PLASMA PARAMETRIC DECAY INSTABILITY DRIVEN BY FREQUENCY MODULATED PUMP

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Abstract. According to the wide spread view point based on results of homogeneous plasma theory [1], stochastic phase modulation of the pump is an effective method for parametric instability control. The parametric decay instability suppression predicted by the theory for the pump frequency broadening exceeding the instability growth rate was observed in several experiments [2,3], where both stochastic and sinusoidal phase modulation was used. The influence of stochastic and sinusoidal pump frequency modulation on the inhomogeneous plasma absolute induced backscattering decay instability is investigated experimentally in the present paper. It is shown that the above conclusions are not universal and probably valid only in the homogeneous plasma case.

1. Experimental situation

The experiment was carried out in the linear plasma device "Granit" [4]. The argon plasma was produced using the electron cyclotron discharge in a tube 2 cm in diameter and 100 cm long placed in a uniform magnetic field of 3kG. The plasma was inhomogeneous both across and along the magnetic field $n_e = n_e(r, z)$. The maximum density was $n_e \approx 10^{12}$ cm^{-3}, electron temperature $T_e \approx 2$ eV and argon pressure 2×10^{-2} Torr. The Trivelpiece-Gould (TG) pump wave (f_0 =2480 MHz) was excited in the plasma with a waveguide.

The backscattering parametric instability $l_0 \to l_0' + s$ excited in plasma was observed under these conditions in previous experiments [5], utilizing a monochromatic pump. As it was shown at small power level $P_0 < 20$ mW the inhomogeneous plasma convective decay instability is excited. The reflected fundamental TG mode - l_0' and ion acoustic wave, propagating along the magnetic field in the direction of decreasing plasma density, are produced by this decay. The satellite, red-shifted by 3 MHz, appears in the spectrum of the signal reflected by the plasma. Its amplitude exponentially grows with pump power.

For a pump power exceeding the threshold value $P_0 > 20$ mW, the dependence of the satellite amplitude on the pump power $A_{ps}(P_o)$ becomes even steeper (Fig.1, curve $\Delta f = 0$). The backscattered signal level increases up to 40–50 dB at the pump wave power variation of a few percents. It was explained by excitation of the absolute instability $l_0 \to l_0' + s$ [6]. According to [6] the absolute instability mechanism is related to the complicated spatial structure of the pump wave, namely to the small fraction of the first radial pump mode $P_1 \leq 0.1\ P_0$. The first radial pump mode results in the occurrence of the second region of resonant three-wave interaction and thus to the feed-back loop establishment. According to [6,7] the instability growth rate as well as the spectrum structure is determined by the time of ion acoustic wave propagation in the feed-back loop. At power $P_0 \sim 40$ mW two times higher than the $l_0 \to l_0' + s$ absolute instability threshold, a strong parametric reflection of the pump wave was observed.

2. Experimental results

The influence of the pump frequency modulation on the $l_0 \to l_0' + s$ absolute instability was investigated in the present experiment. The stochastic, noise-like, and harmonic pump frequency modulation was produced by voltage controlled sweep-frequency generator. The frequency was modulated in the range $f_0 - \Delta f/2 < f < f_0 + \Delta f/2$, where the frequency deviation Δf up to 200 MHz was used.

Because of strong frequency modulation direct observation of backscattered satellite, produced by the instability was not possible in the experiment. The enhanced scattering technique was used instead to study the ion acoustic wave, generated by the parametric instability [7]. For this purpose a small power *(*P_p < 5 mW*)* probing TG (f_p = 2350 MHz) mode was launched into the plasma by the same waveguide which was used for pump wave excitation. The probing wave frequency was chosen less than the minimal value of pump frequency at modulation, $f_p < f_0 - \Delta f/2$. Thus the probing wave backscattering from the decay ion acoustic wave occurs out of the instability region, providing information on the decay wave amplitude and spectra. The dependence of the backscattered signal amplitude on the pump power and modulation was studied in the experiment.

The effect of stochastic pump wave modulation on the backscattered signal amplitude is demonstrated in Fig.1.where its dependence on the pump power is plotted. The suppression of induced backscattering instability is shown to occur for pump frequency broadening $\Delta f \geq 40$ MHz, a factor of 20 larger than the instability growth rate $\gamma \sim 1 \div 2 \times 10^6$ s^{-1}. The corresponding spatial broadening of the decay region is comparable in this case to the size of feed-back loop causing the absolute instability excitation. At smaller deviation, $\Delta f < 40$ MHz the effect of stochastic pump wave modulation on the instability is less pronounced.

The suppression effect is much stronger close to the instability threshold. The absolute instability threshold power P_{th} increases by a factor 1.8 at the frequency deviation increase up to 200 MHz, as it is shown in Fig.2, by circles. However far from threshold at P_0 = 0 dB (Fig.1) which corresponds to the pump power ~ 70 mW, the influence of stochastic pump frequency modulation is much weaker. The instability is not suppressed, but the amplitude of the backscattered wave is slightly decreased. A factor of 2 decrease is observed for Δf = 150 MHz.

A surprisingly weak influence of stochastic frequency modulation on the decay instability was observed also in the regular regime. The backscattered signal consists of several stable narrow lines there, corresponding to the instability eigenmodes [6]. The strong supression was observed there only for Δf = 120 MHz and the spectrum fine structure survived till this, very high value of stochastic frequency deviation.

The effect of the harmonic pump frequency modulation on the induced parametric backscattering instability was also investigated in wide modulation frequency region from 0.1 MHz to 10 MHz. The dependence of the instability excitation threshold on the pump wave frequency deviation at the modulation frequency f_m ~ 1.8 MHz is shown in Fig.2. The suppression here is stronger than in stochastic modulation case. The instability threshold is increased by a factor of 3 for Δf = 150 MHz. Far from instability threshold the influence of modulation on the instability is weaker, as it is observed in the stochastic case.

The instability temporal behavior was investigated in a special experiment utilizing pulse spectrum analyzer. The duration of the spectrum analyzer strobe pulse was about 1 microsecond. A 15 microseconds pulse pump amplitude modulation accompanied by 1.8 MHz harmonic frequency modulation was used in the experiment. The dependence of the backscattered signal amplitude on time for various pump wave frequency deviations is shown in Fig.3. As it is seen from the figure, all curves have well pronounced stage of exponential growth, which is followed by saturation and slower evolution. The instability growth rate is evaluated using the exponential parts of curves. It is shown in Fig.4 against the pump frequency modulation. As it is seen, the deviation increase up to 100 MHz results only in a factor of 3 decrease of the growth rate. The dependence of the grows rate on the deviation is shown in Fig.4 also in stochastic modulation case. The suppression in this case is even weaker.

The dependence of the backscattered signal amplitude on the modulation frequency for different frequency deviation is shown in Fig.5. The broken line corresponds to the scattered signal level for monochromatic pump wave (Δf = 0). The signal is close to this level for modulation frequencies f_m > 1.5 MHz and f_m < 0.6 MHz. However near f_m = 1 MHz a resonant suppression of the signal was observed in a wide range of deviations: 10 MHz < Δf < 100 MHz . It is especially strong for deviation range 40 MHz < Δf < 80 MHz.

This effect, as well as a surprisingly high stability of the coherent regime of the induced backscattering against stochastic frequency modulation, has not got yet a proper theoretical interpretation. The evident growth of the backscattered signal, observed in Fig.5 for Δf = 120 MHz and f_m = 0.5 MHz is associated with the effect of the decay instability enhancement in the case, when the decay point velocity coincides with the ion acoustic velocity [7].

3. Discussion

The above experimental results clearly show that suppression of the instability takes place at pump frequency broadening much higher than the measured growth rate. This observation is in deep contradiction with predictions of the homogeneous plasma theory according to which the suppression should take place for $2\pi\Delta f > \gamma$. The possible explanation for this effect is based on the significant difference of three-wave interaction in the inhomogeneous plasma. Namely, in inhomogeneous plasma different spectral components of the pump wave can interact with the same acoustic wave producing daughter waves at shifted frequency, satisfying condition $f_0 + \Delta f = f' + \Delta f + f_s$. This interaction takes place in a shifted spatial point, satisfying in the case of backscattering the decay condition $2k_0(f_0 + \Delta f, x + \Delta x) = k_s$. In the case of small frequency deviation this shift is given by $\Delta x = 2\pi\Delta f\ (l^2/v)$, where $l^2 = dk_0/dx$, v – group velocity of the daughter wave. The strong suppression of absolute instability should occur when this shift is larger than the size of the feed-back loop L. According to [6] the growth rate of the instability is determined by the time of ion acoustic wave propagation in the feed-back loop L/c_s and given by relation $\gamma = \pi K\ (c_s/L)$, where $K = (\gamma_0 l)^2/(v\ c_s)$ and γ_0 is the instability growth rate in homogeneous plasma theory. Combining the equations written above, it is easy to obtain the criteria for the instability suppression in the inhomogeneous plasma $\Delta f > 0.25(\gamma_0^2/\gamma)$, which has been confirmed in the present experiment.

4. Conclusions

In conclusion it should be stressed that the experiment have demonstrated much smaller effect of the pump spectral broadening on the inhomogeneous plasma parametric instability than it is supposed by the standard decay instability theory [1]. The absolute instability suppression was observed only for the pump spectral width $2\pi\Delta f > 100\gamma$, much higher than the instability resonant width – γ. It is shown. that the absolute instability suppression takes place rather when the spatial broadening of parametric decay region due to the pump frequency broadening exceeds the size of the feed-back loop responsible for the instability excitation. A new criteria for the instability suppression, taking into account this effect is proposed.

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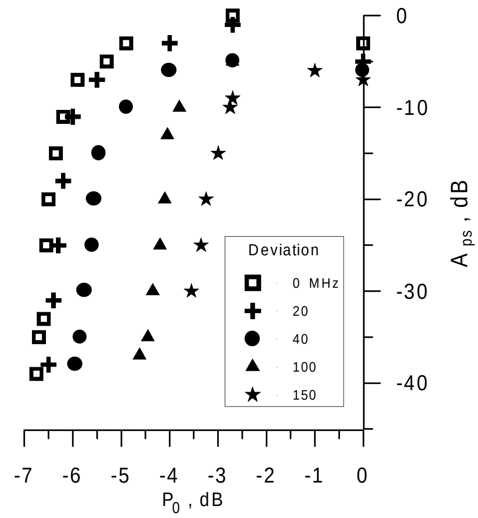

Fig 1. *Dependence of backscattered signal on the pump power for different frequency broadening.*

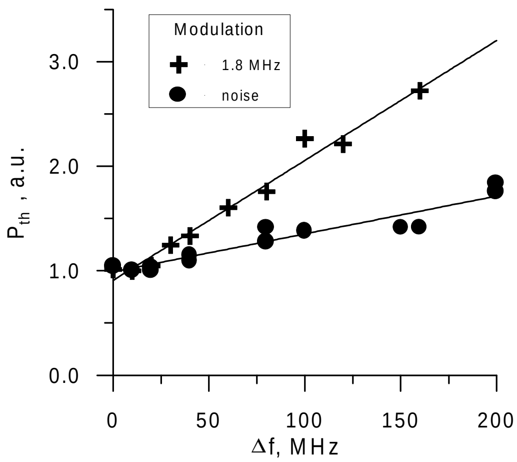

Fig 2. *Dependence of the parametric instability threshold on the pump frequency width.*

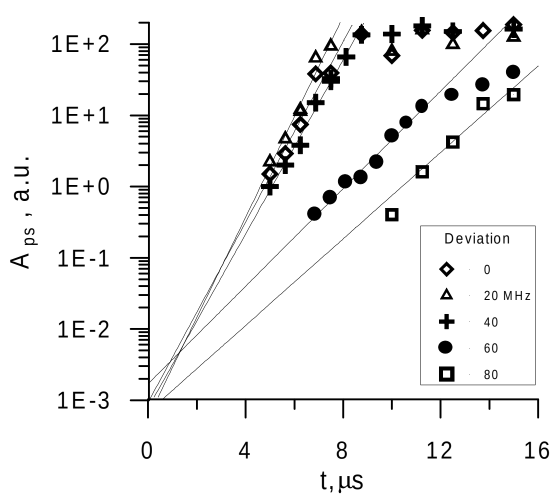

Fig 3. *The time dependence of the backscattered signal for different pump spectra broadening.*

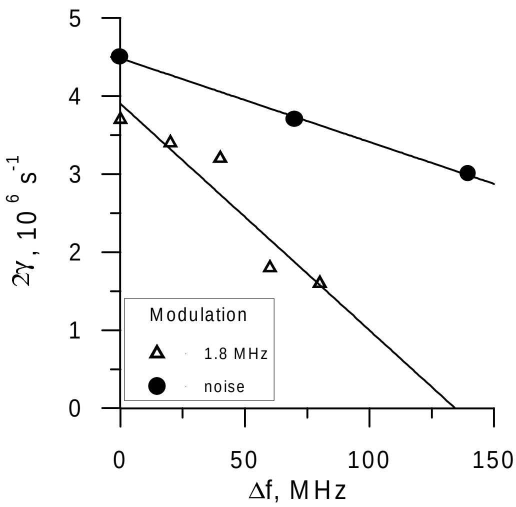

Fig 4. *Dependence of the decay instability growth rate on the pump frequency broadening.*

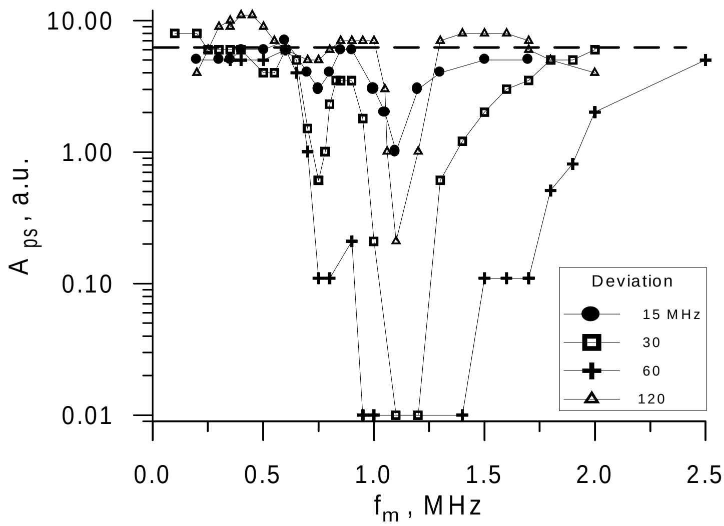

Fig 5. *Resonant suppression of decay instability by harmonic frequency modulation for different pump frequency deviations.*