EPJ Web of Conferences **216**, 04003 (2019) https://doi.org/10.1051/epjconf/201921604003
ARENA 2018

Analog and Digital Signal Processing for Pressure Source Imaging at 190 MeV Proton Beam

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Abstract. Oncological hadron therapy utilizes a beam of charged particles to destroy the tumor cells, exploiting the particular deposition curve that allow minimum damage to the surrounding healty tissues compared to traditional radiotherapy. Sulak and Hayakawa's works have shown the applicability of this technique in clinical scenarios, but the lack of dedicated electronics for this type of experiments affects the spatial resolution that can be obtained with this technique [1]. This work presents an integrated analog front-end dedicated to ionoacoustic experiments that allows to estimate the position of the Bragg Peak with an average deviation of 1% with respect to the real position.

1 Introduction

Hadron therapy is an extremely interesting option for cancer treatment, comparing with photon-based radio-therapy. The ion beam deposits very low energy at the interface, practically no dose after the tumor and releases a specific energy peak inside the tissues, called Bragg Peak (BP). Techniques such as Positron Emission Tomography and Prompt Gamma Ray Imaging are currently used to identify the irradiated area, but they are difficult to implement in real-time during the treatment. Ionoacoustic range verification has been proposed by Sulak in 1979 [1], and exploits the acoustic wave generated by the energy deposition in tissues to estimate the energy deposition site. This technique is very promising since it can be used in real-time during the treatment, and promises sub-millimeter accuracy. Both experimental [2] and modeling [3] studies on ionoacoustic setups give scarce attention to the sensing part that however strongly affects the detection accuracy, like in [2] where commercial sensors and electronics read-out (i.e. not optimized for iono-acoustic detection) induces a very high BP detection error (>2 mm) comparing with simulations. Hence the state-of-the-art heavily lacks advanced and/or dedicated integrated circuits (IC) solutions, for accurate and low-noise acoustic signal detection and processing in both analog and digital domain. For these reasons, this work presents an integrated Analog Front-End (AFE) dedicated to ionoacoustic experiments that allow to sense the ionoacoustic pressure signal at low-noise levels and to calculate the BP position with 1% accuracy w.r.t. its real position.

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[1] Acknowledgments: This activity has been supported by the Proton Sound Detector (ProSD) project funded by the INFN (Italian National Institute for Nuclear Physics)

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2 Methods

A cross-domain model has been developed to derive the characteristics of the input signal to the AFE, as shown in [4] for a sub-clinical 5MeV beam. It utilizes Geant4 to obtain the energy deposition of a 190MeV proton beam, K-Wave for the propagation of the pressure wave and a Matlab model of the transducer to obtain amplitude and noise characteristics of the sensed signal. This allowed to design, dimension and simulate at transistor level an IC dedicated for ionoacustic experiments. A typical ionoacoustic setup is shown in Fig. 1 Left, where the pressure signal generated by the proton beam is sensed by a hydrophone, amplified by a Low-Noise Amplifier (LNA) and acquired by an oscilloscope. A post-processing stage allow to calculate the Time of Flight (ToF) and BP position. The hereby presented AFE aims to substitute the LNA, Oscilloscope and Post-Processing stages with a single IC. This leads to lower cost and size of the setup, lower power consumption and increased portability, and allows detection in real-time of the BP location by minimizing the need of post-processing.

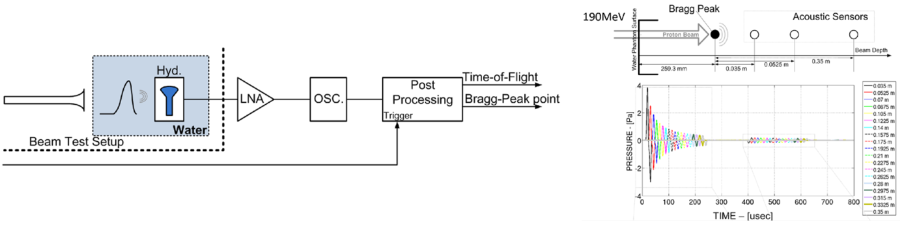

Figure 1. Left: Typical ionoacoustic setup. **Right:** Acoustic wave simulated by cross-domain model.

2.1 Cross-Domain Model

The energy deposition of a 190MeV proton beam incident on a water phantom was modeled using Geant4. The diameter of the beam is 50mm^2, which leads to an energy of 1.5mJ deposited in the BP. The BP depth is 259.3mm, with 17mm FWHM. The energy deposition takes place under stress and thermal confinement conditions, and the pressure increase in the BP area is equal to 170Pa. An array of acoustic sensors were placed on the beam axis at different distances from the BP. The sensed acoustic waves are represented in Fig. 1 Right. Pressure levels varies from 4Pa at 3.5cm from the BP to 350mPa at 35cm from the BP. Signal bandwidth is 42kHz. This pressure is sensed with a commercial hydrophone with 56V/KPa pass-band sensitivity, 170Hz-170kHz bandwidth and 3.5μV$_{\mathrm{RMS}}$ output noise power. The corresponding Signal-to-Noise Ratio therefore ranges from38dB for the nearest transducer to 15dB for the farthest.

2.2 Analog Acoustic Front-End

The hereby proposed AFE is composed by three stages (See Fig.2 Left): a Low-Noise Amplifier (LNA), a 2$^{\mathrm{nd}}$ order Low-Pass filter and a Comparator. The LNA is based on the super-source-follower topology and provides 30dB of amplification and single-ended-to-differential conversion with high input impedance and low-noise characteristics. The Active-Gm-RC Low-Pass filter is an advanced second-order filter that provides 20dB of amplification as well as out-of-band noise rejection [5]. The comparator outputs a single bit signal that is at '1' logic level when an acoustic wave is sensed. This is a efficient and effective way to encode in a single bit signal all the relevant information for BP position estimation. Fig. 2 Right shows the AFE Frequency response in term of magnitude, phase and group delay. Group delay is particularly important in this scenario because it causes a systematic shift in time measurements which has to be taken into account while calculating the ToF. For a signal at 42kHz, the time variation induced by group delay is of 2μs.

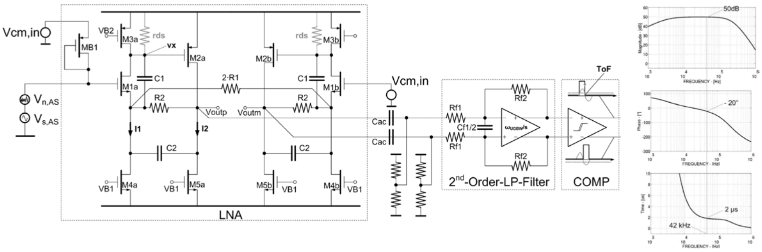

Figure 2. Left: AFE Schematic. **Right:** AFE magnitude, phase and group delay frequency responses.

3 Results

Fig. 3 Left shows the LNA, filter and comparator outputs for transducers at 3.5cm and 35cm from the BP. The signal from the farthest transducer exhibits a lower SNR due to the weaker pressure signal. By running multiple nominal and transient-noise simulations, a histogram of the ToF and BP distance error was extracted for each transducer (Fig. 3 Right). In both cases the average error is around 1%.

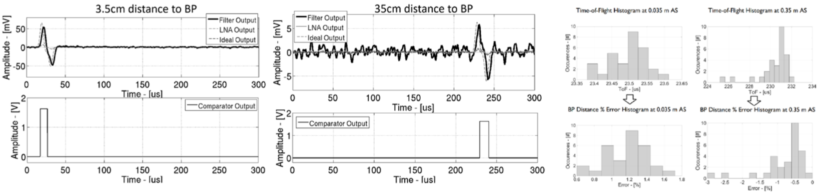

Figure 3. Left: AFE signals vs time. **Right:** Time of Flight and distance error histograms.

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