POSSIBILITY OF THE GIANT SCATTERING ENHANCEMENT DUE TO WAVE TRAPPING IN THE REFLECTOMETRY EXPERIMENT

E. Gusakov [1], S. Heuraux [2], A. Popov [1]

[1] *Ioffe Institute, St.Petersburg, Russia*

[2] *IJL, UMR-CNRS 7198, Vandoeuvre CEDEX, France*

1. Introduction

The effect of microwave scattering is often used for the purpose of plasma wave and fluctuation diagnostics in magnetic fusion devices. The most sensitive and local modifications of this method are based on the so called enhanced scattering effect first proposed by A.D. Piliya in relation with backscattering in the plasma resonance [1]. This effect justified in [2] for the upper hybrid resonance backscattering using the electrodynamics reciprocity theorem occurs in the region of the local amplification of the field. As it was shown in [3] the overlapping of the probing and backscattering field growth regions is very important for the backscattering signal enhancement. The enhanced scattering effect due to the growth of the probing and scattered wave amplitude in the cut off vicinity is responsible for localization of the fluctuation reflectometry measurements and for the high scattering efficiency of this diagnostics. However, in the reflectometry case the field growth is weak and therefore the enhancement effect and localization is not that strong.

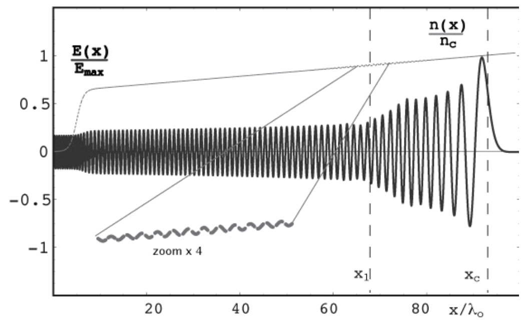

Figure1 *Normalized plasma density (gray dashed curve) and electric field (black solid curve) distributions in a case of single BBS in presence of cut-off. Density gradient length is $390\lambda_0$, δ_1=1%*

The aim of this paper is to show that an amplification of the probing can be realized, which is based on the wave trapping in plasma due to strong Bragg backscattering (BBS) induced by the quasi coherent density perturbations. Two ways of the wave trapping in the artificial cavity are considered relevant for all polarization used in reflectometry. In the first, typical for the

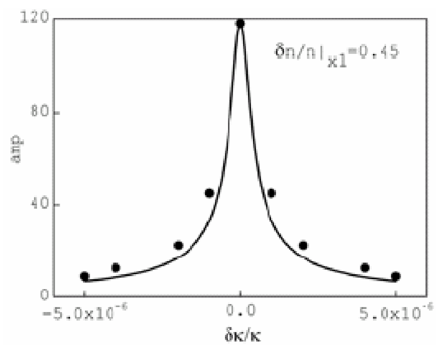

Figure2 *Amplification factor versus $\delta\kappa$. Solid curve – formula, scattered circles-simulation. Density gradient length is $390\lambda_0$.*

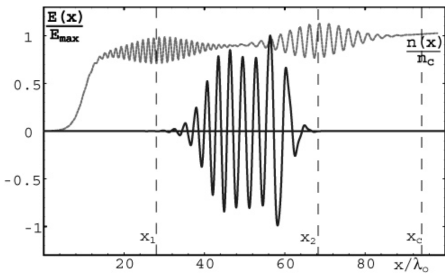

Figure3 *Electric field distribution (black solid curve) and normalized plasma density distribution (grey dashed curve) between two perturbations. Density gradient length is 390λ_0.*

reflectometry experiment, the trapping occurs between one BBS point and the cut off, whereas in the second it takes place between two fluctuations. Enhancement of the wave field in the cavity is investigated both numerically and analytically. Based on the obtained field amplification factors the scattering off the turbulence localized in the cavity region is calculated and shown to be strongly enhanced compared to the standard reflectometry or microwave scattering. Analytical predictions of the enhancement factor are shown to agree well with the results of the full wave 1D numerical modeling.

2. The enhanced scattering effect provided by microwave trapping.

In this section we analyze analytically the wave trapping effect leading to the probing wave electric field enhancement, which is often observed in the 2D numerical computations of fluctuation reflectometry at high turbulence level. As it was shown in [4] this effect persists already in 1D numerical modeling, when an intensive quasi-coherent fluctuation exists in plasma far enough from the cut-off of the probing wave allowing BBS there. Focusing on this case we consider the influence of a single quasi-coherent mode with the radial wave vector κ_1 and the amplitude δn_1 on microwave propagation at plasma parameters for which the cut-off is in the plasma volume, however far from the Bragg resonance (BR). The electric field with the unit amplitude $a_i^{in}=1$, incident on the BR from the plasma edge is described by following expressions on the both sides of the BR, position of which $x=x_1$ is determined by the Bragg resonance condition $2k_\alpha(x_1)-\kappa_1=0$:

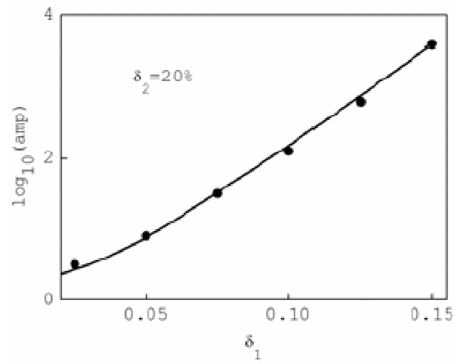

Figure4 *Amplification factor versus fluctuation amplitude δ_1. Solid curve is analytical prediction, circles - numerical modelling. Density gradient length is 390λ_0*

$$E_\alpha(x)=\frac{1}{\sqrt{k_\alpha(x)}}\begin{cases}\exp\left(i\int_0^x k_\alpha(x')dx'\right)+a_r^{out}\exp\left(-i\int_{x_1}^x k_\alpha(x')dx'\right), & x_1-x>>l=\left|dk_\alpha/dx\right|_{x_1}^{-1/2}\\ a_i^{out}\exp\left(i\int_0^x k_\alpha(x')dx'\right)+a_r^{in}\exp\left(-i\int_{x_1}^x k_\alpha(x')dx'\right), & x-x_1>>l\end{cases} \quad (1)$$

where $\alpha = o,e$ correspond to the ordinary mode and extraordinary mode, respectively, $E_{o,e} \equiv E_{z,y}$ and $k_{o,e}^2 = \omega^2/c^2 \cdot \left(1-\upsilon, \left((1-\upsilon)^2 - u\right)/(1-u-\upsilon)\right)$ with $\upsilon = \omega_{pe}^2/\omega^2, u = \omega_{ce}^2/\omega^2$. Here the amplitude a_r^{in} corresponds to the wave reflected from the cut-off and incident onto the BR from there, whereas a_i^{out} and a_r^{out} describe waves radiated from BR to the cut-off and plasma edge, respectively. As it was shown in [5] the waves leaving the BR region result from superposition of the waves directly transmitted through the BR and those reflected there due to BBS. As result

$$a_i^{out} = S_{ii} \big/ \left(1 - S_{ir}\exp(-i2\varphi)\right), \qquad (2)$$

where $S_{ii} = \exp(-\pi Z_1/2)$ and $S_{ir} = (1-i)\sqrt{2\pi/Z_1}\exp(-\pi Z_1/4)/\Gamma(iZ_1/2)$ are elements of S – matrix [5], $Z_1 = (\omega/c)^4\left[h_\alpha \cdot \delta n_1/n_c \cdot l/\kappa_1\right]^2$, $h_o = 1$, $h_e = \left([1-2\upsilon][1-u]+\upsilon^2\right)/[1-u-\upsilon]^2$, $\varphi = \varphi_0 + \delta\varphi$ consisting of the regular WKB phase φ_0 and a smaller part $\delta\varphi(\delta n_1)$ related to the probing wave dispersion relation modification far from the BR due to BBS important at $Z_1 > 1$. According to (2) the transmission is generally exponentially small, unless the specific resonance condition $2\varphi + \varphi_\Gamma(\delta n_1) = 2\pi n,\ n \in Z$, where φ_Γ being a phase associated with the Gamma function, is met by the phase φ minimising the absolute value of the denominator in (2). In this resonant case at $Z_1 > 1$ the wave circulating between the BR and cut off is, on contrary, exponentially large $a_i^{out} \approx \exp(\pi Z_1/2) a_i^{in}$, which is explained by formation of a “weakly coupled cavity” between the cut off and strongly reflecting BR. The wave trapping by the cavity is clearly seen in numerical modelling shown in figure 1. The “cavity” quality factor is determined by exponentially small tunnelling through the BR region. Therefore at high $Z_1 > 1$ the width of the “resonance curve” is very narrow, as it is seen in figure 2, where the dependence of the amplification factor $amp = a_i^{out}/a_i^{in}$ on fluctuation wave number $\delta\kappa$ obtained numerically and analytically is shown. The wave trapping effect manifests itself in the experiment by enhanced scattering produced in the region of high field localisation. A similar wave trapping effect is possible also far from the cut off if a couple of strong quasi-coherent fluctuations satisfying conditions $Z_1(\delta n_1) > 1$,

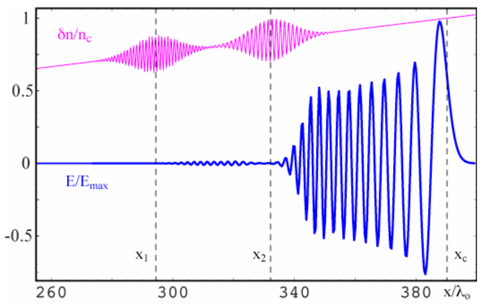

Figure 5. Electric field distribution (blue solid curve) and normalized plasma density distribution (pink curve) between three perturbations and cut-off. Density gradient length is 390λ₀.

$Z_2(\delta n_2) > 1$ exists in plasma. Being good reflectors, these fluctuations situated in the vicinity of corresponding BR are leading to the effective cavity formation. The electric field structure computed for such a cavity is shown in figure 3. The analytical treatment provides in this case the resonance phase condition $2(\varphi_0 + \delta\varphi) + \varphi_\Gamma(\delta n_1) - \varphi_\Gamma(\delta n_2) = \pi(2n+1)$ and the maximal amplification expression

$$a_i^{out} \approx a_i^{in} \exp(\pi Z_1 / 2) / \left(1 + \exp\left[\pi (Z_1 - Z_2)\right]\right) \quad (3)$$

valid for $Z_1 < Z_2$. The perfect fit of this expression to the modeling results is shown in the figure 4, where the field amplification is plotted versus relative density perturbation amplitude. A two stages amplification of the probing field, permitting us to reach a certain numerical limit of the electric field in the "cavity", is shown in figure 5 where two perturbations and cut-off occurs. In this case an amplification factor of the electric field is a product of amplification factors in each of "weakly coupled cavities" $amp_{tot} = amp_{x_1-x_2} \times amp_{x_2-x_c}$. This scheme of enhanced scattering in a "cavity" which position could be controlled externally looks attractive and opens a way to provide local measurements in reflectometry.

3. Conclusions

As a result of analytical treatment performed in a simple 1D reflectometry model for quasi coherent fluctuations we may conclude that the wave trapping effect caused by cavity formation due to strong BBS has a potential for explanation of fast phase variation observed experimentally and open a way, if it is possible to organize specific quasi coherent density perturbations and control their position, to provide localized reconstruction of the radial wave-number spectrum in reflectometry. Within the Born approximation the sensitivity of diagnostics is increased by the square of the amplification factor in the area where the probing electric field is amplified, which provides the localisation of the measurements as it is shown by simulations.

Financial supports of RFBR grants 09-02-00453-a, 07-02-92162-CNRS and ANR06-BLAN-0084 are acknowledged

References

[1] A.D. Piliya, Zh. Tekh. Fiz. 36, 2195 (1966)

[2] K.M. Novik and A.D. Piliya, Plasma Phys. Control. Fusion 35, 357 (1994)

[3] E.Z. Gusakov and A.V. Surkov, Technical Physics Letters 29, 698 (2003)

[4] I. Boucher, C. Fanack, S. Heuraux *et al*., Plasma Phys. Control. Fusion 40, 1489 (1998)

[5] E.Z. Gusakov, S. Heuraux, A.Yu. Popov, Plasma Phys. Control. Fusion 51, 065018 (2009)