Testing Thermo-Acoustic Sound Generation in Water with Proton and Laser Beams*

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Experiments were performed at a proton accelerator and an infrared laser facility to investigate the sound generation caused by the energy deposition of pulsed particle and laser beams in water. The beams with an energy range of 1 PeV to 400 PeV per proton beam spill and up to 10 EeV for the laser pulse were dumped into a water volume and the resulting acoustic signals were recorded with pressure sensitive sensors. Measurements were performed at varying pulse energies, sensor positions, beam diameters and temperatures. The data is well described by simulations based on the thermo-acoustic model. This implies that the primary mechanism for sound generation by the energy deposition of particles propagating in water is the local heating of the media giving rise to an expansion or contraction of the medium resulting in a pressure pulse with bipolar shape. A possible application of this effect would be the acoustical detection of neutrinos with energies greater than 1 EeV.

1. Introduction

The production of hydrodynamic radiation (ultrasonic pressure waves) by fast particles passing through liquids was first predicted already in 1957 leading to the development of the so-called thermo-acoustic model in 19791,2. The model allowed to describe the primary production mechanism of the bipolar shaped acoustic signals measured in an experiment with proton pulses in fluid media3. According to the model, the energy deposition of particles traversing liquids leads to a local heating of the medium which can be regarded as instantaneous with respect to the hydrodynamic time.

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scale. Due to the temperature change the medium expands or contracts according to its volume expansion coefficient $\alpha$. The accelerated motion of the heated medium forms an ultrasonic pulse which propagates in the volume. The wave equation describing the pulse is:

$$\Delta p(\vec{r}, t) - \frac{1}{c_s^2} \frac{\partial^2 p(\vec{r}, t)}{\partial t^2} = -\frac{\alpha}{C_p} \frac{\partial^2 \epsilon(\vec{r}, t)}{\partial t^2}$$

(1)

and can be solved using the Kirchhoff integral:

$$p(\vec{r}, t) = \frac{1}{4\pi C_p} \int_V \frac{dV'}{|\vec{r} - \vec{r}'|} \frac{\partial^2 \epsilon(\vec{r}', t)}{\partial t^2} \left( \vec{r}', t - \frac{|\vec{r} - \vec{r}'|}{c_s} \right).$$

(2)

Here $p(\vec{r}, t)$ denotes the hydrodynamic pressure at a given place and time, $c_s$ the speed of sound in the medium, $C_p$ its specific heat capacity and $\epsilon(\vec{r}, t)$ the energy deposition density of the particles. The resulting pressure field is determined by the spatial and temporal distribution of $\epsilon$ and by $c_s$, $C_p$ and $\alpha$, the latter three depending on the temperature. A controlled variation of these parameters in laboratory experiments and a study of the resulting pressure signals allows therefore a precise test of the thermo-acoustic model. One decisive test is the disappearance of the signal at 4°C in water, the medium considered in the following, due to the vanishing $\alpha$ at this temperature.

However, in previously conducted experiments investigating this effect in different liquids, the observed pulses could not be unambiguously verified as thermo-acoustical\textsuperscript{3,4,5,6}. There the variation of the pulse amplitude with the temperature in water showed not the predicted dependency and particularly not the disappearance of the signal at 4°C.

2. Conducted Experiments

The experiments presented in this paper were performed with a pulsed 1064 nm Nd:YAG laser facility located at our institute, and the 177 MeV proton beam of the “Gustaf Werner Cyclotron” at the “Theodor Svedberg Laboratory” in Uppsala, Sweden. The beams were dumped into a 150 × 60 × 60 cm$^3$ water tank, where the acoustic field was measured with several position-adjustable hydrophones (pressure sensitive sensors based on the piezo-electric effect). The temperature of the water was varied between 1°C and 20°C with a precision of 0.1°C by cooling and gradual controlled homogeneous reheating of the whole water volume.

The spill energy of the proton beam was varied from 10 PeV to 400 PeV, the beam diameter was approx. 1 cm and the spill time 30 $\mu$s. For 177 MeV
protons, the energy deposition in the water along the beam axis ($z$-axis, beam entry into the water at $z = 0$ cm) is relatively uniform up to $z = 20$ cm ending in the prominent Bragg-peak at $z \approx 22$ cm. The laser pulse energy was adjusted between 0.1 EeV and 10 EeV at a beam diameter of a few mm, the pulse length was fixed at 9 ns. The laser energy density deposited along the beam axis had an exponential decrease with an absorption length of $(6.0 \pm 0.1)$ cm. The two experiments enabled us to use different spatial and temporal distributions of the energy deposition as well as two different kinds of energy transfer into the medium, i.e. by excitation by both beams and additionally by ionisation by the proton beam.

The sensors used were characterised and found to be linear in amplitude response, the frequency response was flat up to the main resonance at 50 kHz with a sensitivity of approx. $-150$ dB re $1$ V/$\mu$Pa. The sensitivity dependence on temperature was measured and the relative decrease was found to be less than $1.5\%$ per $1^\circ$C.

For every set of experimental parameters the signals of 1000 beam pulses were recorded, with a sampling rate of 10 MHz, sufficient for the typical frequency range of the signals of 5 kHz to 100 kHz.

3. Results

The measured bipolar signals were found to be in good agreement with simulations based on the thermo-acoustic signal generation mechanism. The hydrodynamic nature of the signal was proven by determining the propagation times of the signals at different positions in the $x$-direction perpendicular to the beam axis. They were consistent with the expected propagation times for sound in water. Also the investigated signal dependencies on beam energy, beam width and sensor distance from the beam show very good agreement with the simulation based on the thermo-acoustic model.

Figures 1 and 2 show the temperature dependence of the peak-to-peak amplitude of the bipolar signals for the two experiments, where a positive (negative) sign denotes a leading positive (negative) peak of the signal. The two data sets shown in each figure were recorded by two sensors positioned at $x = 10$ cm perpendicular to the beam axis and at $z = 12$ cm and $z = 22$ cm along the beam axis, respectively. In the case of the proton beam setup the hydrophone positions correspond roughly to the $z$-position of the Bragg-peak and a $z$-position half way between the Bragg-peak and the beam entry into the water, respectively. For comparability, the same positions and the same sensors were chosen for the laser experiment.
Figure 1. Measured signal amplitude of the bipolar acoustic signal produced by laser pulses at different temperatures fitted with the model expectation as described in the text. All amplitudes were normalised to 1 at 15.0°C.

Figure 2. Measured signal amplitude of the bipolar acoustic signal produced by proton pulses at different temperatures fitted with the model expectation as described in the text. The non-thermo-acoustic signal at 4.0°C was subtracted at every temperature. The amplitudes were afterwards normalised to 1 at 15.0°C.

The laser beam signal shown in Fig. 1 changes its polarity around 4°C, as expected from the thermo-acoustic model. The model expectation for the signal amplitude, which is proportional to $\alpha/C_p$ and vanishes at 4°C, is fitted to the experimental data. In the fit an overall scaling factor and a constant temperature shift were left free as fit parameters. The fit yielded a zero-crossing of the amplitude at $(3.9 \pm 0.1)^\circ$C, where the error is dominated by the systematic uncertainty in the temperature setting. The zero-
crossing is in good agreement with the expectation of 4.0°C. Analysing the proton data in the same way yielded a shape slightly deviating from the model expectation, and a zero-crossing significantly different from 4.0°C at (4.5 ± 0.1)°C. In view of the results from the laser beam measurements, we subtracted the residual signal at 4.0°C, which has an amplitude of approx. 5% of the 15.0°C signal, from all signals, assuming a non-temperature dependent effect on top of the thermo-acoustic signal. The resulting amplitudes shown in Fig. 2 are well described by the model prediction.

The source of the small non-thermo-acoustic signal which was only seen in the proton experiment could not be unambiguously verified with these experiments. The obvious difference to the laser experiment are the charges involved both from the protons themselves and the ionisation of the water. For clarification further experiments are needed either with ionising neutral particles (e.g. synchrotron radiation) or with charged particles (e.g. protons, α-particles) with more sensors positioned around the Bragg-peak. With such experiments it might be possible to distinguish between the effect of ionisation in the water and of net charge introduced by charged particles.

4. Conclusions

We have demonstrated that the sound generation mechanism of intense pulsed beams is well described by the thermo-acoustic model. In almost all aspects investigated, the signal properties are consistent with the model. Relying on the model allows to calculate the characteristics of sound pulses generated in the interaction of high energy particles in water with the input of the energy deposition of the resulting cascade. A possible application of this technique would be the detection of neutrinos with energies \(\gtrsim 1\text{ EeV}^7\).

References

1. G.A. Askariyan, Atomnaya Energiya 3, 152 (1957).
2. G.A. Askariyan et al., Nucl. Inst. Meth. 164, 267 (1979).
3. L. Sulak et al., Nucl. Inst. Meth. 161, 203 (1979).
4. S.D. Hunter et al., J. Acoust. Soc. Am. 69, 1557 (1981).
5. S.D. Hunter et al., J. Acoust. Soc. Am. 69, 1563 (1981).
6. V.I. Albul et al., Instr. Exp. Tech. 44, 327 (2001).
7. T. Karg et al., 1st International ARENA Workshop, Zeuthen (2005).