4 \text{ cm}^{-1}$$

$$\vartheta = \tan\left(q_{ym} / k_{sx}\right)^{-1} = 5.3^0$$



Parametric decay in CTS experiment at ASDEX-UG

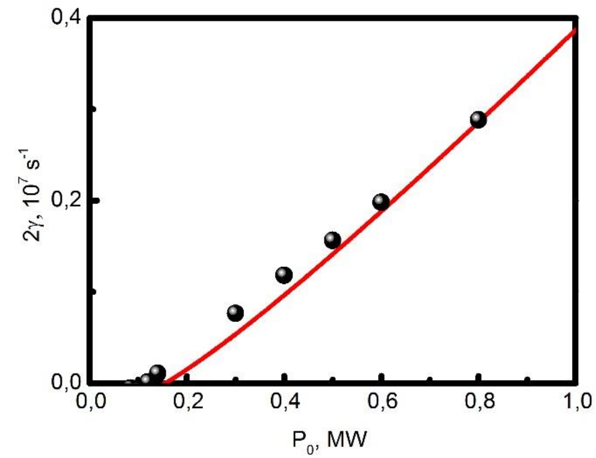


$$B_0 = 2.5 \text{ T}$$

$$f_0 = 105 \text{ GHz}$$

$$T_{e,i}\left(x_{\text{inf}}\right) = 200 \text{ eV}$$

$$n\left(x_{\text{inf}}\right) = 0.7\times 10^{14} \text{cm}^{-3}$$



$$\delta \simeq 0.5\%$$

$$w = 2 \text{ cm}$$

$$\Delta_{\text{ETB}} = 2 \text{ cm}$$

$$q_{ym} = 2.02 \text{ cm}^{-1}$$

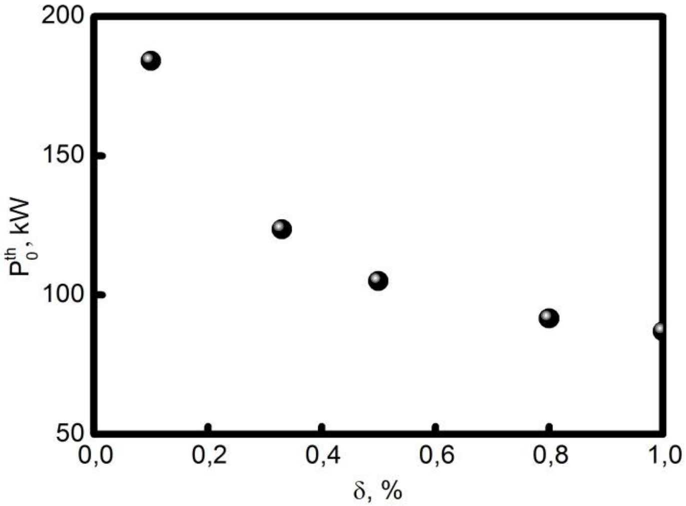
$$f_s = 101.4 \text{ GHz}$$

$$\vartheta = \tan\left(q_{ym} / k_{sx}\right)^{-1} = 6.3^0$$

$$P_0^{th} = 0.105 \text{ MW}$$

The PDI threshold is three orders of magnitude lower than the standard theory prediction

Parametric decay in CTS experiment at ASDEX-Upgrade

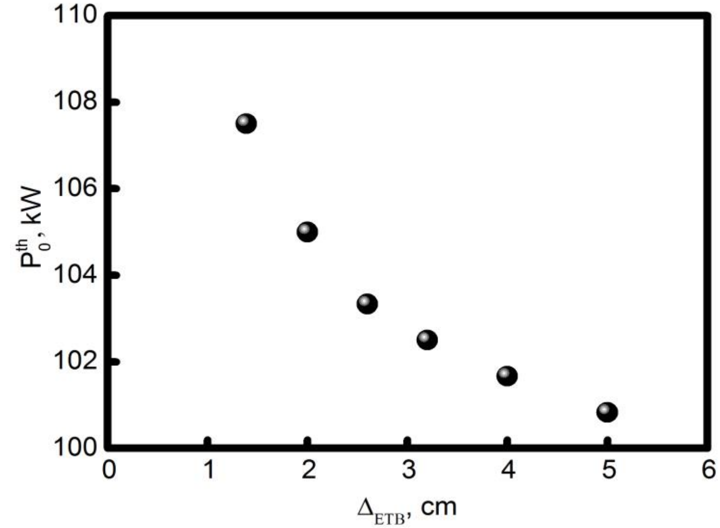


$$B_0 = 2.5\ \mathrm{T}$$

$$f_0 = 105\ \mathrm{GHz}$$

$$T_{e,i}\left(x_{\mathrm{inf}}\right) = 200\ \mathrm{eV}$$

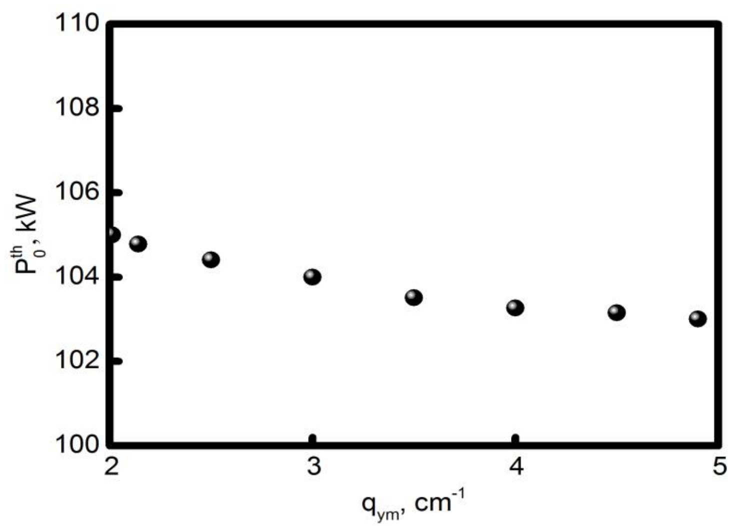
$$n\left(x_{\mathrm{inf}}\right) = 0.7 \times 10^{14}\,\mathrm{cm}^{-3}$$



$$w = 2\ \mathrm{cm}$$

$$\Delta_{\mathrm{ETB}} = 2\ \mathrm{cm}$$

$$f_s = 101.4\ \mathrm{GHz}$$



$$\delta \simeq 0.5\%$$

$$q_{ym} = 2.02\ \mathrm{cm}^{-1}$$

$$\vartheta = \tan\left(q_{ym} / k_{sx}\right)^{-1} = 6.3^0$$

Conclusions

- It is predicted that the lower hybrid wave 2D trapping in the edge transport barrier leads to the low power-threshold induced forward-scattering absolute parametric decay instability of ordinary mode pump. The minimum power-threshold is less than 400 kW in a single microwave beam in ITER and less than 200 kW in ASDEX-Upgrade.
- This nonlinear effect, leading to anomalous scattering of heating power, could easily occur in O1-mode ECRH experiments at ITER, where multiple megawatt pump beams are planned for utilization. This effect can have a significant impact on the performance of the ECRH system at ITER and should be taken into account seriously when planning the future experiments.
- It is possible to investigate the forward-scattering PDI in O2-mode ECRH and CTS experiments in ASDEX-Upgrade