Proton Sound Detector for Beam Range Measurement in FLASH Hadron Therapy

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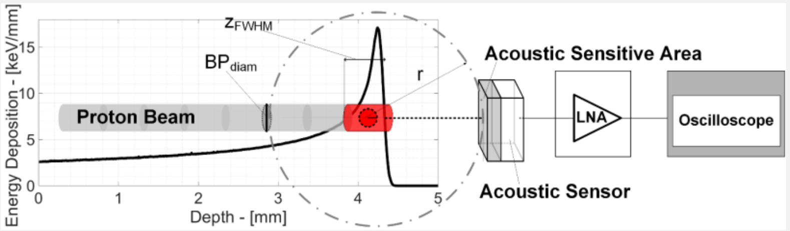
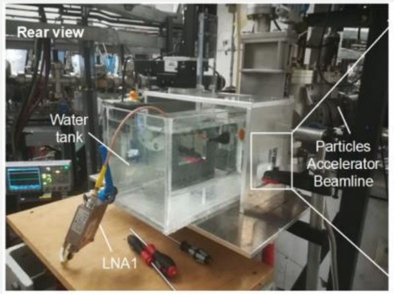
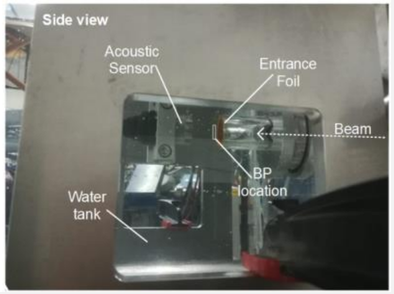
ABSTRACT - Proton Sound Detectors (ProSDs) sense (at low latency, <1 ms) the thermoacoustic signal generated by the fast energy deposition at the Bragg peak of a proton beam penetrating an energy absorber.
ProSDs are especially promising for experimental monitoring of high pulse rate (FLASH) hadron therapy treatments working in-sync with the beam.
This paper presents a mixed signal detector, capable of sensing and processing high rate (1k beam shots/sec) ionacoustic signals with low latency (<1 ms). The system was validated by measuring the dose deposition of a 20 MeV proton beam in water, achieving 3.43% precision (±2.75 GyRMS) after 50 ms acquisition (77.56 Gy total dose deposition).



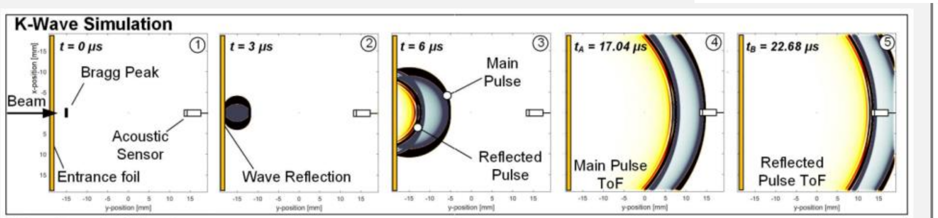


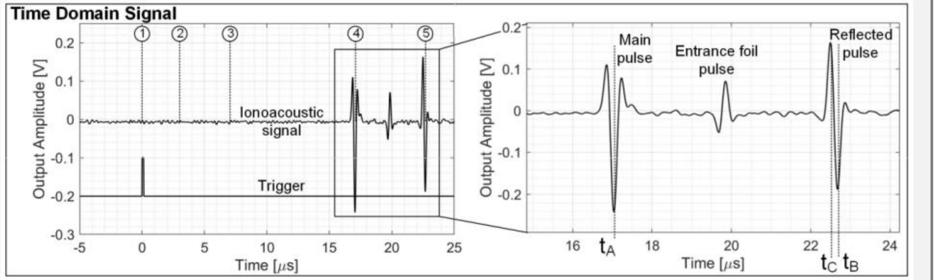


Ionoacoustic Experimental Setup

The Detector is composed by a piezoelectric acoustic sensor and low-noise analog front-end (60-80 dB low-noise amplifier, 4.5 MHz -3dB 3rd order low-pass filter and 10-bits 80 MS/sec A/D converter) and a DSP stage on a Xilinx Spartan 6 FPGA. It performs event-driven data acquisition (triggered by the beam shot) and a custom c++ GUI is used for signal processing and visualization. The Detector and the embedded DSP have been validated with a sub-clinical 20 MeV proton beam with ~106 protons/shot and 1000 shots/sec rate. The Detector sensitivity is 173 mV/Gy (w.r.t. Bragg peak).

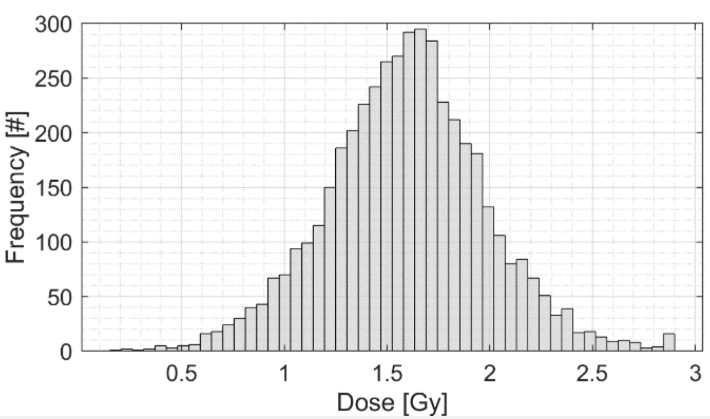
Ionoacoustic Signal



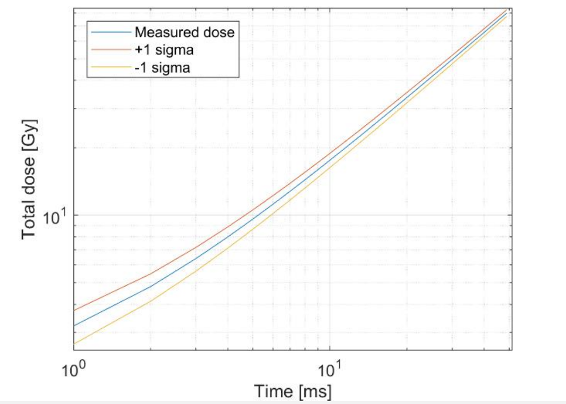


The ionoacoustic signal from 20 MeV protons has 2 MHz frequency and is characterize by a main pulse and a reflected pulse. The amplitude of the main pulse is proportional to the dose deposition at the Bragg Peak and can be used to measure the beam current.

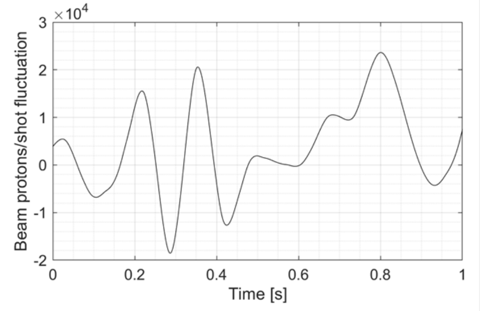
Experimental Results

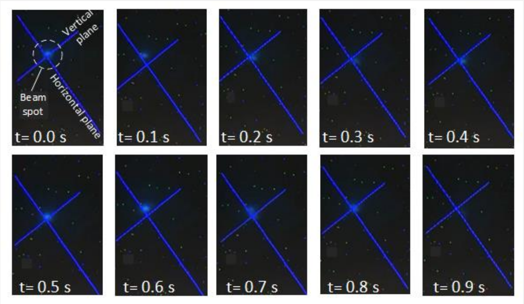


Measured acoustic sensor output signal is 276 mV0-peak corresponding to 1.59 Gy dose at the Bragg peak, consistent with 1.6 Gy dose/shot calculated from the beam current and Bragg peak physical size. By repeating the measurement 8000 times, the measured dose precision has been found equal to 388 mGyRMS (24.4%) due to random noise fluctuations.



By characterizing the noise performances (62.9 mVRMS, equivalent to 363 mGyRMS, from sensor and electronics themal/flicker noise) it is possible to measure the dose deposition variations due to random beam fluctuations over time, equal to 138 mGyRMS or 8.6% of proton number/shot. The cumulative dose after 50 shots (50 ms acquisition) is 77.56 Gy ± 2.75 GyRMS (3.43%).





Finally, the ionoacoustic signal amplitude has been recorded for 1 s. By low-pass filtering, a slow ~7 Hz fluctuation in the ionoacoustic signal amplitude becomes observable. Such slow fluctuation is compatible with the beam fluctuation around the horizontal beam axis visible in the CCD beam spot monitoring system.

Conclusions - Compared to nuclear imaging techniques, Proton Sound Detectors promise sub-mm and sub-ms monitoring of the Bragg peak location, dose deposition and beam characteristics. The low-latency, high precision and low instrument complexity (and cost) make this technique appealing for experimental verification/monitoring of the proton beam range for both medical (hadron therapy) and physics research.