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Accurate simulation and validation of the detector response for improved Bragg peak localization via ionoacoustics

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Purpose: Accurate in-vivo range monitoring based on the ionoacoustic effect requires knowledge of the detector response to recover the original acoustic emission from the Bragg peak.

Methods: We investigated the influence of the detector response (electrical and spatial impulse responses, EIR and SIR respectively) on the accuracy of ionoacoustic range verification. We performed ionoacoustic measurements in water for pulsed 20 MeV proton beams at the Maier-Leibnitz Tandem accelerator in Garching. The measurements were repeated for several detectors of different technologies (PZT and CMUT), shapes and position, herewith actively changing the detector's EIR and SIR. The experimental results were compared to our in-house simulation framework, based on FLUKA to calculate the initial energy deposition and the k-Wave Matlab toolbox for wave propagation, considering both, idealized point detectors and realistic detectors. For a given configuration, we obtained a triplet of signals (experiment and simulations for ideal sensors and realistic detectors) which allowed to obtain the spatially dependent total impulse response (TIR) of a specific detector.

Results: Different spatial positions change the relative orientation and distance of the detector to the Bragg peak, which ultimately yielded distinct ionoacoustic signals. We derived the spatially independent EIR by deconvolving the simulated SIR from measurements to obtain the detector TIR for a given configuration. Good agreement was achieved between the experimental and simulated data by applying the same EIR and updating the simulated SIR with the detector position, showing the correct TIR modelling. Knowing the EIR from a calibration measurement and the SIR from simulation allows a deconvolution of the TIR to recover the original ionoacoustic signal which gives rise to the underlying pencil beam dose deposition.

Conclusion: Deconvolution of the detector impulse response allows accurate estimation of the ionoacoustic signals, improving the accuracy of post-processing operations such as time-of-flight calculations, triangulation or dose reconstruction algorithms.

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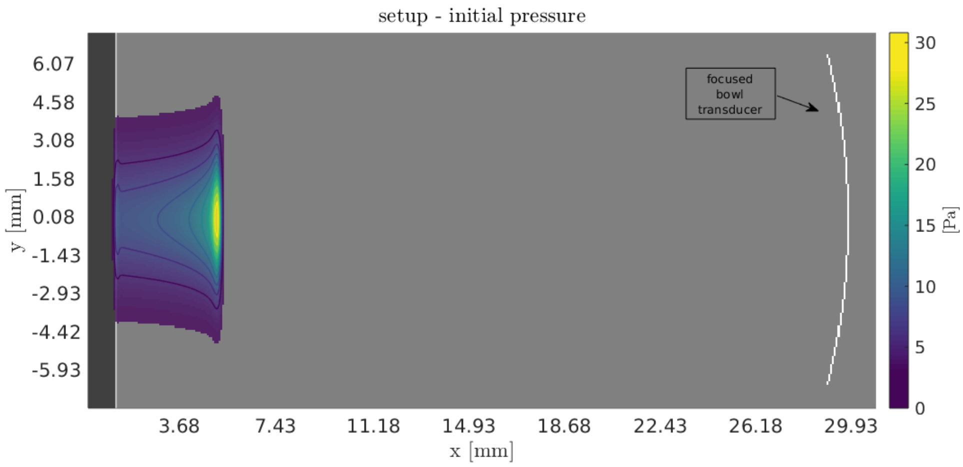
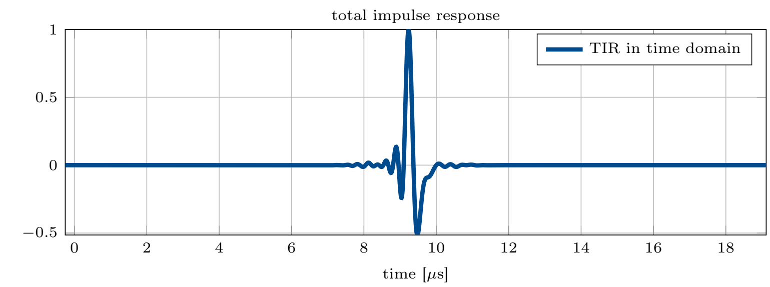


Figure 1: 2D Transversal image of the 3D simulation framework showing on the left the induced pressure distribution on the basis of 20 MeV protons entering a water phantom. A pseudo-spectral method is then used for propagating acoustic waves through the homogenous medium. A focused ultrasound transducer in the from of a bowl is modelled on the right side to capture the ionoacoustic pressure wave.



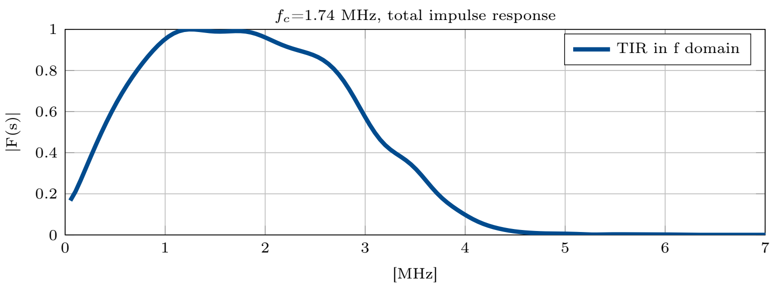


Figure 2 and 3 show the derived total impulse response in time and frequency domain for the given transducer configuration and pressure distribution shown in Figure 1. The TIR fully describes the detector response and allows in a subsequent step a deconvolution from a measured signal to recover the original ionoacoustic wave from.