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Analog and Digital Signal Processing for Pressure Source Imaging induced by a 20 MeV Proton Beam

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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. This peak is called Bragg Peak and its shaping is also very sharp, increasing this way the dose deposited in depth. Thus, the efficacy of this technique is strongly related to the capability to detect the Bragg Peak during the on-going clinical treatment.
The first experimental results concerning the proton-induced thermo-acoustic effect for BP range verification were presented in 1979 by Sulak et al. using a 200 MeV pulsed beam at 100 TeV deposited energy [1]. Then this technique was clinically tested by Hayakawa et al. [2] measuring a clear acoustic signal generated in a patient irradiated by a pulsed proton beam. The sensors superficially placed over the skin of the patient detected a clear acoustic signal. Unfortunately, sensors and electronics measurements were affected by a significant noise power, leading to a relatively low accuracy (3mm, however comparable with PET/gamma). Both experimental [2] and modeling [3] studies on the iono-acoustic setup 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.
Methods. This paper follows this important research trend presenting a complete proton-to-voltage analysis, that starting from beam physical characteristics (energy, pulse shaping, etc) calculates the pressure signal at the BP and emulates the sound waves propagation in water. The proton beam has been simulated using Geant4 to estimate the spatial distribution of the energy deposition in a case-of-study of a 20 MeV energy with a total deposited dose of 2 Gy and beam pulse of 50ns. Pressure waves simulations are used as input signal of a dedicated analog front-end specifically optimized for this application. The analog signal sensed by the acoustic sensor array is conditioned by a Low-Noise-Amplifier (LNA), a 2nd-order 5 MHz -3dB-Bandwidth Sallen-Key band-pass filter feeding a 10b 50 MSample/rate A-to-D converter for digitalization. Thanks to the high-resolution digital data, the pressure signal provides very accurate ToF measure and, more importantly, a beam-forming algorithm can be adopted to estimate the proton source and perform a 3-D acoustic imaging of the pressure source.
Results. The hereby described model provides the tools to accurately simulate both bandwidth and power of the acoustic signal generated by the proton beams. The acquisition and conditioning electronics was therefore developed and optimized for iono-acoustic experiments. Finally experimental results providing a 3-D imaging of the acoustic source referred to this specific case of 20 MeV protons will be presented.
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