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# Dynamics of the Plasma Wave Breaking Phenomena

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Interaction of powerful electromagnetic waves with plasma accompanied by wave breaking phenomena and fast electron generation attracts considerable attention at present as a possible way of strong electric field production and further ion acceleration. In the present paper we describe results of a model experiment in which propagation and absorption of strong electrostatic wave pulse in inhomogeneous magnetized plasma is studied and substantial electron acceleration effect is observed under conditions, when the wave breaking should occur according to estimations. The termination of these effects due to reflection from the ionization front caused by intensive wave is as well studied.

The experiments were performed in a linear plasma device "Granite" [1] where plasma was produced using the electron cyclotron discharge in a tube 2 cm in diameter and 100 cm long. The experiment parameters are as follows: magnetic field $H$ = 3500 Oe, the argon gas pressure is $10^{-2}$ Torr, the plasma inhomogeneity scale along magnetic field and across it are $a$=5 cm and $b$=0.4 cm accordingly, the maximal electron density is $n_e = 10^{12}$ cm$^{-3}$, electron temperature is $T_e$ =2 eV. An electron plasma wave (EPW) at frequency $f = \omega/(2\pi) = 2.84$ GHz in the form of the fundamental Trivelpiece-Gould mode was launched into the plasma by waveguide. The dispersion relation for this wave is $k_\perp^2 = [\omega_{pe}^2(r, z) / \omega^2 - 1]\, k_\parallel^2$, where $k_\parallel^2$ and $k_\perp$ are the components of the wave vector parallel and transverse to the magnetic field. The high density plasma ($n_e(r,z) > n_c$ , where $n_c$ - critical electron density) creates a plasma waveguide for EPW shown in fig. 1, where $P_0$, $P_t$, $P_s$, $P_r$ are incident, transient, scattered and reflected power correspondingly. It is weakly inhomogeneous in axial direction. Propagating towards decreasing electron density to a point of a plasma resonance (focal point), where $\omega = \omega_{pe}(0, z)$

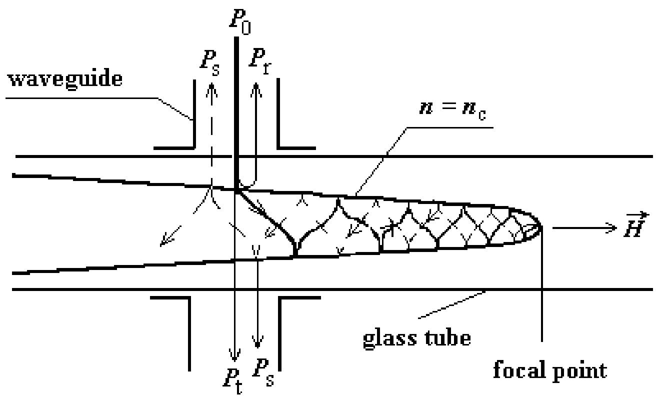


**Fig. 1.** *The scheme of EPW excitation and propagation.*

the wave slows down and its electric field increases drastically. The oscillatory energy of electrons given, according to [1], by $W_{\sim} = \frac{P}{\pi \omega n_c} k_{\|}^3 \exp\left(-2ak_{\|}\frac{\nu}{\omega}\right)$, at power about 20 W is already close to the energy of trapped electrons $W_{ph} = \frac{m\omega^2}{2k_{\|}^2}$ corresponding to phase velocity $\omega/k_{\|} = 4 \times 10^8$ cm/s. At this condition intensive resonance interaction of wave with electrons and, as a consequence, the capture of electrons should take place. The wave breaking can occur at a higher pump power leading to generation of fast electrons at energy close to double oscillatory energy in the breaking point which scales as $W^*$ (eV) ≈ 90 $P^{0.4}$ (W).

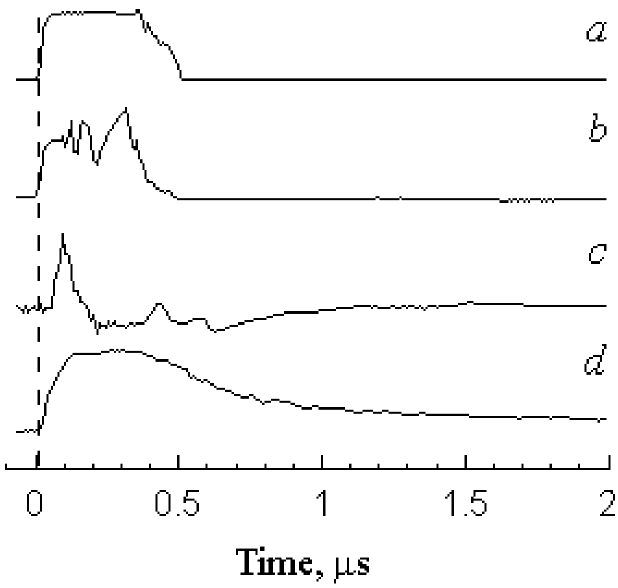


**Fig. 2.** *Oscillograms of incident (a), reflected (b) microwave pulses, electron current (c) and plasma luminosity(d).*

In the present paper the interaction of strong EPW pulses at power up to several kW with plasma is studied using multi-grid analyzer, spectroscopic, cavity, electromagnetic diagnostics and enhanced microwave scattering technique. Parameters of microwave pump in present experiments are as follows: incident pulse power is $P \sim 50 - 10000$ W, pulse duration is up to 2 µs, pulse front is $t_f \sim 40$ ns, repetition frequency is 300 Hz.

As it is seen in Fig. 2*c* immediately after turning on of 10 kW pulse at frequency 2840 MHz (Fig. 2*a*) a sharp burst of current of electron possessing energy higher than 500 eV is observed. Simultaneously the luminosity in the focal point increases (Fig. 2*d*). The electron distribution function measured by the analyzer has a pronounced tail at energy $W >> T_e$, which can be characterized by effective temperature $T_h$. Its dependence on the pump power measured with different time resolution after the pulse switch on is shown in Fig. 3.

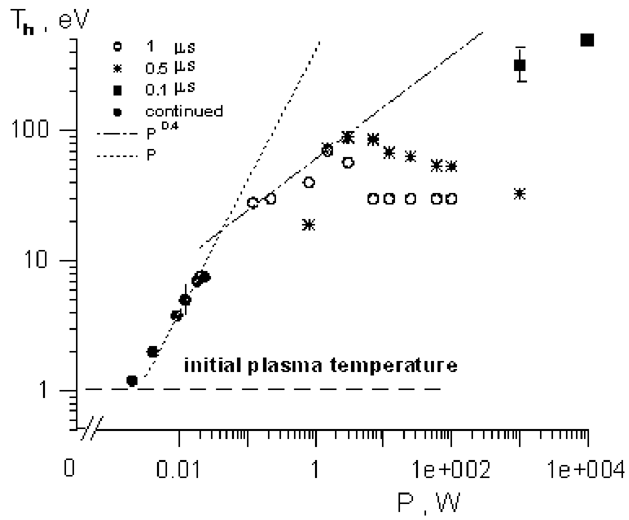


**Fig. 3.** *Dependence of electron effective temperature on the pump power.*

Until $P \leq 0.5$W the accelerated electron temperature $T_h$ increases as linear function of $P$, then the growth rate reduces and approaches the dependence $T_h \sim P^{0.4}$ corresponding to theoretically prescribed.

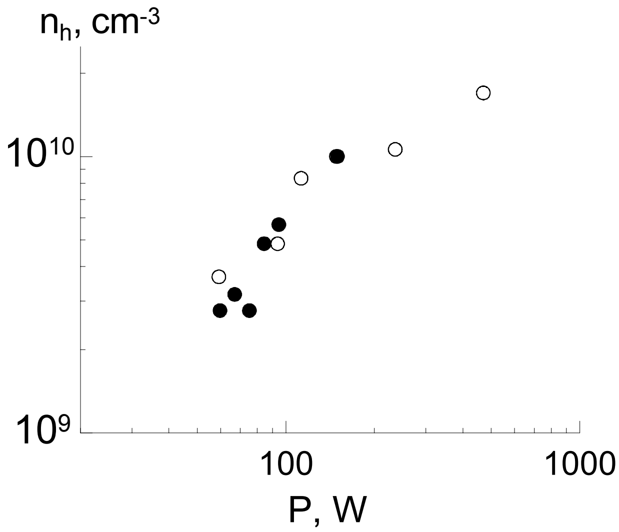


**Fig. 4.** *The number of accelerated electrons versus pump power.*

To estimate an absolute number of accelerated electrons a special experiment utilising a Rogovskiy coil placed on the discharge quartz glass tube was performed. The calibration measurements were carried out using the current pulses at pulse duration 0.05÷3 μs which were provided by the standard generator. As result of the calibration the error bars were fixed at the level of ~10%. It is shown that the current peak amplitude is not dependent on the coil position along plasma column relative to the focal point. The accelerated electron density averaged over the cross section $n_h$ was determined from the measured current $i$ and the electron tail parameters using relation $n_h = i/S\ e<v_{Th}>$, where $e$ is electron charge, $<v_{Th}>$ is average electron velocity in the tail. The fast electron flow cross section $S$=0.015 cm$^2$ was determined in spectroscopic measurements from the radius of additional luminosity region. The dependence of electron density $n_h$ on pump power is shown in fig. 4. It is seen that the density changes in range from $4\times10^9$ cm$^{-3}$ up to $2.5\times10^{10}$ cm$^{-3}$ at the pump power increase from 50 W up to 500 W. The upper value corresponds to $n_h$=0.25$n_c$. The duration of electron acceleration decreases with growing pump power, as it is seen in multi-grid analyser data shown in fig.5.

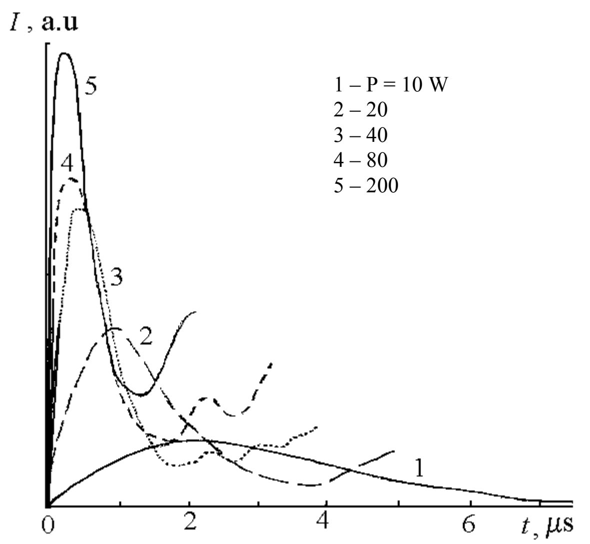


**Fig. 5.** *Waveforms of accelerated electron current for different pump power.*

Simultaneously with fast electron current termination oscillations are observed at the microwave detector measuring microwave signal reflected by plasma (see Fig.2*b*). These oscillations correspond to a microwave at frequency up-shifted by up to 20MHz in respect to the pump. This frequency shift decreases in time, as it is seen in fig.6, but it is not dependent on the pump power. The time of their onset decreases with the pump power. Most likely this microwave at the shifted frequency is generated in the vicinity of the focal point due to reflection from the steep density hump produced by intensive ionisation caused by electron oscillations in the microwave field. (The energy of these oscillations exceeds the ionisation potential in argon $E_i$ = 15.76 eV already at $P$ = 5 W.) The time resolved spectroscopic measurements of neutral and ionised Ar radiation have shown significant narrowing of the radial density distribution in the hump. It should lead to formation of a plasma waveguide possessing much smaller cross-section than initial one existing in unperturbed plasma. One should expect the strong EPW reflection effect at the boarder of these two plasma waveguides. According to time resolved measurements of density distribution along magnetic field performed with the cavity method this boarder is moving in the density gradient direction at the speed of $10^7$ cm/s, thus leading to the frequency up-shift of the reflected EPW due to the Doppler effect.

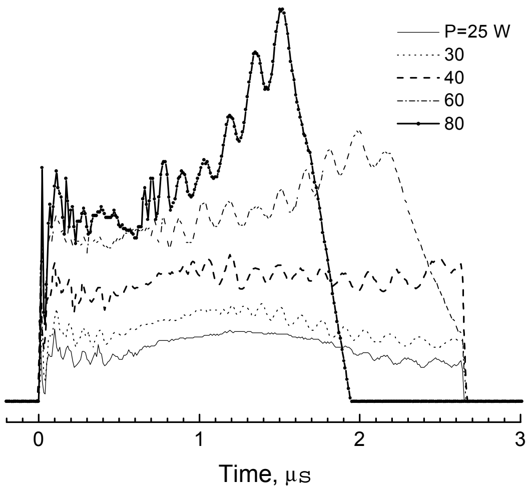


**Fig. 6.** *Reflected microwave pulses after homodine detection for different pump power.*

In conclusion we should underline that intensive electron acceleration was observed under conditions when wave breaking phenomena should occur in the vicinity of the resonance point of electron plasma wave. Acceleration in which up to 25% of electrons take part was terminated by reflection of the pump wave accompanied by its frequency up-shift. Generation of strong ambipolar electric field accompanied by ion acceleration is expected in this situation.

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**References**

1. V.I. Arkhipenko et al, Plasma Physics Reports **7** (1981) 396-404.