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First experimental demonstration of accurate Bragg peak localization with ionoacoustic tandem phase detection (iTPD)

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Purpose: Ionoacoustics induced by thermal expansion from stopping protons is used to localize its Bragg peak. A challenge of ionoacoustic is the poor signal-to-noise ratio at clinical relevant doses. To overcome time-domain limitations, we propose ionoacoustic tandem phase detection (iTPD), a new frequency-based measurement technique based on lock-in amplifiers.

Methods: A lock-in amplifier allows to detect the ionoacoustic signal of known frequency buried in noise. Its phase shift to a reference signal is analyzed to obtain the time of flight (ToF) and thus the distance between Bragg peak and the ultrasound detector. Experimental ionoacoustic measurements with 3.5 MHz PZT transducers and lock-in amplifiers were performed in water using pulsed 20 MeV proton bunch trains at the Maier-Leibnitz Tandem accelerator in Garching. We aimed to detect a 2.5 MHz ionoacoustic signal that repeats itself every 10 kHz and derived the phase shift between the arrival of protons and ToF of the acoustic wave. To fully exploit the precision and the sensitivity of the lock-in technique, we used two lock-in devices in master-slave mode, each performing a tandem demodulation to obtain the relative phase between the two signals.

Results: To avoid ambiguities in the phase readout, the ToF to be measured needs to fit into the period of the second demodulation frequency which was in our configuration 10 kHz (100 µs). We measured a ToF of 21.121 µs and reached thereby a Bragg peak location accuracy within 80 ±50 µm in the idealized homogenous experimental setup. However, reflections of the ionoacoustic signal within the water phantom compromised the phase readout as they entail the same 2.5 MHz frequency but a different phase.
Conclusion: Our first proof-of-concept measurements using iTPD demonstrated a Bragg peak localization accuracy that motivates further research in this direction towards clinical application.
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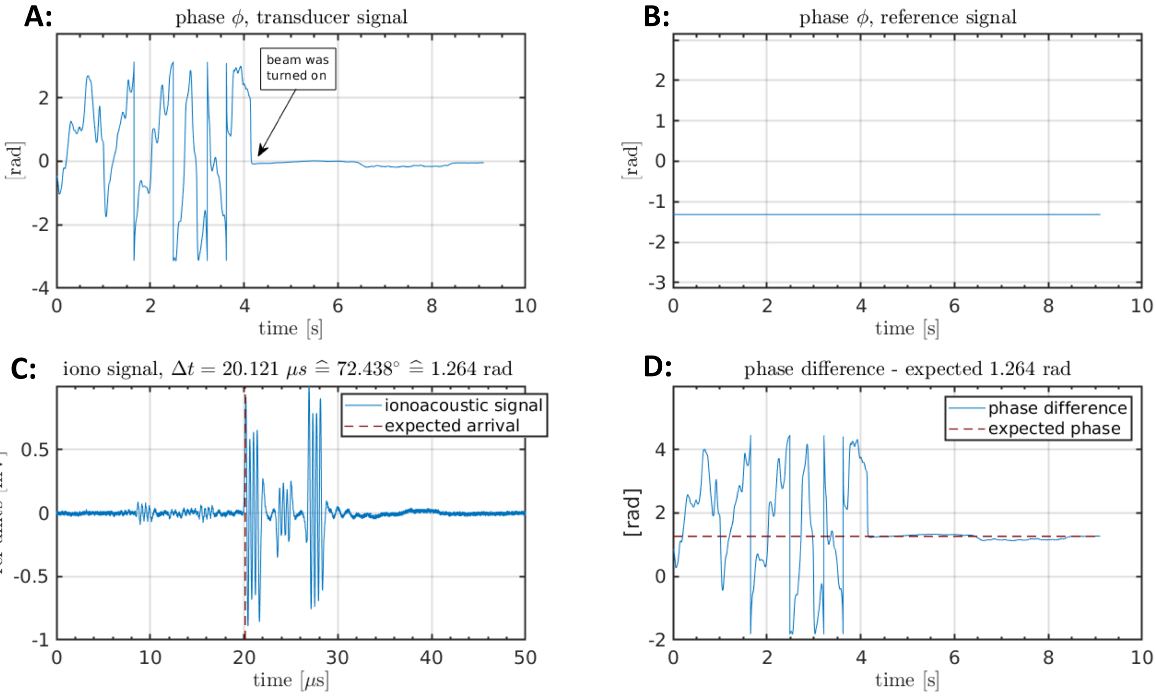

Figure A depicts the phase of the lock-amplifier from the ultrasound transducer measuring the ionoacoustic signal. It can be seen, that after switching on the beam around 4 seconds, the phase stabilizes.
Figure B plot denotes the reference phase which is stable throughout the whole measurement
Figure C plot depicts the measured ionoacoustic signal from a proton pulse excitation of 4 subsequent 200ns proton pulses
Figure D plot highlights the phase difference measurement of both lock-in amplifiers. The red dashed line shows the expected phase difference of 1.264 rad, which is based on a time based analysis using cross correlation.