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Anomalous reflection control by the pump frequency modulation

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Introduction

The parametric decay instability (PDI) excitation is a reason for anomalous reflection and absorption of electromagnetic waves in experiments on laser fusion and RF heating in magnetic confinement devices. Based on results of homogeneous plasma theory [1], the random pump phase modulation was proposed in [1] for the PDI control. However, a more detailed theoretical analysis performed in [2] in the framework of inhomogeneous plasma model demonstrated a weak sensitivity of the PDI to the random pump phase modulation. Experimental investigations of the harmonic pump frequency modulation influence on the inhomogeneous plasma PDI performed in [3] had recovered even more complicated picture. As it was shown in [3], the weak PDI sensitivity to the pump frequency modulation is only observed for the fast modulation. In the case of slow modulation, on contrary, enhancement of the instability was reported, explained by the effect of convective losses suppression from the moving decay region investigated in [3, 4]. The observation of PDI suppression possibility in narrow modulation frequency range was mentioned in [3], as well, however without explanation. The possibility to use this effect for feed back control of the BS PDI was demonstrated in [5].

In the present paper the strong suppression of the most dangerous absolute induced back scattering (BS) PDI by the pump frequency modulation is studied experimentally in detail and shown to reduce anomalous reflection and to increase substantially the pump absorption.

The experimental situation

The experiment is carried out at the linear magnetized plasma device with magnetic field of 0.35 T, in which inhomogeneous plasma ($n_e = n_e(z, r)$) was produced by ECR discharge in argon at pressure 1-2 Pa. The electron plasma pump wave at frequency f_0 = 2.5 GHz – (EPW) – was excited in this plasma using a waveguide system. In vicinity of resonant (focal) point, where $n_e(z, 0) = n_c$ (i.e., $2\pi f_0 = \omega_p = (2\pi n_e e^2/m_e)^{1/2}$), the electric field of the electron plasma wave increases. The growth of electric field in the vicinity of focal point is so significant, that a parametric decay instability of stimulated backscattering $l \rightarrow l' + s$ is excited at a relatively small pump wave power P_0 of 20 mW. The instability excitation mechanism, according to [6], is related to the complicated spatial structure of pump wave, namely to the small fraction of the first radial mode present in the pump along with the dominant fundamental radial mode

($P_1 \leq 0.1P_0$) This small fraction interacting with the back scattered wave leads to excitation of the ion acoustic wave in spatial point shifted by $\delta z \approx 0.5$ *cm.* This ion acoustic wave propagates back to the decay region where it experiences amplification, thus leading to formation of the feedback loop and onset of the absolute PDI. The absolute decay instability is a coherent process with the limited number (1÷3) of oscillatory modes excited, which close to the threshold manifest themselves by narrow lines in the acoustic wave frequency spectrum (Fig. 1, a). The instability growth rate and an unstable spectrum structure are determined by the time of the ion-sound wave circulation in the feedback loop $\tau = \approx 2.5\ 10^{-5} s$.

The resonant PDI suppression effect

The enhanced scattering [6] technique is applied to study the decay ion acoustic wave. For this purpose the probing EPW at frequency $f_p = 2.35$ GHz $< f_0$ and small power ($P_p < 5$ mW) is launched into plasma by the same waveguide system. In the vicinity of its own resonance point the probing wave is effectively back scattered off the parametrically driven small scale IA wave. The scattered wave amplitude and spectrum is proportional to the IA one.

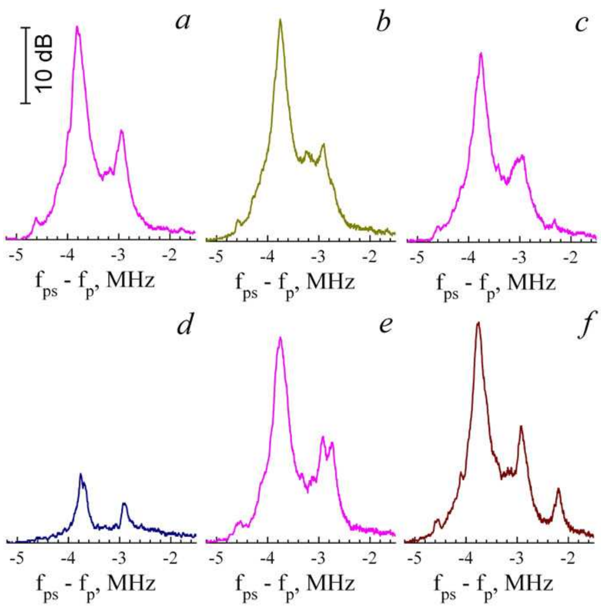

Fig. 1. *BS signal spectra at harmonic frequency modulation (deviation of 5 MHz). a – no modulation, b – modulation frequency is 0.5 MHz, c – 0.7, d – 0.85, e – 1.0 and f – 1.7 MHz.*

The $l \rightarrow l' + s$ absolute instability spectrum observed experimentally in the probing wave BS spectrum is shown in fig. 1, *a*. This spectrum coinciding with the pump BS spectrum consist of several stable narrow lines at frequency $f_{ps}^{(k)} = f_p - f_{IA}^{(k)}$ corresponding to the instability eigen modes. The lines spectral separation varies depending on experimental conditions in the range 0.4 – 0.9 MHz in agreement with the estimation $f_{IA}^{(k)} - f_{IA}^{(k-1)} \approx \tau^{-1}$.

Application of the harmonic pump frequency modulation $F_0(t) = f_0 + \delta f \cos\{2\pi f_m t\}$, (here δf is the frequency deviation, f_m is the modulation frequency) results in additional lines appearing in the BS spectrum at frequencies $f_{IA}^{(k)} \pm f_m$. The variation of the BS spectrum and one of these lines at growing f_m is shown in fig. 1, *b – f*.

As it is seen in fig. 1, *d*, suppression of the BS signal occurs at the coincidence of the modulation frequency and the eigen mode frequency difference $f_{IA}^{(k)} - f_{IA}^{(l)}$. At small frequency deviation δf and close to the PDI threshold the suppression region is very narrow, confirming the resonant nature of the effect (see fig. 2, *a*). It is important to note that frequency modulation leads not only to suppression of the probing wave BS, the IA wave generation and accordingly anomalous reflection, but also to enhancement of the pump wave absorption in the vicinity of the resonance point. The last statement is confirmed by observations of the plasma luminosity growth initiated by the pump frequency modulation switching on. As it is seen in fig. 2, *b*, the growth possesses a sharp maximum at the modulation frequency corresponding to the strongest suppression of the BS signal. A similar dependence on the modulation frequency is shown by measurements of fast electron production at >20 eV energy (Fig. 3) performed along the magnetic field using multi grid fast particle analyzer.

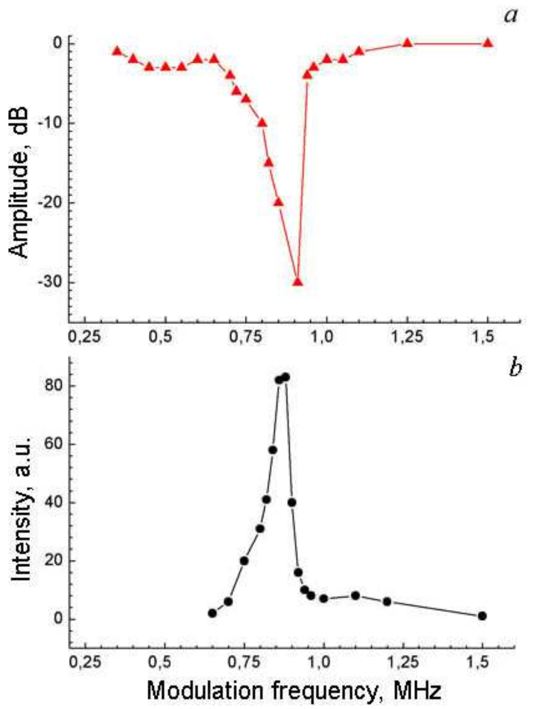

Fig. 2. *Dependence of the BS signal (a) and plasma luminosity growth (b) on the modulation frequency.*

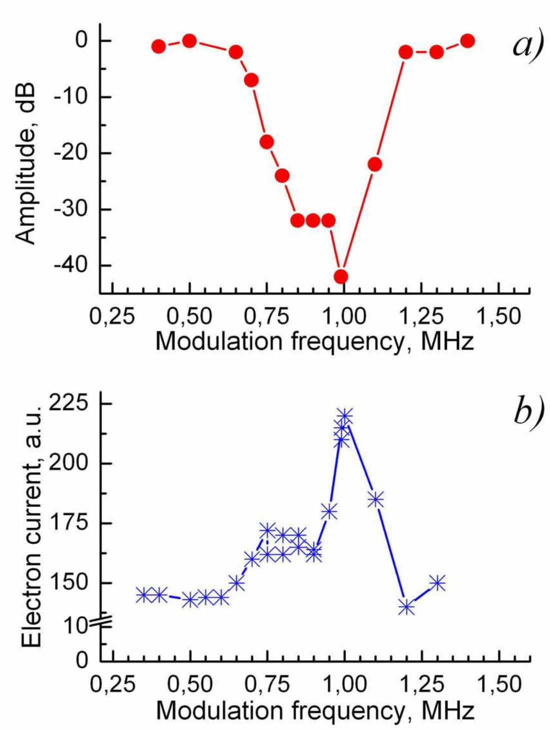

Fig. 3. *Dependence of the BS signal (a) and accelerated electron current growth (b) on the modulation frequency.*

The PDI feed-back control experiment

Based on the observations of a very high sensitivity of the PDI to the pump frequency modulation at the PDI eigen frequencies it was proposed to use a signal obtained as a result of the backscattering signal double frequency down-conversion for the pump frequency modulation. The corresponding scheme providing the control signal at the absolute PDI eigen frequency was developed. This scheme filters the backscattering signal suppressing the signal at frequencies of both the pump wave and ion acoustic wave simultaneously.

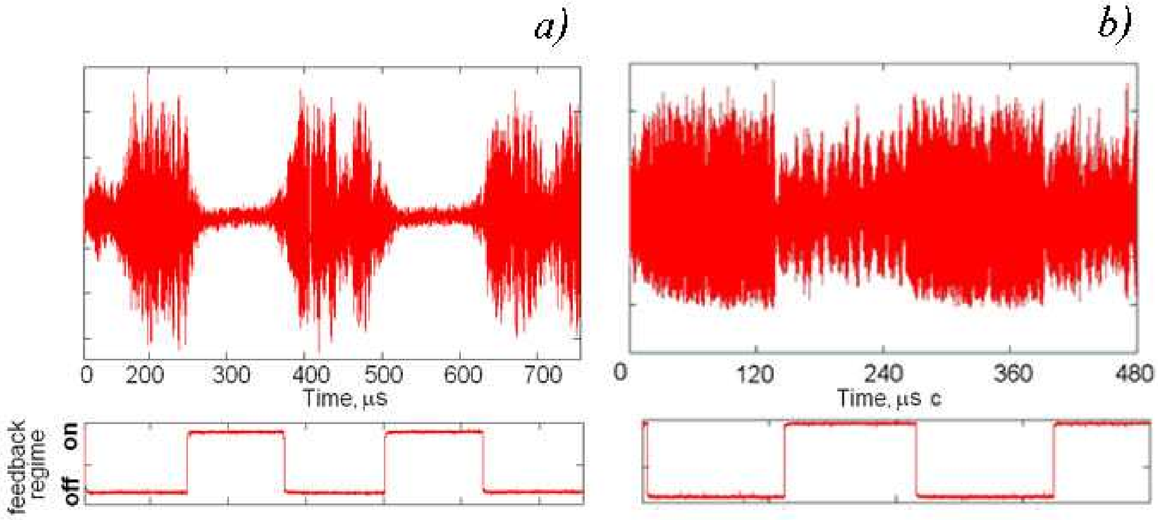

Fig. 4. *Oscillogram of the homodyne detection signal from plasma (above) and feedback regime (below) close to the PDI threshold (a) and at the PDI saturation stage (b) .*

As a result of the scheme utilization, the possibility of substantial (a factor more than 5) suppression of PDI ion-acoustic wave was demonstrated. The strong suppression effect is seen in fig. 4, where both the detected backscattering and feed-back control signal are shown. Quite naturally the PDI suppression was more pronounced close to the threshold. Measurements of fast electron production at energy higher than 20 eV show the increase of accelerated electron current by a factor more than 1.5 at feed-back switch on leading to the PDI suppression.

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