Ionoacoustics project context notes

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Document purpose

The aim of this document is to provide context to facilitate making plans for an ionoacoustic experiment/project with Ken Long et al.

The content is:

1. Examples of measurements made in literature – one at high proton energy one at low proton energy - and some comments after considering them.
2. An explanation and plot of stress confinement time which informs our required pulse lengths.
3. An explanation and plot of acoustic frequencies as a function of wavelength to provide insight into the acoustic frequencies expected to be generated by Bragg Peaks of a given size.

Overall, I think the examples of prior work and below considerations suggest we could aim to use clinically realistic energies, and this may point us to using μs scale pulses and low frequency detectors but we need to calculate the exact size of the beam and BP. It could be helpful to simulate the specific experiment to get a sense of what we would/would not be able to detect. I'd particularly like to understand better how much signal we would get from the BP as opposed to from the cylindrical beam prior to the BP. It might also be helpful to have the option to use lower energies to get more easily detectable signals. Detectability of signals from the BP seems much more clearly possible (and relatively easy) at lower energies. However, this would require shorter pulses (<<1 μs) and probably also different detectors (higher frequency).

Acronyms

BP = Bragg peak
PRF = pulse repetition frequency
PZT = lead zirconate titanate (the most common piezoelectric material used in piezoelectric transducers)
SNR = signal-to-noise ratio

Examples of two measurements made in literature

To provide an indication of what is detectable, here are two examples of measurements in literature. The first was done at low energy, the second at higher energy.

Example 1: Low energy in a water phantom[1]

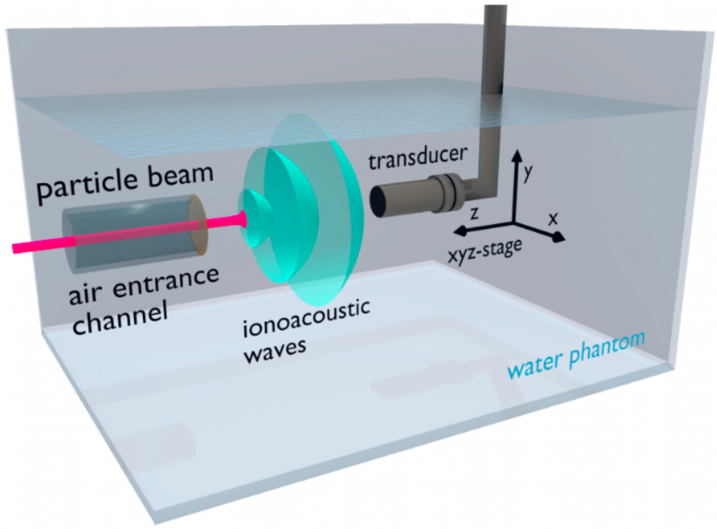

FIG. 1. Setup used for ionoacoustic experiments: Water phantom with air-filled entrance channel, separated by a polyimide entrance foil to water, and ultrasound transducer mounted onto a remote controlled xyz-stage.

Figure. Figure 1 from Assmann et al[1] with the original caption.

Assmann et al[1] detected acoustic signals generated by a proton beam at 20 MeV (Maier-Leibnitz-Laboratory, TU Munich). The system had a chopper/buncher allowing pulse lengths in the range 8 ns - 4.3 μs and PRFs of 1-10 kHz (100-1000 μs gaps). The BP depth was 4 mm and the BP axial extent was 300 μm. Two detectors were used: a 3.5 MHz PZT transducer and a 10 MHz PZT transducer, both of ≈10 mm diameter (≈100 mm^2 area). Using a 500 ns pulse length, the authors quoted a lower limit of detection of about 10^5 protons per pulse using 16 averages. An example of a clear signal, evidently of high SNR, was shown (their figure 2) obtained using 2 x 10^6 protons in a 110 ns pulse. For context, their figure 1 showing their experimental setup is replicated above. Basically, this mm scale experiment needs 10^5-10^6 protons, ≈100 ns pulses and generates MHz frequencies detectable using cm scale standard PZT transducers with only a few averages.

Assmann et al[1] estimated the pressure in the BP as 250 Pa per 10^6 protons. This suggests their minimum detectable 10^5 protons produced 25 Pa in the BP. It is difficult to assess this however, because we would need to estimate how much of this pressure reaches the phantom surface to see if it's consistent with the expected sensitivities for their detector.

The reason for the choice to operate at low energies in this work seems to be that the signals are easier to detect. A statement from the paper's discussion section (pasted below) backs this up.

(SNR) of the ionoacoustic pulse are advantageous. In clinical situations, however, with proton energies above 100 MeV, the SNR will be reduced due to a higher noise level (thermal, scattering), lower signal amplitude because of the less sharp (in time and space) dose deposition, and, not least, the generally higher signal attenuation in tissue. Therefore, improving the SNR is the main challenge for ionoacoustics in clinical applications. Current tendency in therapy accelerator

Figure. Extract from [1] shedding light on their choice to use a low energy setup.

Example 2: High energy in a water phantom[2]

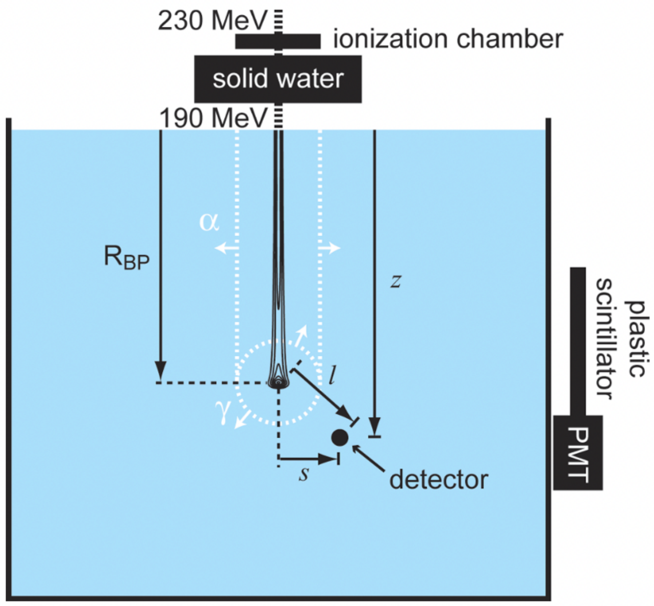

FIG. 1. Illustration of the experimental setup (not too scale and only one detector position is shown). The 230 MeV proton pulse is incident from the top. The hydrophone is placed at a depth z and a lateral distance s from the beam propagation axis. The distance between Bragg peak and detector, l, is given by $l = \sqrt{s^2+(z-R_{\mathrm{BP}})^2}$. The white dashed lines show a cartoon of the protoacoustic waves emitted by the proton heated volume. The α wave is cylindrically emitted by the pre-Bragg peak deposition. The spherical γ wave is emitted by the Bragg peak volume.

Figure. Figure 1 from Jones et al[2] with their original caption.

Jones et al[2] detected acoustic signals generated by a proton beam at 190 MeV (IBA C230 cyclotron, Roberts Proton Therapy Center, U. Penn.) The pulse length was on the order of 10 µs. The PRF was 100 Hz (10 ms gaps). There were some 10^7 protons per pulse. The BP depth was 24 cm. I could not find the axial size of the BP. However, other work reports mm scale BPs for similar energies (using heavy ions)[3]. The signal frequency content peaked near to 10 kHz, suggesting cm scale features (see "Acoustic Frequencies" below). However, it seems the strongest signal came from the wave emitted by the cylindrical proton beam prior to the BP (marked α in the figure above), not the BP (the frequencies are consistent with the cm scale beam width). The authors measured pressures of 5 mPa per 10^7 protons, 5 cm away from the beam. They used about 1000 averages (increasing about SNR 30x). The detector was an omnidirectional Brüel and Kjær 8105 hydrophone, sensitive to <100 kHz (https://www.bksv.com/en/transducers/acoustic/microphones/hydrophones/8105). If the sensitivity of this is comparable to large piezoelectric detectors operated in low MHz frequencies, one might expect a sensitivity limit on the order of 100 mPa (from my own detector meta-analysis), which would seem consistent with the signal being detectable (5 mPa per 10^7 protons x 30 for averaging = 150 mPa, etc.) For context, their figure 1 showing their experimental setup is replicated above. Compared to the low energy study above, 100 times more protons and 100 times more averages were needed to detect signals so detectability appeared to present a greater challenge. Also, lower acoustic frequencies were detected (likely determined by the beam dimensions) and the signal from the BP is unclear. Due to the cm scale beam providing most of the signals, there was a higher threshold (≈10 of µs) for the required pulse length. The reason for using this system seems to be that it is more representative of clinical energies. Although the strongest signal was acknowledged to come from the beam prior to the BP, it was claimed that the spherical wave from the BP was also detected (gamma in the figure). I found it difficult to assess whether this was really true from the data in the paper (the signal traces were unconvincing to my quick looks). However, the paper does conclude they can tell the range of the BP so presumably they must have detected it.

Comments

The two experiments above are basically looking at the same thing (feasibility of ionoacoustic detection). However, due to the different energy levels in use and differences in what was detected, the practicalities of the experiments (phantom size, detector type, beam structure) are completely different. This is partly because the different energies lead to different BP characteristics (depth, width) thus different acoustic characteristics (frequencies, pressures, propagation distances) and requirements (pulse lengths, required number of protons to be detectable). It is also partly due to the fact that the second study focussed on measuring signals from the incident (cm scale width) cylindrical beam as well as the BP.

Given that signals have been detected at clinical energies, it seems that attempting to use clinical energies makes sense for reasons of direct clinical relevance. However, from the second study above I am a bit unsure as to whether the BP signals were really detected or whether they only detected the beam prior to the BP. To guarantee detectability, it could be helpful to have the option of going to lower energies because detectability appears less challenging. However, we might not be able to use the same detection system (frequency response) or source parameters (pulse lengths) for high and low energies. For the higher energy route, we may be OK with longer pulses (>1 μs maybe even >10 μs; to be determined by the exact size of the BP and beam) and low frequency detectors (perhaps 100 kHz and lower; determined likewise). The below sections provide more detail on these requirements. I don’t know enough about the requirements for radiobiology experiments or what Lhara will produce.

Stress confinement

Stress confinement determines our required maximum pulse length. The plot below shows the stress confinement time as a function of the source size.

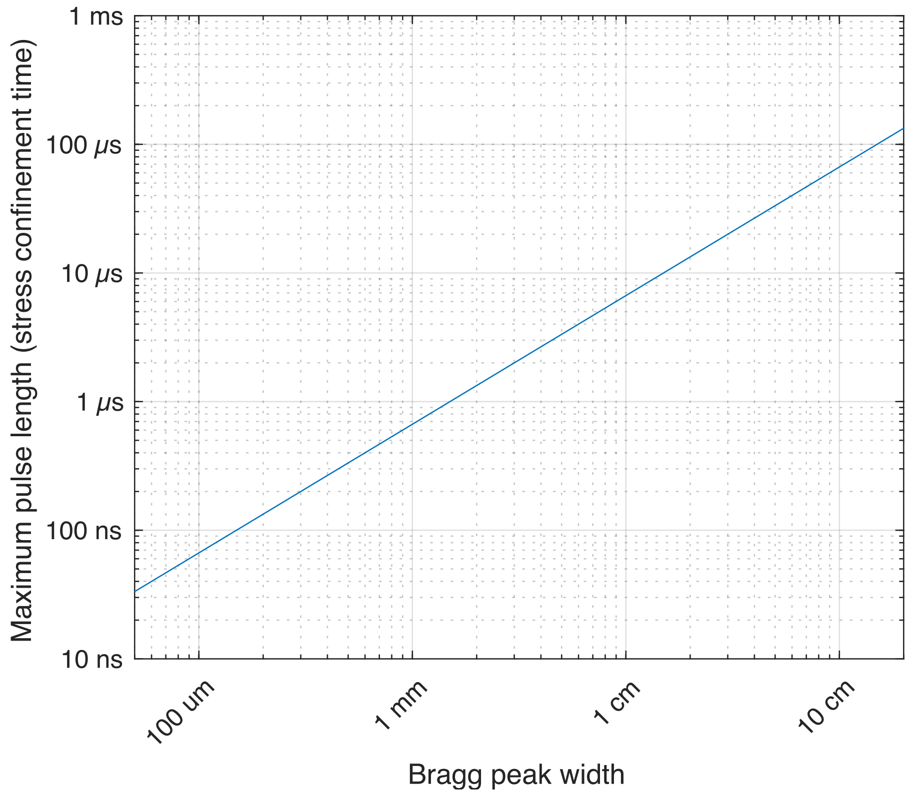

Figure. Stress confinement time (maximum pulse length for efficient acoustic generation) as a function of the acoustic source size (≈BP dimensions).

Stress confinement describes the situation in which energy is deposited effectively “instantaneously” from an acoustic perspective (within the time it takes a sound wave to exit the acoustic source). This provides an upper limit on the pulse length for efficient acoustic generation in ionoacoustics that depends on the source size.

The plot shows that for a 100 μm scale BP, we want a sub 100 ns pulse length, whereas, for a multi cm BP, we can go into the 10s of μs.

Acoustic frequencies

If the spatial extent of the source limits the generated acoustic frequency content (valid for a short pulse), we expect waves on the same spatial scale as our sources. In other words, the strongest wavelengths will be comparable to the source (BP) size. The plot below shows the frequency as a function of wavelength in water (assuming a sound speed of 1500 m/s).

100s of µm scale sources will generate MHz frequencies (as in Assmann et al[1]), while multi cm scale BPs will generate frequencies in the 10s of kHz (as in Jones et al[2]).

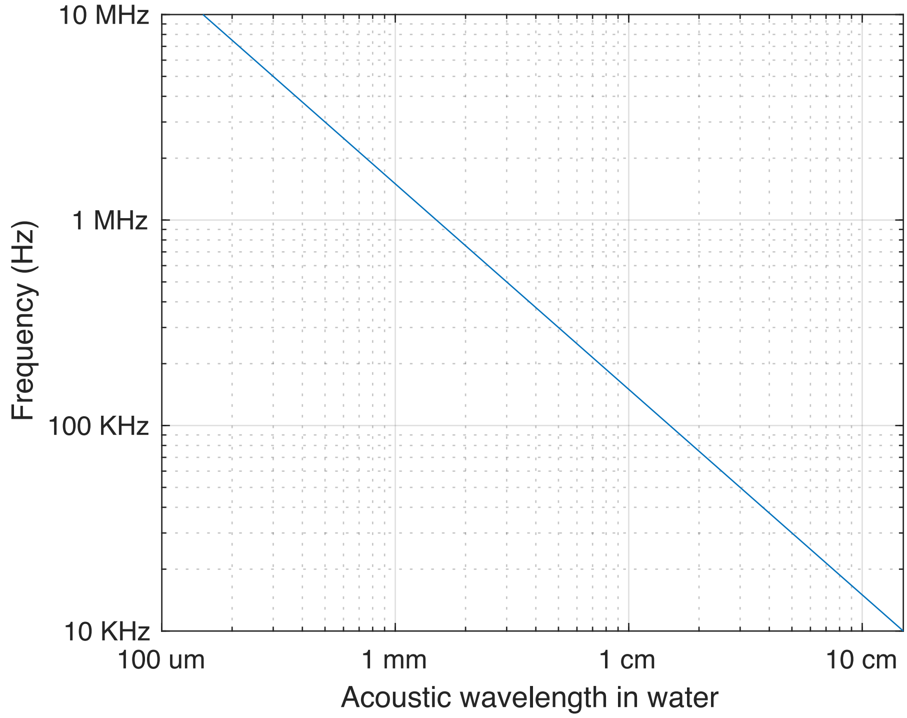

Figure. Frequencies of acoustic waves of a given wavelength in water.

References

1. Assmann, W. *et al.* Ionoacoustic characterization of the proton Bragg peak with submillimeter accuracy. *Med. Phys.* **42**, 567–574 (2015).
2. Jones, K. C., Vander Stappen, F., Sehgal, C. M. & Avery, S. Acoustic time-of-flight for proton range verification in water. *Med. Phys.* **43**, 5213–5224 (2016).
3. Lehrack, S. *et al.* Ionoacoustic detection of swift heavy ions. *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.* **950**, 162935 (2020).