Proton Sound Detector for Beam Range Measurement in FLASH Hadron Therapy

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 penettating 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).

SUMMARY

Background and aims

Proton Sound Detectors (ProSDs) sense the proton-induced thermo-acoustic pulse generated by particle beams penetrating a water energy absorber. This signal is directly proportional to the deposited dose.

Compared to nuclear imaging techniques, ProSDs have < 1 ms latency and sub-mm precision, making this technique particularly suitable in real-time monitoring of high dose depositions, as in the case of FLASH hadron therapy.

However, to quickly acquire and process this information, advanced and specific digital signal processing (DSP) stages are required.

For this reason, this paper presents a digital system on FPGA as back end element of the Detector, operating in sync with 1k shots/sec beam and finally providing digital domain proton induced acoustic tracks within 1 ms latency.

Methods

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 ~10^6 protons/shot and 1000 shots/sec rate. The Detector sensitivity is 173 mV/Gy (w.r.t. Bragg peak).

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 mGy_{RMS} (24.4%) due to random noise fluctuations. By characterizing the noise performances (62.9 mV_{RMS}, equivalent to 363 mGy_{RMS}, 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 mGy_{RMS} or 8.6% of proton number/shot. The cumulative dose after 50 shots (50 ms acquisition) is 77.56 Gy ± 2.75 Gy_{RMS} (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.

Acknowledgments

This work is supported by the Proton Sound Detector project funded by the Italian Institute for Nuclear Physics (INFN)

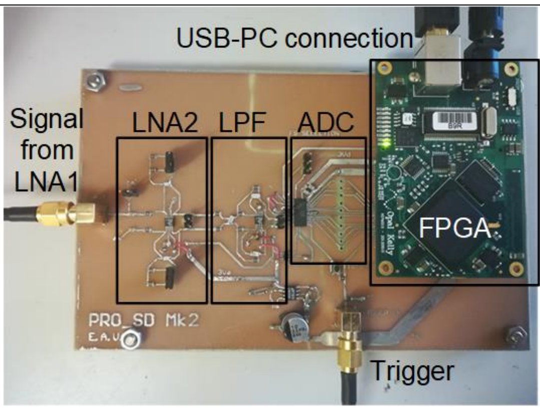

Figure 1 – Detector electronics board

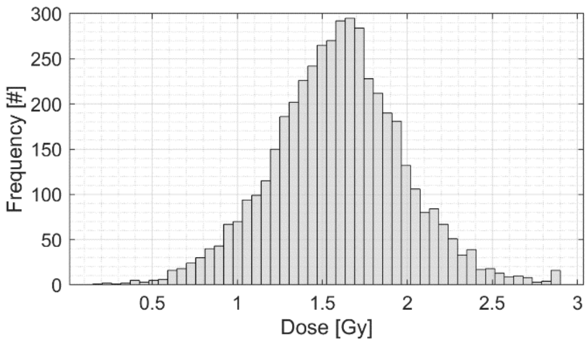

Figure 2 – Histogram of measured dose deposition at the BP

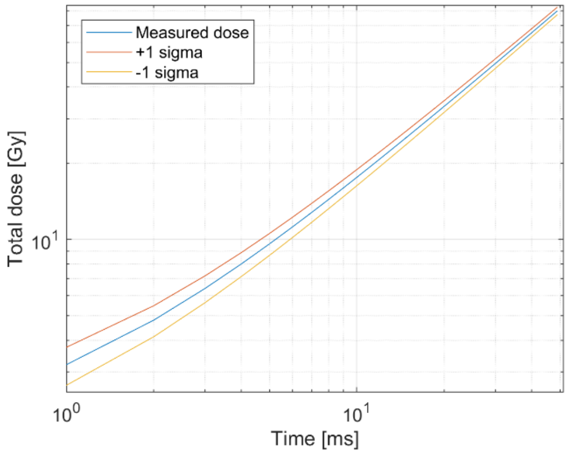

Figure 3 – Measured cumulative dose vs. time with +/- 1-sigma precision

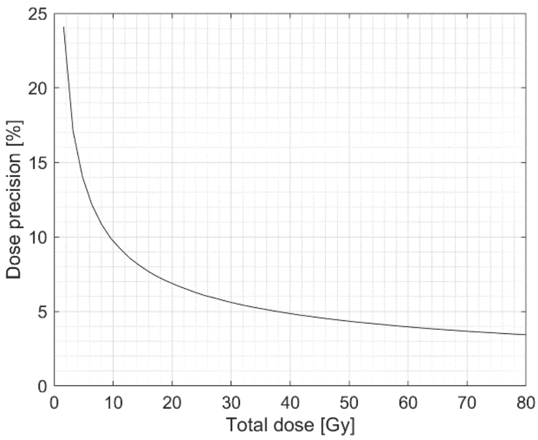

Figure 4 – Relative precision w.r.t. total dose vs. total delivered dose

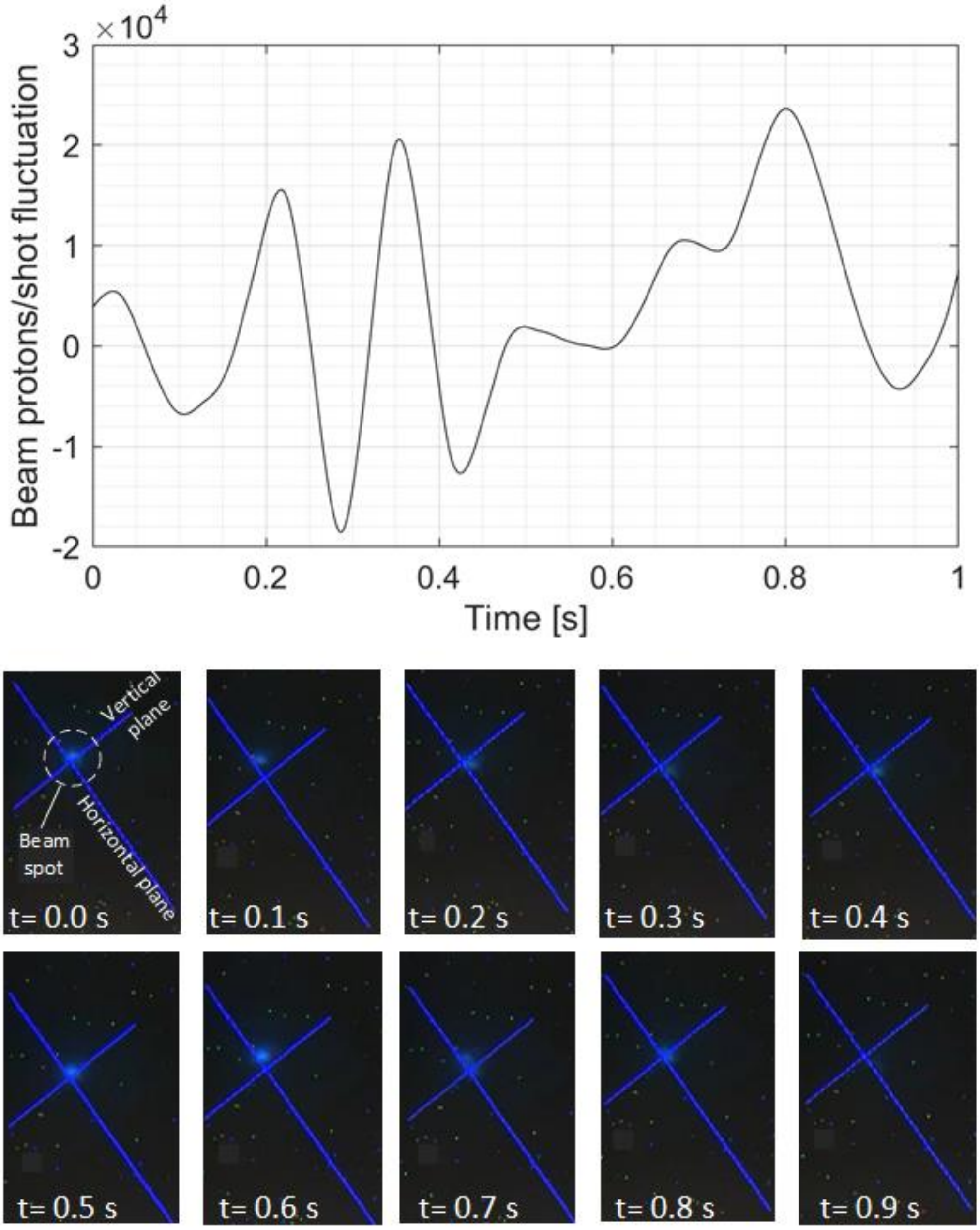

Figure 5 – Slow beam oscillations around the horizontal axis are observable by measuring the ionoacoustic signal amplitude over time