A study of the excitation of acoustic oscillations in metals by electrons and protons is described. For thin metal plates, the amplitude of the electric signal is independent of the energy of the electrons and is proportional to the ionization losses of the charged particles. The dependence of the amplitude of the acoustic signal on the energy of the incident electrons and protons is considered and a comparison between the Cherenkov radiation, thermoelastic, and dynamic models is made.

In [1-3] it was shown that for the passage of relativistic electrons through a metal, ultrasonic oscillations will occur. These studies were carried out over a wide range of energies $E_0 = 1.5-1000$ MeV and electron numbers per pulse of $N = 10^8-10^{15}$. The main conclusion of [2, 3] was the proposal of a linear relation between the amplitude of the acoustic signal $U$ and the total number of electrons in the current of the pulsed accelerator $N$. Experiments were carried out both for instruments with a total absorption of energy of the electron pulse [1, 2] and for instruments with thin absorbers when the energy loss of the electrons was significantly less than the initial energy [3].

A block diagram of the experimental apparatus is shown in Fig. 1. A beam of electrons from a linear accelerator 8 falls upon a plate of the material to be studied 1 on whose surface a piezodetector 2 consisting of 16 plates of a ferrosalt crystal of area $3.4 \text{ cm}^2$ is attached. The resonant voltage of the detector occurs at a frequency of $f = 65.0$ kHz. The electric signal from the piezodetector is amplified by a transistor resonant preamplifier 3 with a gain of $\sim 50$ and after a cathode follower passes to a matched attenuator 4 with an attenuation of $10^3$. After the attenuation, the signal is amplified in a final transistor amplifier 5 and passes to the vertical input of an oscilloscope 6 whose display is synchronous with the pulsed accelerator 7. The total gain of the entire system is $\sim 10^6$, and the pass band is $\Delta f = 1$ kHz.

All the experiments were carried out on FTI linear accelerators of the Academy of Sciences of the Ukrainian SSR which had the necessary magnetic spectrometers to be used to measure the energy and spectral distribution of the electron beams [4].

In [5] it was established that, for thin absorbers whose thickness is $h \ll t_0$ in radiation thickness units, the amplitude of the acoustic signal is independent of energy within the limits $E_0 = 80-225$ MeV. In Fig. 2 is shown the dependence of the amplitude of the acoustic oscillations on the energy of the incident electrons for different materials (aluminum, copper, lead; $h = 0.2$ cm). For materials with large $Z$, the thickness $h$ is comparable to $t_0$. In this case an essential contribution is played by the secondary electrons in the electron-phonon avalanche which partly explains the growth of the acoustic signal amplitude for lead.

It is thus necessary to study the nature of the acoustic radiation from beams of charged particles in metals by the choice of an upper limiting or working frequency $f$ of the system used such that two coherence conditions are satisfied:

$$c_d f > d, \quad T = \frac{1}{f} \approx \tau_1,$$

where $c_d$ is the velocity of the acoustic waves propagating in a given material (metal), $T$ is the period of the oscillations, $d$ is the transverse linear dimension of the incident electron beam (or the transverse linear dimension of the avalanche in a thick layer of target material), $\tau_1 = 1.5 \mu\text{sec}$ is the duration of the current pulse of the linear accelerator or proton synchrotron.
If Eq. (1) is not satisfied, then the amplitude of the acoustic signal will begin to depend on the geometric characteristics of the beam: the length $l_1$ and the transverse dimension $d$. In these experiments, the transverse beam dimension was $d \sim 0.5 \text{ cm}$ for an electron energy of $E_e = 250 \text{ MeV}$. However, it should be noted that for decreasing energy, the transverse mean dimension increased, and for an energy of $E_e = 70 \text{ MeV}$ it was $\sim 2 \text{ cm}$ at the position of the plate. For a lead plate the first of the conditions in Eq. (1) is not satisfied so that $(c_s/f)p_b < d$ right up to an electron energy of $\sim 170 \text{ MeV}$. Therefore, a consideration of only the coherence condition of the applied radiation and the ratio between the target thickness and the thickness in radiation-units of the given metal can give an explanation of growth of the acoustic signal with energy for Cu and Pb in Fig. 2. A methodological procedure for studying the coherence region is described by us in [6]. If Eq. (1) is satisfied, the phase shift of the acoustic waves at the frequency $f$ for any beam particles is small in the transverse and longitudinal directions. Since the amplitude of the acoustic signal $U \sim N$, where $N$ is the total number of particles in the current pulse of duration $\tau_1$, the energy of the acoustic oscillations $E_a$ will be related to the number of particles $N$:

$$E_a = \alpha U^2 = \beta N^2,$$

where $\alpha$ and $\beta$ are some dimensional quantities independent of the geometric dimensions of the incident beam.

References [3, 5, 6, 7] show that the basic form of the electron energy losses, which are transformed into ultrasonic waves for electron energies less than a critical value $E_e < E_{cr}$ or for thin plates where $h < t_0$ in radiation length units, is ionization losses. Estimates show that the contribution of the acoustic losses to the total energy loss of the electrons in the material is very small and, in principle, not only ionization but also other forms of energy losses of the electrons are transformed into acoustic waves. For example, using Eq. (2), it is possible to calculate, for a thin aluminum plate ($h = 0.2 \text{ cm}$), the ratio of the acoustic energy of a single electron $E_a/N^2$ to the ionization losses $E_{ion}$ of a single electron with an initial energy of $E_e = 250 \text{ MeV}$:

$$\frac{E_a}{E_{ion}N^2} = \frac{U^2}{R_s E_{ion}N^2} \approx 10^{-25},$$

where $R_s = 18.8 \text{ } \Omega$ is the amplitude of the "acoustic" impedance [3]. The correlation of the acoustic signal with the large total loss of energy of the electrons was studied by us for Al, Cu, Fe, Pb in [6, 7]. For Al, the ionization energy loss is dominant while, for Pb, for example, the ionization and absorption parts of the radiation losses are approximately equal. New studies by us have shown that the amplitude of the acoustic signal is proportional to the absorption of energy in the plates.

In the case of protons of energy $E_p \leq 200 \text{ MeV}$, the braking is determined exclusively by ionization losses and, therefore, a comparison of data obtained in experiments measuring acoustic waves excited by electrons and protons, permits an unambiguous determination of the nature of these waves.

The experimental studies with beams of electrons and protons were carried out using the same type of method. A beam of protons from an external ITEF pulsed-beam synchrotron with an energy of $E_p \leq 200 \text{ MeV}$, after collimation (the beam dimension could be changed from 0.3 to 2 cm), fell upon a thin ($h = 0.2 \text{ cm}$) aluminum plate $1 (50 \times 10 \text{ cm}^2)$ on one of whose end-faces was attached an acoustic detector. The acoustic signal after amplification was recorded on an S1-17 oscilloscope screen 6.

In this experiment, the proton current was measured using a transit induction sensor, and the number of protons in the pulse of duration $\sim 1.6 \mu\text{sec}$ was $10^7-10^{10}$.