Parametric decay instability control by non-monochromatic pumps

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Abstract. The wide variety of physical effects accompanying the parametric decay instability driven by the frequency modulated pump is studied experimentally and theoretically. It is shown that pump frequency modulation does not influence the instability when the modulation frequency is much faster than the decay wave transient time in the interaction region. However in the case of slower modulation it is demonstrated that the resonant enhancement and suppression may take place depending on the modulation rate. A scheme of active parametric decay instability feed-back control is proposed. A possibility of deep instability suppression by launching of an additional (small power) pump wave possessing a frequency shifted by the value equal to the frequency separation of ion acoustic eigen modes is demonstrated as well. The recovery of microwave power absorption at the parametric decay instability suppression is shown using measurements of the plasma luminosity and fluxes of accelerated electrons.

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. In laser fusion experiments excitation of stimulated Raman and Brillouin scattering instabilities and two plasmon decay can lead to substantial reflection of light and generation of fast electrons changing the power deposition in the target [1]. In RF heating experiments PDIs, especially excited at the plasma edge, cause variations of power absorption profiles which are not always favorable as in lower hybrid heating [2]. Anomalous reflection is also accompanying RF heating experiments as in the case of electron Bernstein wave heating where the induced backscattering PDI [3] due to relatively low power thresholds [4] is often observed. Moreover, as it was shown recently, the PDI is observed at ECR heating on TEXTOR tokamak as well [5, 6].

According to the homogeneous plasma PDI theory the frequency width of a PDI is determined by its growth rate $\gamma_0$ [7]. Therefore the frequency broadening of the pump wave $\Delta \omega$ exceeding the PDI growth rate ($\Delta \omega/\gamma_0 > 1$) should lead to the PDI threshold growth. Practically the pump wave spectral broadening can be associated with different mechanisms among which the finite frequency width of the generation of powerful oscillators and multi-mode pump composition. The pump frequency broadening can be caused by the pump phase and frequency modulation as well. Based on results of homogeneous plasma theory, the random pump phase modulation was proposed in [8] for the PDI control. However, a more detailed theoretical analysis performed in [9] in the framework of inhomogeneous plasma theory demonstrated a weak sensitivity of the PDI to the random pump phase modulation. It should be mentioned that theoretical conclusions [9] were obtained within the model utilizing extremely fast (delta-correlated) pump phase modulation, in particular, much quicker than the...
transient time of the slow daughter wave in the decay region. In the present paper we demonstrate in the case of slower modulation a wide variety of physical effects accompanying the parametric decay instability driven by the frequency modulated pump in inhomogeneous plasma, in particular the PDI resonant enhancement and suppression.

2. The experimental approach
2.1. Experimental installation “Granit”
The experiment was carried out at the linear magnetized plasma device [10] (see figure 1a) with magnetic field of about 0.35 T, in which plasma was produced by 200 W ECR discharge at frequency 9.8 GHz in a tube 2 cm in diameter and 100 cm long filled by argon at pressure 1–2 Pa. Plasma diffuses from ECR region along discharge tube and magnetic field, its density exponentially decreases with scale $a = 3–5$ cm. Inhomogeneity scale across magnetic field is $b \approx 0.4$ cm. The electron density estimation provided by the cavity method in the middle part of installation results in value of $n_e = 10^{12}$ cm$^{-3}$, electron temperature was measured by the multi-grid analyzer at the level of $T_e = 2$ eV. The axial and radial distribution of plasma luminosity was controlled by the optical diagnostics utilizing the fiber light guide. The microwave radiation backscattered in plasma was studied in the waveguide using microwave homodyne detectors and spectral analyzers.

2.2. The Trivelpiece-Gould mode pump wave
The electron plasma pump wave (Trivelpiece-Gould (TG) mode) at frequency $f_0 = \frac{\omega_0}{2\pi} = 2480$ MHz was excited in this plasma using a waveguide system possessing electric directed along the balloon axis. The dispersion relation for this wave is given by $k_{\perp}^2 = \left[ \frac{\omega_{pe}^2}{\omega_0^2} - 1 \right] k_{\parallel}^2$,

where $k_{\parallel}$ and $k_{\perp}$ are the components of the wave vector parallel and transverse to the magnetic field, $\omega_{pe}$ is the electron plasma frequency.

The high density plasma $(n_e, r, z > n_e)$, where $n_e$ - critical electron density) creates a plasma waveguide weakly inhomogeneous in axial direction for the electron plasma wave (EPW). According
to the results of analytical theory [10] accounting for the realistic 2D plasma geometry in the vicinity of the hybrid resonance, where \( \omega = \omega_{\text{pe}}(0, z) \), EPW field there takes a form

\[
E = \left( \frac{2P_0}{\omega_0} \right)^{1/2} \frac{k^{3/2}}{(3r_a^2 b k^2 + 1)^{1/2}} \exp\left[ -ik' z - \frac{k}{2b} r^2 - i(\omega - \omega_0)t \right] + cc,
\]

(1)

where \( P_0' = \kappa P_0 \) is the part of power \( P_0 \), which goes into excitation of fundamental radial TG mode \( (\kappa \approx 0.2) \); \( k' \) is the component of wave vector \( k \) along the exterior magnetic field direction. It is defined in the neighbourhood of the resonance point from the equation:

\[
3r_d^2 (k + ik^*)^2 - \frac{z}{a} - \frac{2}{(k + ik^*) b} + i\eta^* = 0,
\]

(2)

where \( \eta^* \) – imaginary part of the longitudinal dielectric plasma permeability.

The calculated dependencies of electric field amplitude and wave vector for TG mode are shown in figure 1b. The calculation parameters measured or calculated using experimental data were as follows: \( P_0 = 20 \) mW, \( \kappa = 0.2 \), \( f_0 = 2350 \) GHz, \( T_e = 1.8 \) eV, \( a = 5 \) cm, \( b = 0.43 \) cm, \( v_{\text{e}a} = 4.7 \times 10^7 \) cm/s, \( \delta = 0.003 \) – the fraction of super thermal electrons in the resonance point, \( T_h = 8 \) eV – effective temperature of the super thermal electron tail.

2.3. Accelerated electron generation

Propagating, as a Gaussian wave beam (the fundamental plasma waveguide mode), towards decreasing electron density to a point of a plasma resonance, where \( \omega_h = \omega_{\text{pe}}(0, z) \), the wave slows down. Its wave number parallel to magnetic field increases, the beam width decreases and, consequently, its electric field grows drastically. After that the collisional absorption of wave as well as its interaction with electrons via the Landau mechanism should take place in the vicinity of the resonance leading to the wave absorption. Accordingly the electron distribution function differs substantially from the Maxwellian dependence for energy exceeding the thermal one \( E >> T_e \) (figure 2a) and may be well approximated by the bi-Maxwellian dependence

\[
f_e(v) = \left( \frac{m_e}{2\pi T_e} \right)^{1/2} \exp\left( -\frac{m_e v^2}{2T_e} \right) + \delta \left( \frac{m_e}{2\pi T_h} \right)^{1/2} \exp\left( -\frac{m_e v^2}{2T_h} \right),
\]

(3)

Figure 2. The multi-grid analyzer characteristics (a) and the fast electron tail effective temperature for growing pump power (b). 1 – initial plasma, 2 – \( P_0 = 1 \) mW, 3 – 4, 4 – 9, 5 – 12, 6 – 18, 7 – 23, 8 – 35, 9 – 50 mW.
As it is seen in figure 2b, the effective temperature of the super thermal electron tail \(T_h\) grows with EPW power when it is small. However this growth saturates at the power level of 20 mW, thus indicating reduction of the power fraction absorbed due to the Landau damping [11].

2.4. Experimental manifestation of absolute parametric decay instability at monochromatic pump

The saturation of the effective sub-thermal electron tail temperature growth shown in figure 2b at \(P_0 > 20\) mW was always accompanied by excitation of stimulated backscattering (BS) parametric decay instability \(l_0 \rightarrow l_0' + s\) occurring in the vicinity of resonance point [10]. It was found that at very low power level \(P_0 \sim 10\) mW the convective decay instability accompanied by the generation of a reflected fundamental TG mode \(l_0'\) and an ion-acoustic wave \(s\) propagating along the magnetic field toward the lower density is excited. In this case, a satellite arises in the spectrum of the scattered signal down shifted from the pump frequency by about 3 MHz (see figure 3a). At small instability threshold excess (10 mW < \(P_0 < 20\) mW) the dependence of the BS signal on the pump power (Figure 3c) was exponential, typical for convective decay instability [12, 13]. However at higher pump power \(P_0 > 20\) mW, even steeper dependence was observed in [14] indicating the absolute instability onset (see figure 3e, curve 1). The absolute instability mechanism, according to [14], 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 TG mode \((P_t \leq 0.1P_0)\). This small fraction interacting with the BS wave leads to generation of the ion acoustic (IA) wave in spatial point shifted by \(\delta z \approx 0.3–0.5\) cm from the main decay region. This IA wave propagates back to the decay region where it experiences amplification and generates the BS fundamental TG mode \(l_0'\), 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 of oscillatory modes excited, which close to the threshold manifest themselves by narrow lines in the BS spectrum (Figure 3a-d). According to [15], the instability growth rate and an unstable spectrum structure are determined by the time of the IA wave circulation in the feedback loop \(\tau = \frac{\delta z}{c_s} - \frac{a}{c_s} \approx 1.5–2.5 \times 10^6\) s, where \(c_s\) is the IA velocity.

3. Absolute PDI at non-monochromatic pump

The frequency modulated microwave pump was provided by a voltage controlled oscillator possessing minimal and maximal frequencies 2200 and 3200 MHz correspondingly. The output of the generator

![Figure 3](image-url)
in the present experiment took a form $U(t) = U_0 \cos \left( 2\pi \int_0^t f_0 \pm \Delta f \left[ U_c(t') \right] dt' \right)$, where $\Delta f(U_c)$ — frequency deviation as a function of control voltage $U_c$. For this generator maximal deviation $\Delta f_{\text{max}} \sim \pm 500 \text{ MHz}$ at the voltage variation in range from 3 V up to 20 V, a band-pass of the control input was up to 50 MHz. It allows controlling the pump frequency at high rate and using different frequency variation waveforms. The pump could be amplified using travelling-wave tube amplifiers up to the level of 1 W.

The amplitude of parametric satellite was measured using enhanced scattering technique [10]. For this purpose the probing wave at frequency $f_p = 2.35 \text{ GHz} < f_0$ and small power ($< 5 \text{ mW}$) was launched into plasma, so that $f_0 - f_p < f_{\text{max}}$. In vicinity of own resonance point the probing wave is effectively scattered on excited in plasma ion-sound wave and scattered wave amplitude is proportional to ion–sound one.

### 3.1 Linear pump frequency modulation

To obtain the pump frequency modulation close to linear the saw-tooth voltage from special generator was used as control voltage for sweep-generator. In this case the frequency of pump was modulated as $f = f_0 - \Delta f / T$, where $f_0 = 2650 \text{ MHz}$; $\Delta f = 300 \text{ MHz}$; $T \geq 1 \mu s$ — modulation period. Then the frequency variation rate is given by expression $v_{sw} = \frac{\Delta f}{T}$ resulting in drift of the three wave resonance point where the PDI takes place in inhomogeneous plasma. The corresponding decay point velocity is equal to $v_d = \frac{2 \alpha \Delta f}{f_0}$.

![Figure 4](image)

**Figure 4.** The PDI spectra at different sweep speed (a), satellite amplitude $A_{ps}$ against the normalized velocity of decay point displacement (b) and a burst of ion-acoustic wave in decay region at $v_d/c_s \sim 1$ (c).

The acoustic velocity calculated for the experimental plasma parameters $c_s = (T_e/M_{Ar})^{1/2} \sim 2.2 \times 10^5 \text{ cm/s}$. At higher and smaller frequency modulation rate the scattering signal decreases substantially. Its dependence on the decay point velocity normalize by the ion acoustic speed is shown in Figure 4b. It possesses a well pronounced maximum at $v_d \equiv c_s$ indicating the resonant nature of the enhancement effect. In this case the direction and velocity of decay point drifting in plasma are close to ion–acoustic
wave ones. It results in significant decreasing of the convective energy losses in decay region and, as consequence, leads to PDI stimulation, which is revealed in scattered signal amplitude growth. According to [16], the spatial amplification coefficient expression which describes the slow decay wave amplification in the presence of linear frequency modulated pump wave in the inhomogeneous plasma can be written as the following

$$S = \frac{\pi p^2}{|v_2 - v_1| |v_2 - v_3|}$$

where $\ell$ is the phase mismatch length, $v_1$ and $v_2$ are the velocities of decay waves.

Since the PDI stimulation is resonant and its duration is short in time, so the excited ion-acoustic wave in decay region looks like a soliton (Figure 4c). It should be noted that during time of reverse variation of the frequency the scattered signal was suppressed to the level less than -20 dB.

### 3.2 Harmonic pump modulation

To obtain the harmonic frequency modulation the controlling voltage was formed using the standard sinusoidal RF generator.

**Figure 5.** The scattered signal amplitude against the modulation frequency for different widths of the pump wave spectrum (a) and waveforms of microwave detector signals at $f_m = 0.5$ MHz (b) and 1 MHz (c).

Figure 5a shows the scattered signal amplitude as a function of the modulation frequency for different widths of the pump wave spectrum. The dashed line parallel to the abscissa shows the level of the scattered signal for a monochromatic pump wave ($\Delta f = 0$). The signal is close to this level at $f_m >$

**Figure 6.** BS signal spectra at harmonic frequency modulation (deviation of 5 MHz). a – no modulation, b – modulation frequency is 0.5 MHz, c – 0.7 MHz, d – 0.85 MHz, e – 1.0 MHz and f – 1.7 MHz. The arrow indicates the additional line caused by the pump frequency modulation.
1.5 MHz and \( f_m < 0.6 \) MHz. The certain increase in the scattered signal is observed for \( \Delta f = 120 \) MHz and \( f_m = 0.5 \) MHz. It is related to the enhancement of decay instability occurring if the velocity of propagation of the decay point coincides with that of the ion-acoustic wave as in case of linear frequency modulation. Therefore the corresponding microwave detector signal looks like a sequence of bursts (Figure 5c).

Drastically resonant suppression of the parametrically scattered signal is observed around modulation frequency \( f_m = 1 \) MHz within a wide range of deviation values. To clarify the nature of this suppression the experiment was performed for the coherent regime of the \( I \rightarrow I' + s \) absolute instability when scattering spectrum at pump power of 40 mW consist of two stable narrow lines at frequency \( f_{ps}^{(k)} = f_p - f_{IA}^{(k)} \) (Figure 6a) 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 \( f_{IA}^{(k)} - f_{IA}^{(k-1)} \approx \tau^{-1} \) derived in [14]. Application of the harmonic pump frequency modulation results in additional lines appearing in the BS spectrum at frequencies \( f_{IA}^{(k)} \pm f_m \). The variation of the BS spectrum at growing \( f_m \) is shown in Figures 6b – 6f. Arrows in figures 6b, c, e and f are indicating additional lines caused by the pump frequency modulation. As it is seen in Figure 6d, suppression of the BS signal occurs at the coincidence of the modulation frequency and the eigen mode frequency difference \( f_{IA}^{(k)} - f_{IA}^{(l)} \) \( \sim \frac{C_1}{\alpha} \).

At small frequency deviation \( \delta f \) and close to the PDI threshold the suppression region is very narrow, confirming the resonant nature of this effect (see Figure 7a), whereas at larger deviation and the threshold excess the BS suppression become deeper and broader in modulation frequency.

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 (Figure 7b) and super thermal electron production at energy higher than 20 eV (Figure 7c) in the decay region initiated by the pump frequency modulation switching on. We used the retarding potential about 20 V on the analyzer in order to exclude the contribution of thermal electrons with average energy of about 2 eV.

3.2.1 The PDI feed-back control experiment. Based on the observations of a very high sensitivity of PDI to the pump frequency modulation at frequency close to the difference of 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 [17]. The developed feed-back scheme provides the control signal at the absolute PDI eigen frequency difference \( f_{IA}^{(k)} - f_{IA}^{(l)} \). It filters the backscattered signal suppressing the signal at pump frequency and at the probing frequency. At the microwave detector it mixes the IA frequencies amplifying the signal at frequency \( f_{IA}^{(k)} - f_{IA}^{(l)} \) and suppressing simultaneously the signal at the ion acoustic wave frequencies \( f_{IA}^{(k)} \) and \( f_{IA}^{(l)} \).
The possibility of substantial (a factor of 5) suppression of the PDI ion-acoustic wave and anomalous pump wave reflection using the feed-back scheme was shown for frequency deviation of 7.5 and 10 MHz. It is important to note that the PDI suppression was not possible with a control signal at IA frequency \( f_{IA}^{(k)} \) proportional to the IA wave amplitude provided by the scheme in the case when the pump wave frequency was not filtered out.

3.3 Stochastic pump modulation

It should be stressed that resonant enhancement of the convective amplification coefficient is possible not only for linear or harmonic pump frequency modulation, but also for stochastic modulation with finite correlation time as was shown in the numerical modeling [16].

To produce the stochastic frequency modulation of the output signal the controlling voltage \( U_c \) was formed using a photomultiplier current in the photon–counting mode, when a photocathode was illuminated by a filament lamp. In this case, the spectrum of the photocurrent approximates the white–noise spectrum. To change the correlation time of controlling voltage signal from 0.01 up to 2 μs the limitation of photomultiplier frequency band by RC–filter was used in experiments.

In Figure 8 the detected homodyne signal (upper waveform) and time dependence of pump frequency are shown for the case of stochastic modulation with deviation \( \pm 50 \text{MHz} \). The splashes of oscillations at frequency of about 3MHz corresponding to daughter ion–sound wave frequency seen in the upper picture coincide with the periods of linear frequency modulation, as shown in the bottom waveform in Figure 8b.

3.4 PDI suppression by complementary pump.

PDI suppression method developed in previous sections, unfortunately, is difficult to realize at high (lasing) frequencies or with powerful RF generators because the fast modulation technique is needed. However a possibility of the deep PDI suppression by launching of the additional (small power) pump wave possessing a frequency shifted by the value equal to the frequency separation of ion acoustic eigen modes exists in these full-scale experiments. To demonstrate it in our model experiment, the parametric decay instability \( l \rightarrow l' + s \) was excited by the EPW pump at frequency \( f_0 = 2335 \text{ MHz and} \)}
power of about 40 mW resulting in red-shifted satellite observed in BS spectrum (Figure 9(a)). When additional EPW at frequency \( f_p = f_0 + 5 \text{ MHz} \) and small power \( (P_p \sim 15 \text{ mW}) \) was launched into plasma by the same waveguide system a complicated BS spectrum consisting of two pump lines and two down shifted satellites was observed due to BS of the additional pump off the parametrically driven small scale ion-sound wave (Figure 9(b)).

At high enough pump frequency difference \( |f_p - f_0| \geq 2 \text{ MHz} \) (Figure 9(b) and (f)) the complementary pump do not influence the pump BS spectrum. However, as it is seen in Figure 9(c) and (e), at frequency difference \( |f_p - f_0| \approx 1 \text{ MHz} \) the main pump BS decreases by several orders of magnitude, thus indicating the next to total absolute PDI suppression. At \( |f_p - f_0| < 1 \text{ MHz} \) the BS signal recovers, however possessing different spectrum shown in Figure 9(d). At the variation of complementary pump power from 40 mW to 4 mW the optimal suppressing frequency changes from 1.2 MHz to 0.8 MHz. The physical reason for this change is related to the variation of ion acoustic eigen mode frequency due to density profile flattening caused by growth of absorbed microwave power. A more detailed analysis of suppression efficiency dependence on frequency reveals several suppression maxima corresponding to easier and deeper suppression of the absolute instability. The pump frequency difference corresponding to these maxima is equal to the frequency difference of ion acoustic eigen modes excited by the instability and observable as separate lines in BS spectrum in Figure 9(a). It should be also mentioned that the strongest suppression occurs at the complementary pump power comparable to the main pump power.

It is natural to assume that the anomalous backscattering suppression due to the complementary pump influence should result in enhancement of power absorbed in plasma and accordingly in growth of fast electron production and plasma luminosity. The measured luminosity distribution is shown in Figure 10(a) for the cases of \( f_p - f_0 = 5 \text{ MHz} \) and \( f_p - f_0 = 1 \text{ MHz} \) corresponding to spectra (b) and (c) in Figure 9. The hybrid resonance position is given in Figure 10 by arrow. As it is seen in Figure 10(a), suppression of the instability at \( f_p - f_0 = 1 \text{ MHz} \) is accompanied by plasma luminosity growth compared to the case \( f_p - f_0 = 5 \text{ MHz} \) and by shift of the luminosity maximum further from the EPW.

![Figure 9](image9.png)

*Figure 9.* Scattered signal spectra at different frequencies of additional pump wave.

![Figure 10](image10.png)

*Figure 10.* Axial plasma luminosity distribution (a) and analyzer voltage current characteristics (b) registered at pump frequency difference of 5 MHz (2) and 1 MHz (3), 1 – background plasma. Arrow corresponds to the hybrid resonance position.
excitation region indicating suppression of the anomalous reflection and absorption growth.

The fast electron analyzer situated in the low density plasma at 5 cm from the hybrid resonance (see Figure 1) also registered evidences of the RF power absorption growth at the PDI suppression. As it is seen in Figure 10(b), the effective temperature of the fast electron tail, which was 4.2 eV in the unperturbed plasma, enhanced up to 7.1 eV at application of the two-frequency pump in the case $f_p - f_0 = 5$ MHz and further increased up to 9.3 MHz when the pump frequency difference take the resonance value $f_p - f_0 = 1$ MHz providing the deepest instability suppression.

4. Conclusions

The wide variety of physical effects is accompanying the parametric decay instability driven by the frequency modulated pump. As it is confirmed experimentally, the pump frequency modulation does not influence the instability when the modulation frequency is much faster than the decay wave transient time in the interaction region. In the case of slower modulation, the resonant enhancement and suppression may take place instead. Coming to the physical reason of the observed effects it is necessary to stress that the physical reason for the observed PDI resonant enhancement is provided by suppression of convective losses of the daughter wave from the decay region, drifting due to the slow pump frequency modulation at the ion acoustic speed. The strong resonant suppression of the most dangerous absolute inhomogeneous plasma PDI is observed at a minimal frequency deviation (less than 1%) when the modulation frequency is equal to frequency separation of the stable lines observed in the backscattering spectrum which correspond to ion acoustic wave eigen modes excited in plasma by the absolute PDI. Based on this effect a scheme of active PDI feed-back control was proposed.

A possibility of deep instability suppression by launching of an additional (small power) pump wave possessing a frequency shifted by the value equal to the frequency separation of ion acoustic eigen modes is demonstrated as well. The recovery of microwave power absorption at the parametric decay instability suppression is shown using measurements of the plasma luminosity and fluxes of accelerated electrons.

Keeping in mind that excitation of discrete frequency spectrum due to creation of feedback loop, when the part of energy taken away by a daughter wave from the decay region is retuned back is the common feature of absolute PDIs, both the harmonic modulation and the feedback control methods may be recommended for the PDI suppression. In the case of laser fusion experiments due to the short interaction time only the first method based on harmonic pump frequency modulation is applicable, whereas in RF heating experiments both methods can be useful.

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