EXCITATION OF ELASTIC OSCILLATIONS IN SOLIDS BY A PULSED PROTON BEAM

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INTRDUCTION

At present, the beams of charged particles are used not only in fundamental researches but they have found a wide application in solving the plasma electronics problems [1], modification of material surfaces properties [2] and in a number of other applications.

Beams of the charged particles, interacting with solids, excite elastic oscillations [3,4]. The energy flows of pulsed intense beams can achieve 10^{12}-10^{14} W, that considerably exceeds the power of known controlled energy sources. Therefore, the use of intense beams for generation of elastic oscillations is of increasing interest.

It is possible to mark three basic mechanisms of elastic pulse excitation by intense beams of charged particles, namely: shock, thermoelastic, and ablation ones. The shock mechanism - generation of oscillations by transfer of beam momentum to the target - is the basic mechanism in the range of small energies, when the effective reflection of particles from target surface prevails. Thus the double momentum of beam pulse is transferred to the target. With increasing of beam energy, the particles penetrate into target substance, transferring to the target both momentum and energy.

Irradiated volume is heated up and deformed, exciting an elastic wave. If the absorbed energy results in intensive evaporation of a target, the ablation mechanism is included forming a pulse of pressure due to the ablation process. The pulsed pressure to 10^8 Pa in solids can be achieved with the thermoelastic mechanism and 10^9- 10^{12} Pa with ablation development [4], while modern piezoelectric and magnetostriction converters used in ultrasonic engineering have allowable pressure only to 10^7 Pa.

In this connection of increasing interest is the use of charged particles beams for generation of ultrasonic oscillations, which are greatly required in physics and engineering. At present the ultrasound has a wide application for the intensification of technological processes, defectoscopy, modification of material properties, signals processing and propagation.

The experimental works performed early [3, 4] with electronic and ion beams have a demonstrating character, the fact of excitation of elastic pulses in the condensed substance was established. Besides, the excitation of pressure pulses by ion beams is more effective, comparatively to electronic ones, since ion beams have considerably larger energy linear losses.

EXPERIMENTAL SET UP

In the given work the experimental results on research of excitation of ultrasonic oscillations with a proton beam in a specific system represented by the acoustic waveguide are represented. The transition to heavy particles, in comparison with electrons, has allowed to find out the effect of ultrasound excitation at the comparatively low beam currents of about 5-20 mA. The energy of the beam remained constant - 5 MeV, the duration of beam pulse varied from 5 μsec up to 20 μ sec, cross section of the beam was 1 cm^2. The scheme of the experimental setup is represented in Fig 1. The proton beam falls down the edge face of the acoustic waveguide (2). Excited oscillations were registered by piezosensors (3_1-3_4) placed along waveguide length. The signals were fed to the electronic oscillograph. As an acoustic waveguide the prism manufactured from an acrylic plastic with the sizes $1.5 \cdot 1.5 \cdot 60$ cm^3 was used. The choice of the given material is caused by the fact that its wave resistance ρv_s is close to the wave resistance of liquids, with which the irradiator should be matched (ρ is density, v_s is sound velocity).

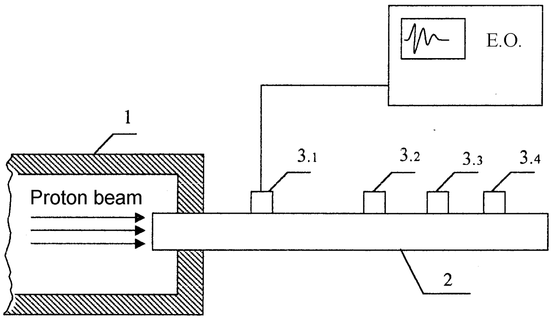

Fig. 1 Scheme of experimental setup

EXPERIMENTAL RESULTS

In the work the spatial-amplitude characteristics of excited oscillations and spatial distribution of the acoustic wave amplitude in the waveguide are investigated, the modes of excited waves are identified.

The characteristic oscillogram of oscillations (a), registered by piezosensors 3_1-3_4 is represented in Fig.2 This oscillogram is obtained by means of the sensor 3_1, placed at the distance 15 cm from the interaction region of the beam with the target (waveguide edge). The sensor sensitivity is 1.5 μV/Pa, maximum amplitude corresponds to the value of pressure ~ 10^3 Pa. The bottom oscillogram (b) is the calibration signal of frequency 100 kHz.

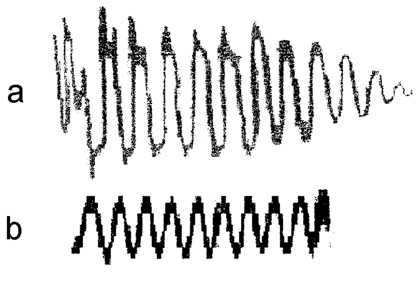

Fig. 2 Characteristic oscillograms of elastic oscillations (a) and calibrating signal (b).

From the analysis of oscillograms it follows, that the excited oscillations represent harmonic damping sound oscillations at characteristic frequency ~ (0.8-1) .10^5 Hz. Parameters of ion beam during measurements are the followings: current 20 mA, energy 5 MeV, pulse duration 10 µsec.

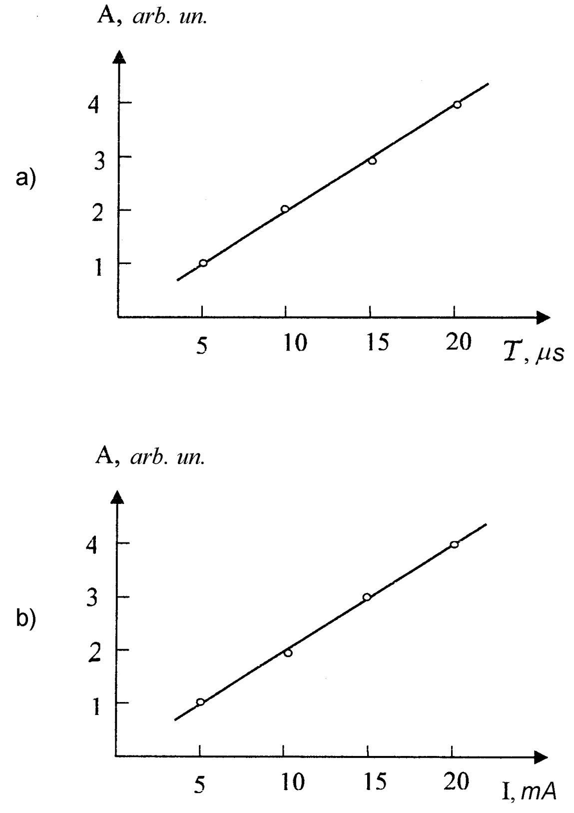

Fig.3 Dependencies of oscillations amplitude upon the value of beam current (a), and upon pulse duration (b)

The dependencies of the maximum amplitude of oscillations upon beam current and pulse duration were investigated. In the diagrams of Fig.3 the dependencies of oscillations amplitude upon the value of beam current (a), at pulse duration of 10 µsec., and upon pulse duration (b), at beam current of 10mA are represented. The values of amplitude are given by arbitrary units. Each point in the diagrams is evaluated by averaging the experimental measurements for 5 pulses. From the represented results it follows, that the maximum amplitude grows directly proportionally to increase of beam current and pulse duration. It is necessary to note especially, that the frequency of excited oscillations and character of damping in all cases remains constant.

In the diagram of Fig.4 the change of the maximum amplitude of oscillations along the waveguide is shown. The measurement of distance was made from place of beam interaction with target - waveguide edge. As it follows from the represented diagram, the amplitude decreases by the exponential law.

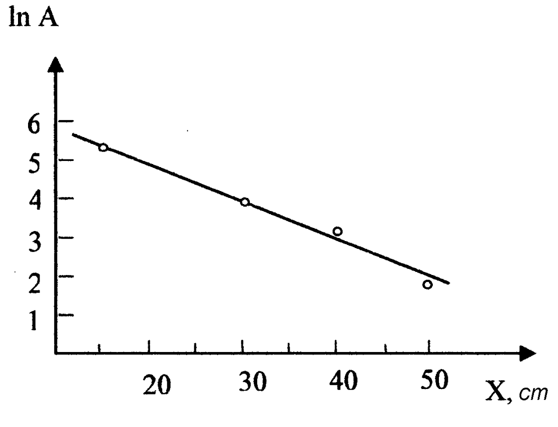

Fig.4 Change of the maximum amplitude of oscillations along the waveguide

THEORY

For the determination of excited frequencies range and oscillations identification it is necessary to consider the character of acting force and properties of the system - acoustic waveguide. In this case the external acting force is displayed as impact working during some time (duration of beam pulse). The most probable mechanism of energy transfer to the acoustic system resulting the oscillations excitation, is the thermoelastic one.. Really, at the fixed beam energy 5 MeV, current 5-20 mA, area of cross section 1cm^2, the density of energy flow is equal $q = (2.5\text{-}10)\cdot 10^8$ W/m^2, that is lower by some orders of magnitude than the critical q^*, at which ablation arises [4].

$$q^*\tau = \frac{\lambda\delta}{\alpha}T \quad \text{if} \quad \delta >> (\alpha\tau)^{1/2} \tag{1}$$

where $T=0.1L/R$, α and λ are the temperature and thermoelastic factors, respectively, δ is the length ionization proton losses in target; in this case it makes the value ~ 10 -2cm; L is mole evaporation heat, R is universal gas constant,τ is duration of beam pulse.

The acoustic properties of the acoustic waveguide are determined by its geometrical sizes and elastic properties of material. In this case there may be the propagation of harmonic eigenwaves extending along the waveguide without change of the wave form. By the structure of sound field each eigen wave represents a single wave propagating along the waveguide and standing in a transversal direction. In solid rods the eigenwaves are characterized by critical frequencies and essential dispersion. The acoustic field of the wave propogating along the axis Z, is determined by the relation:

$$P_{nm} = A_{nm}\cos\frac{n\pi}{d}x\cos\frac{m\pi}{l}y \times \\ \times \exp\left(\pm i\sqrt{k^2 - \left(\frac{n\pi}{d}\right)^2 - \left(\frac{m\pi}{l}\right)^2}\,z - i\omega t\right) \tag{2}$$

where A_{nm} is the wave amplitude, x, y are the transversal directions of waveguide, d and l are the appropriate cross sizes, n and m are the numbers of waves, which take meanings 0,1,2,3 ..., k is wave number. The dispersion of phase and group velocities is given by expressions:

$$v_{ph} = \frac{v_s}{\sqrt{1 - \left(\frac{n\pi}{kd}\right)^2 - \left(\frac{m\pi}{kl}\right)^2}} \qquad (3),$$

$$v_g = v_s\sqrt{1 - \left(\frac{n\pi}{kd}\right)^2 - \left(\frac{m\pi}{kl}\right)^2} \qquad (4).$$

If $\kappa > \sqrt{(n\pi/d)^2 + (m\pi/l)^2}$, then wave propagation takes place; if $k < \sqrt{(n\pi/d)^2 + (m\pi/l)^2}$, then wave propagation is impossible. The critical frequency, being lower for the wave be not propagating, is determined from the relation:

$$\omega^2_{nm,cr} = v_s^2\left[\left(\frac{n\pi}{d}\right)^2 + \left(\frac{m\pi}{l}\right)^2\right] \qquad (5).$$

If $\omega<\omega_{mn,cr}$ the phase velocity goes to infinity, and group velocity to zero to (3) and (4), respectively. The wave nature turns into oscillatory one with the amplitude decreasing along the waveguide by the exponential law. The fact of excitation of namely this wave is proved experimentally (oscillogram of Fig. 2, diagram of Fig. 4). Under the conditions of experiments the minimum meaning of critical frequency is equal: $f_{11,cr} \approx 1.2\ 10^5$ Hz, $(\omega=2\pi f)$. The registered frequency has value (0.8-1) 10^5 Hz and does not depend on beam current and pulse duration. The excitation of sound wave at the given frequency is caused by oscillatory properties of the system. The influence of pulsed nonsinusoidal force on it results in occurrence of damping oscillations at eigenfrequency. Proceeding from the Hooke law, it is possible to show that the characteristic frequency f of «sounding» will be determined only by elastic properties and geometrical sizes of the oscillatory system.

$$f = \sqrt{\frac{E}{\rho\lambda}} \qquad (6)$$

Here E is the Young module, λ is the characteristic wavelength determined by the waveguide cross sizes. For the given material $E \sim 7.5*10^9$ Pa, ρ= 1.2 10^3 kg/m^3, waveguide cross sizes $d = l = 1.5$ cm determine the length of the first order wave λ=3 cm. At these parameters of the oscillatory system the calculated frequency coincides with measured one.

It should be noted, that the critical frequency of a given acoustic waveguide ($1.2*10^5$ Hz) differs from registered one (under critical, equal to $0.8\text{-}1*10^5$ Hz), by the value of measurements error. However, the fact of exponential decrease of amplitude along the waveguide, i.e. the absence of wave group velocity, is essential argument for the benefit of the offered model for acoustic field excitation in ultrasonic range at under critical frequency.

DISCUSSION

On the basis of the given quantitative characteristics of measurements it is possible to make energy estimations of the efficiency of oscillations excitation. The value of acoustic pressure in solids characterizes the volumetric density of elastic energy. The measured maximum amplitude of pressure at distance 15 cm. from the place of beam interaction with target has value ~ 10^3 Pa. Then, taking into account the waveguide volume, in which the energy of an elastic standing wave is located, and the spatial distribution of amplitude (Fig. 4), it is possible to conclude, that about 10% of beam energy was transformed to the energy of elastic oscillations. As it follows from the diagrams of Fig. 3, the amplitude of oscillations grows linearly with increasing of beam current and pulse duration. It corresponds to the model of thermoelastic mechanism of oscillation excitation [3,4], from which it follows that elastic wave amplitude is directly proportional to the volumetric density of the absorbed energy.

Thus, the possibility of ultrasound generation in solids by a pulsed beam of the charged particles is experimentally shown. Use of proton beam has allowed to find out the phenomenon of oscillation excitation at low currents ~ 5 mA. The transition to intense proton and ion beams will allow to elaborate generators of ultrasonic oscillations with high power levels.

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