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MICROPHONE DETECTED IONACOUSTIC SIGNAL FROM METALS

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ABSTRACT

An experimental system for studying the acoustic signal generated by a modulated MeV ion beam in metals is described. For detection, a closed cell on the rear side of the copper or aluminium sample, a half-inch condenser microphone, and a lock-in amplifier were employed. The signal was found to be proportional to beam current and particle energy, and inversely proportional to cell length. A decrease of the signal magnitude and an increase of the phase delay with increasing modulation frequency and sample thickness were also observed.

АННОТАЦИЯ

Описывается экспериментальное оборудование, пригодное для исследования акустических сигналов, возбуждаемых модулированным пучком ионов с энергией в несколько МэВ. Для детектирования сигналов на задней стороне образцов из меди и алюминия помещены закрытая ячейка, микрофон конденсорного типа размером полдюйма и один "lock-in" усилитель. Установлено, что величина сигнала пропорциональна интенсивности и энергии пучка ионов и обратно пропорциональна длине ячейки. При увеличении частоты модулирования и толщины образца амплитуда сигнала уменьшалась, тогда как запаздывание фазы сигнала возрастало.

KIVONAT

Egy olyan kisérleti elrendezést irunk le, mely alkalmas néhány MeV energiáju modulált ionnyalábbal keltett akusztikus jelek vizsgálatára. A jelek detektálására a réz vagy aluminium minta hátoldalán elhelyezett zárt cellát, egy fél-inches kondenzer mikrofont és egy lock-in erősitőt használtunk. Azt találtuk, hogy a jel arányos az ionnyaláb intenzitásával és a részecskék energiájával, és forditva arányos a cella hosszával. A moduláló frekvencia, illetve a minta vastagság növekedtével a jelamplitudó csökkent, mig a jel fázis késése nőtt.

INTRODUCTION

The ionacoustic or, in general, the particle acoustic effect is, in a phenomenological sence, analogous to the more extensively studied photoacoustic effect involving sound generation by a chopped or pulsed beam of light [1]. These effects manifest themselves both in acoustic vibrations of the radiation-absorbing solid sample and in pressure changes in the surrounding air.

The radiation-induced acoustic signals are assumed to have a thermal origin, i.e. to be due to heat deposition by the radiation in the sample [2] . Perry as well as Sieger and Lefevre found that the evolution of the vibration signal on pulsed excitation with electrons [3] and protons [4] was closely related to the actual heat deposition profile in metals.

It is noted, however, that the vibration signal depends not only on thermal but also on thermoelastic and acoustic properties of the sample, and may be affected by specific nonthermal signal generation mechanisms such as electrostriction [5] , acoustic Cerenkov radiation [6] , momentum transfer [6,7] , strain effects [8,9], and stimulated Brillouin-scattering [10], too. Some non-thermal excitations are subjected to quick thermalization [11], but some others are not and these may even prediminate the signal [9]. The numerous possible contributions complicate the structure of the vibration signal, as was the case e.g. with inacoustic imaging of aluminium samples [7].

The pressure signal, on the other hand, can usually unambigously be described in terms of heat diffusion from the sample to the gas [2] and, hence, the detection of the pressure signal should be preferred when primary information on heat deposition is to be obtained [12]. Such a technique has been widely used in photoacoustic studies and is called the gas--microphone detection scheme [2]. In that method, the sample is placed in a small gas-filled cell having a window for the exciting light beam, and fitted with a precision microphone.

Despite its advantages, microphonic detection of the particle acoustic signal has only rarely been pursued. Mascarenhas et al. [13] constructed a particle acoustic X-ray dosimeter employing a cell of 20 mm diameter and 2 mm height and a condenser microphone with a sensitivity of 100 μV/Pa. The X-rays were intensity-modulated by a mechanical chopper and absorbed by a 0.2 mm thick lead disk in the cell. The microphone signal was processed by a lock-in amplifier to reduce random noise. At 90 kV this system was capable for measuring exposure rates from 5.10^{-7} $C.kg^{-1}.s^{-1}$ (2mR/s). It could also be calibrated with respect to absorbed energy fluence rate, thus having a potential use for determining absorbed dose rates of X-rays.

If electron or ion beams were to be measured with a setup similar to that of Mascarenhas et al., strong ionization of the cell gas would, at best, introduce difficulties in signal interpretation. Therefore, in an earlier paper [14] , rear side detection [15] was proposed for ionacoustic studies with microphones i.e. the cell gas is situated beyond rather than in front of the sample and is thus shielded by the sample from the radiation (fig.1).

THEORY

In our calculations for the rear side pressure signal the basic concepts of the thermal wave theory of Rosencwaig and Gersho was adopted [16,17] . Critically damped heat waves were assumed in the sample and the gas, and also coupling to pressure changes through an adiabatic process in the gas. When the wavelength of the thermal waves in the solid is much larger than the range of the incident particles, heating by the beam can be regarded as occuring on the sample surface. Then the time--dependent part of the temperature distribution is:

$$\begin{aligned} T(x) &= 2S\left[e^{\sigma_s x} + R_\Sigma\left(e^{\sigma_s x} + e^{-\sigma_s x}\right)\right] \qquad & -l \le x \le 0 \\ T(x) &= 2S(1+R)(1+R_\Sigma)e^{(\sigma_g-\sigma_s)l}e^{\sigma_g x} \qquad & -(l+l_g) \le x \le -l \end{aligned} \tag{1}$$

with

$$S=h/(2k_s\sigma_s);\ \sigma_i=(1+i)\sqrt{\omega/(2\beta_i)};\ \beta_i=k_i/(c_i\ \varrho_i)$$

$$R=(K_s-K_g)/(K_s+K_g);\ K_i=\sqrt{k_i\ c_i\ \varrho_i};\ i=s,g$$

$$R_\Sigma=Re^{-2\sigma_s l}/(1-Re^{-2\sigma_s l})$$

in the above equations, the input parameters are h, the amplitude of the time-dependent part of the intensity of the absorbed radiation, k , c , and ϱ, the thermal conduction coefficient, the specific heat at constans stress/pressure, and the mass density, respectively. The time dependence of the intensity and the temperature can be expressed by the factor $e^{i\omega t}$ where ω is the modulation frequency. The symbols β, K, σ , and R are defined as the thermal diffusivity, the thermal effusitivity, the complex wave number of the heat waves, and the thermal reflection coefficient, respectively. R_Σ is the fractional contribution to multiply reflected heat waves to the temperature of the heated surface [17] . The indices s and g refer to 'sample' and 'gas', l and l_g are the thicknesses of the sample and the gas, respectively.

The pressure signal is proportional to the temperature of the rear surface of the sample:

$$p=AT(-l) \qquad (2)$$

where A is given by the equation [16] :

$$A=\frac{P_0\gamma}{l_g}\ \frac{1}{R(\sigma_g)}\ \frac{1}{\sqrt{2}\,\bar{T}}\,e^{-i\pi/4} \qquad (2a)$$

with p_0 , γ , and $\bar{T}$ being the static pressure, the specific heat ratio, and the temperature of the gas, respectively.

EXPERIMENTAL

For the experimental studies an ion beam from the 5 MV Van de Graaff accelerator of the Central Research Institute for Physics (KFKI) was intensity modulated by deflector coils and focused on the sample (see Fig.2). In Fig.3 the details of the sample-cell assembly are shown. The thin central part of the beam tube's end-piece forms the sample and the cell machined of stainless steel is attached to the rear side of this end-piece. The inner diameter of the cell was chosen so that half-inch microphone could be fitted in. Since good sealing of both the accelerator tube and the cell was compulsory, rubber gaskets were made use of at all interfaces. It was found that any leakage to the cell would reduce the signal magnitude and simultaneously increase the noise level. On mounting the cell, however, its pressure equalization vent had to be open to avoid overpressure in the cell which would make the microphone inoperative. The ionacoustic signal was picked up in the cell by a BK 4165 half--inch condenser microphone of 46.8 mV/Pa sensitivity, and amplified by a lock-in amplifier Model KFKI NV-255. A reference signal for the lock-in was obtained from the signal generator driving the deflector coils.

Each time before taking acoustic data the actual waveform of the modulated current was displayed on a Tektronix T912 oscilloscope and its r.m.s. value at the fundamental frequency was measured by the lock-in. For current measurements the microphone had to be removed from the cell to avoid grounding the sample electrically which would result in no current flow through the resistor R indicated in Fig.2. The lock-in reading with respect to current measurements had previously been calibrated by comparing the voltage drop on this resistor with the absolute value of the current measured independently for the unmodulated beam.

RESULTS AND DISCUSSION

Two pairs of current and signal waveforms obtained with a 2 MeV He^+ beam modulated at 20 Hz and at 80 Hz are shown in Fig.4. The copper sample was 1 mm thick and the volume of the cell was 1.3 cm^3. Similar waveforms were measured with a 2 mm thick aluminium sample, too. The achieved signal-to-noise ratios were excellent in spite of the rather noisy environment of the accelerator.

The dependence of the signal on beam current, particle energy, cell length, modulation frequency, and sample thickness were also studied. In Fig.5a the r.m.s. value of the ionacoustic signal from an 1 mm thick copper sample and 0.72 cm^3 cell volume is displayed as a function of the r.m.s. value of the modulated current. Adjustment of the current was carried out by changing the modulation depth of the 2 MeV He^+ beam. The signal normalized with respect to current is plotted against particle energy in Fig.5b. This experiment was performed on the same sample, but using proton beams and a cell of 2.4 cm^3 volume. It can be seen from Figs.5a and 5b that the pressure signal is proportional to beam current and particle energy. Interpretation of this result is straightforward. Eqs. (1) and (2) show that the signal is proportional to intensity which may, in turn, be expressed as a bilinear form of current and energy:

$$h = C\, I\, E / F$$

where F is the cross-section of the cell [18], C is equal to $\sqrt{2}$ if h, I, E, and F are in units of W/m^2, A, eV, and m^2, respectively.

The vibration signal was found to be also proportional to current and energy, however, proportionality with particle momentum, rather than energy was now expected [7].

The dependence of the signal on an effective cell length, $l_g = V/F$, where V is the cell volume, is shown in Fig.5c. These measurements were taken with a 2 MeV He^+ beam and an 1 mm thick copper sample. The data obtained with the 0.72 cm^3, 1.3 cm^3, and 2.4 cm^3 cells could be properly fitted to straight lines on the log-log scales having slopes of -1 for both modulation frequencies of 20 Hz and 60 Hz. The signal magnitude is thus inversely proportional to cell length, which is a well-known relation in photoacoustics, and is also reflected by Eq. (2a).

The dependence of the signal on modulation frequency and sample thickness is characterized by a monotonic decay of the magnitude and a steady increase of the phase delay with increasing frequency and thickness (Fig.5d). (The phase was defined as the difference between the signal and current phases taking into account the phase reversal owing to microphone polarization [19] . Fig.5d refers to copper samples of various thicknesses and a 1.3 cm^3 cell. Experimental data are represented by circles for the 1 mm, triangles for the 2 mm, and squares for the 3 mm thick samples, whereas the solid curves were obtained by using Eqs. (1) and (2). The empty circles correspond to the slopes of the linear functions of Fig.5a modified by the factor of 1.3/0.72, i.e. the volume ratio of the cells.

The signal magnitudes represented by the filled-in symbols have been normalized to the calculated value at 20 Hz by a factor of the order of unity. This normalization accounted for current changes between subsequent current and signal measurements. A similar uncertainty was encountered by other authors, too [4] . This normalization unfortunately prevented the absolute comparison of the copper aluminium signals.

In conclusion, a system for studying the gas-microphone ionacoustic signal has been constructed and a thermal wave model has been proposed to account for the dependences of the signal on various beam, sample, and cell parameters. General agreement between experiment and model has been realized.

Since the signal provides primary information on heat deposition by modulated ion beams, microphonic detection would, in principle, provide a means of nondestructive depth profiling modulated heat source (as opposed to pulsed ones). This is of practical importance because there is a broad class of accelerators delivering stationary beams.

The detection of the ionacoustic signal with a microphone would also make it possible to do pure thermal wave imaging of inhomogeneous samples. Since ion beams may be well focused and also have a well defined range, gas-microphone ionacoustic micrographs may yield good lateral and depth resolution.

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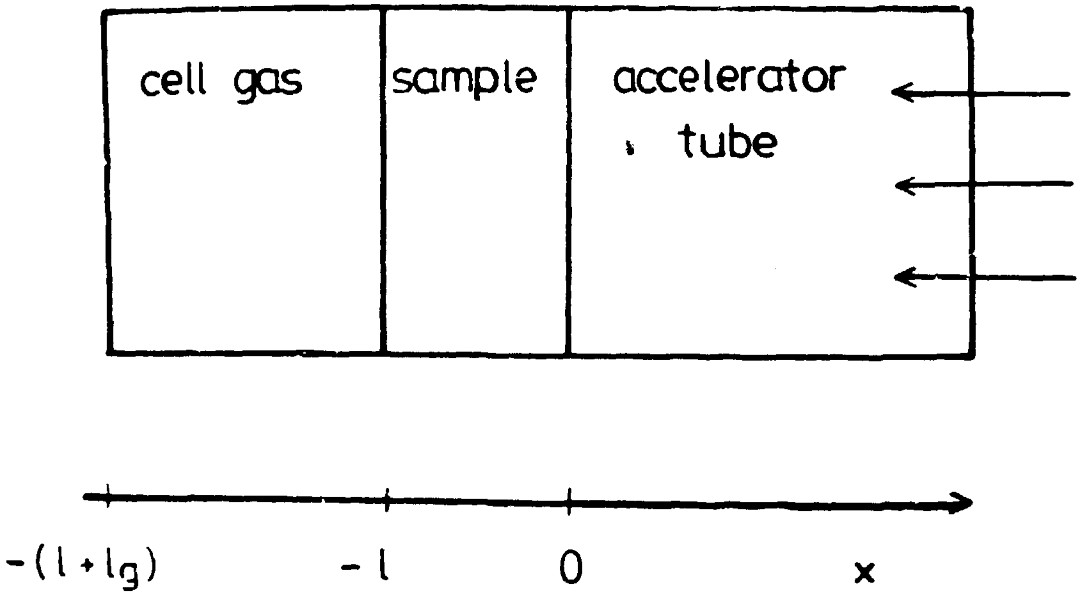

Fig. 1. The rear side detection scheme

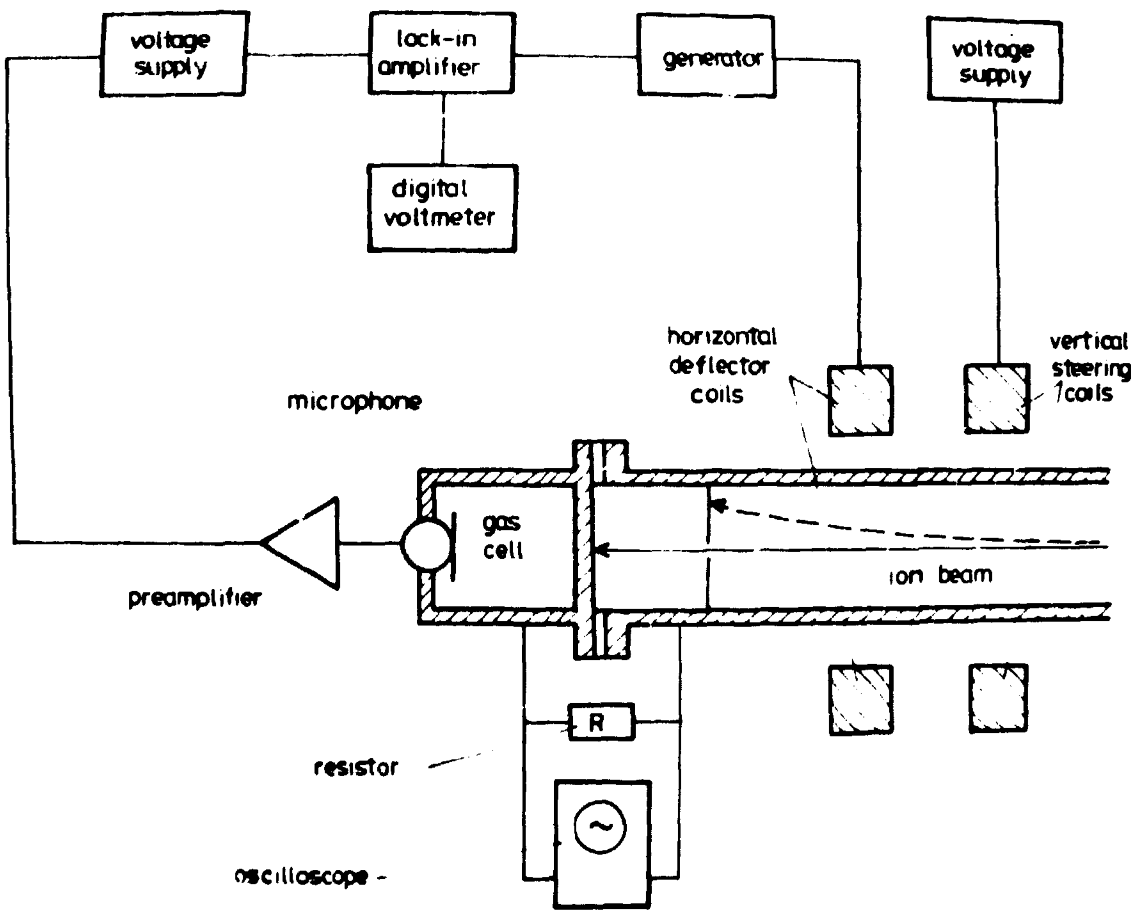

Fig. 2. Diagram of the ionacoustic system with microphonic detection

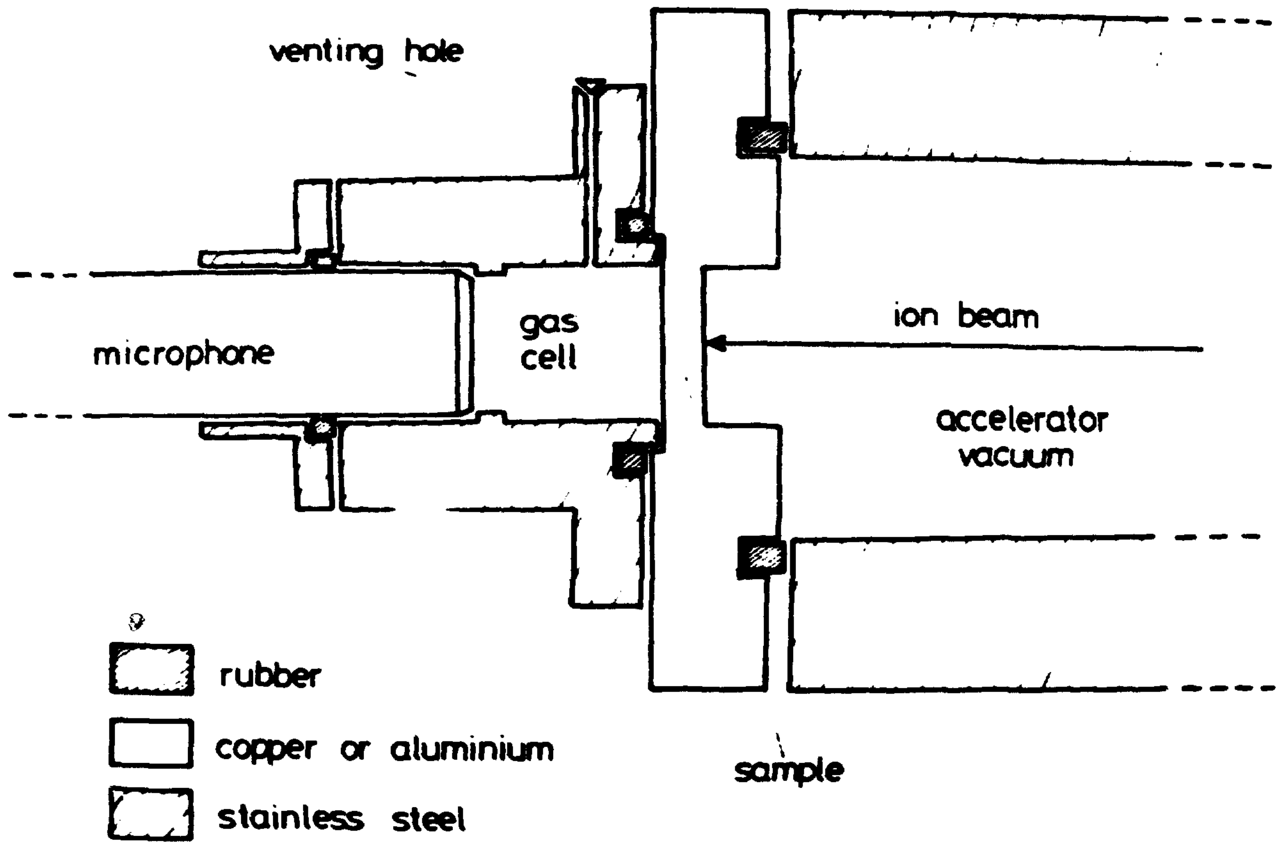

Fig. 3. Design of the ionacoustic sample-cell assembly

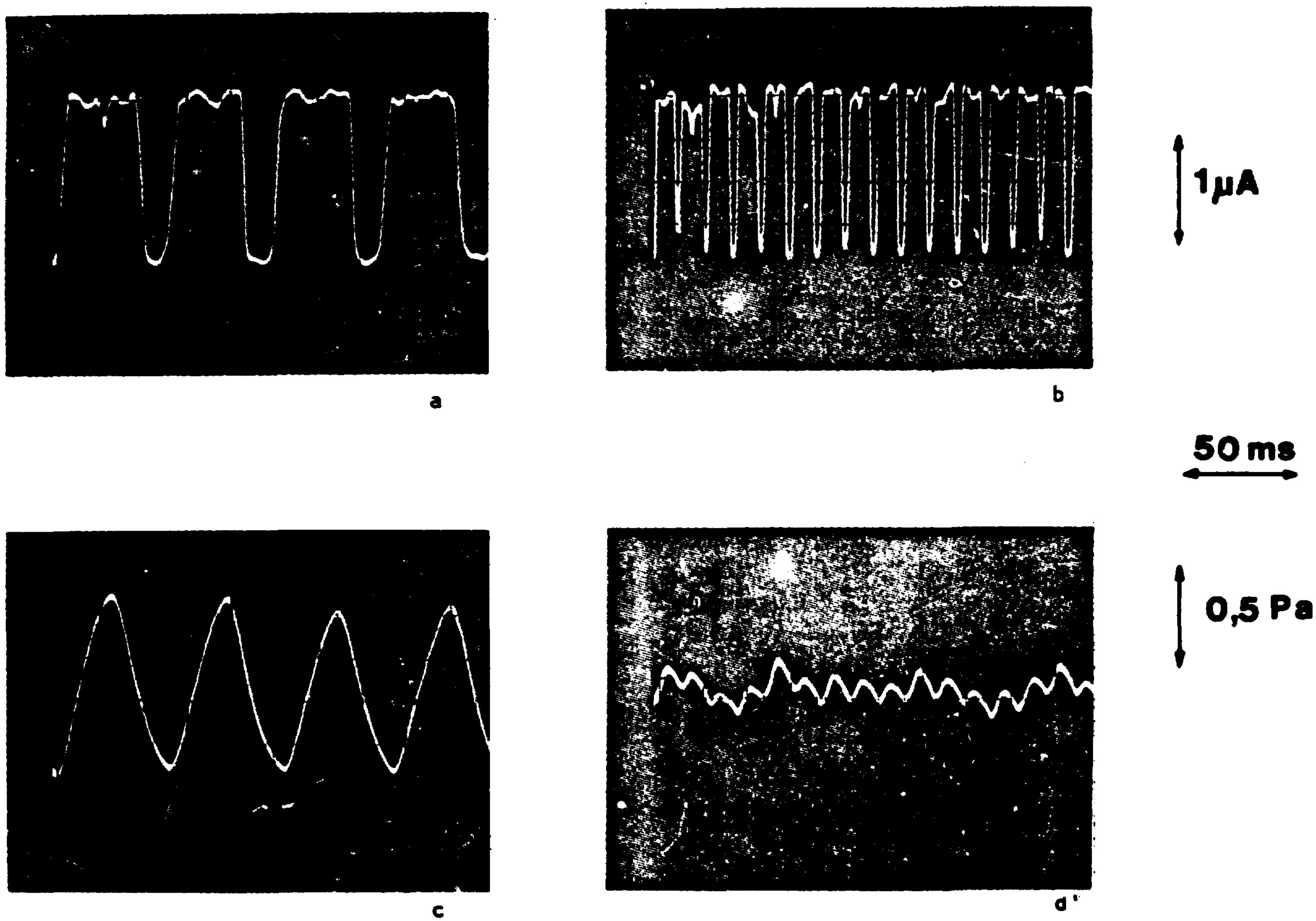

Fig. 4. Typical waveforms of the modulated ion current (upper traces) and the corresponding ionacoustic signal (lower traces) at 20 Hz (a,c) and at 80 Hz (b,d)

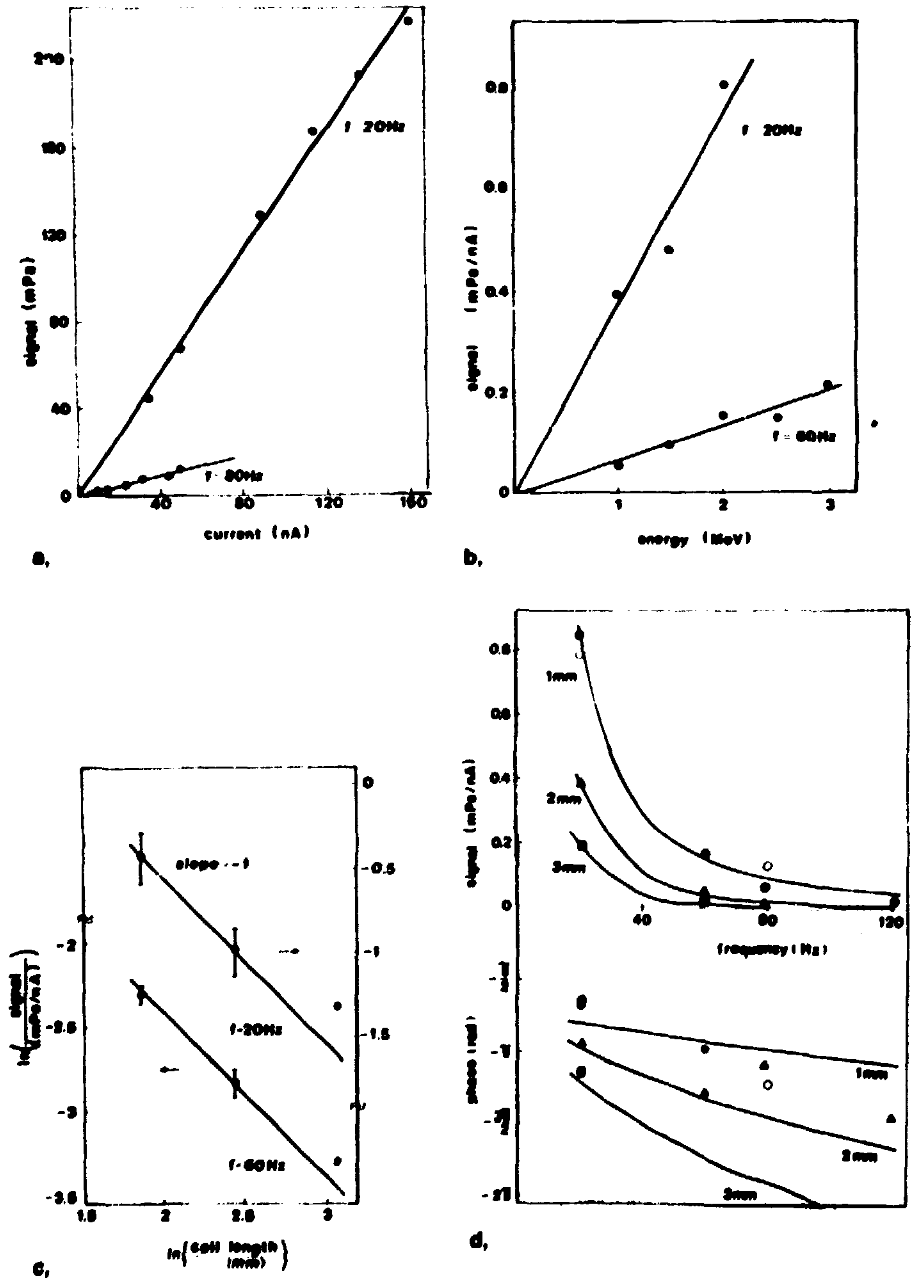

Fig. 5. Dependence of the gas-microphone ionacoustic signal on beam current (a), particle energy (b), cell length (c), and modulation frequency (d). See text for details

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