Range Verification of Pulsed Proton Beams from an FFA Via Ionoacoustic Measurement

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INTRODUCTION

In proton therapy, range uncertainty is one of the biggest issues that can offset the physical dose advantage gained by the Bragg peak (BP). There are multiple sources of range uncertainty, including conversion from CT number to stopping power ratio, anatomical changes of the patient, organ motion, etc. and much effort has been made to reduce the uncertainty [1].

On-line range verification using ionoacoustics is one of the promising approaches to reduce the uncertainty. It uses the phenomena that medium, when hit by pulsed proton beams, undergoes slight temperature rise, which is followed by the generation of the pressure wave. By measuring and analyzing the arrival time of the wave, it is expected to identify the beam range with submillimeter accuracy [2].

Given the fact that the shorter pulse width is preferable to create a detectable pressure wave, Fixed-Field alternating gradient Accelerator (FFA), with its fast extraction mode, may be expected as one of the optimum accelerators that can generate the detectable signals for range verification [3].

This study used the 100 MeV short-pulsed proton beam from FFA at Kyoto Univ. and estimated the beam range using two types of relative time-of-flight (TOF) metrics. As described later, compared to the conventional TOF metric, which measures the time between beam injection and acoustic wave arrival time, this approach is expected to give the range value that is insensitive to the detector poisoning errors.

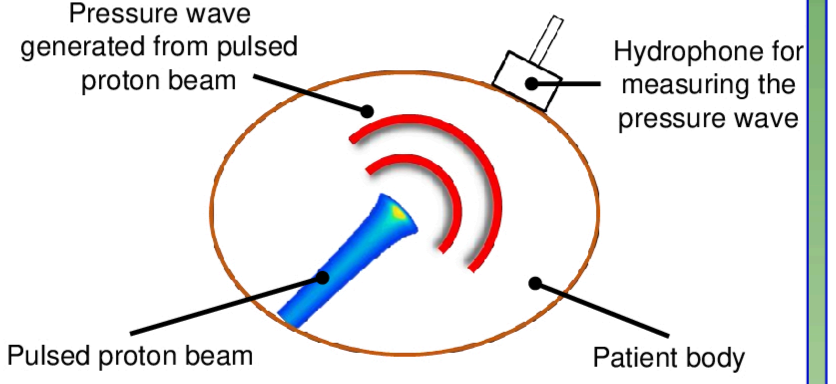

Figure 1. Schematic figure of range verification using ionoacoustics

AIM

To assess the accuracy of proton range using the relative TOF metric of acoustic waves by comparison with the range estimated by the depth dose measurement with an ionization chamber.

METHOD

Accelerator performance and beam property

The accelerator performance and beam property of FFA was summarized in Table 1. Depth dose measurement was performed twice using BP chamber (PTW34070, Freiburg, Germany). Beam property of FFA is equivalent to those of scanning pencil beams used in clinical applications, except that the pulse width was several orders of magnitude smaller than that used in clinical machines.

Table 1. Performance of FFA and beam property

Beam energy	100 MeV
Beam range	77.6 ± 0.5 mm
Beam pulse width(1σ)	21 ns
Number of particles/pulse	(1.17 ± 0.06) × 10^8 /pulse
Beam size (1σ)	4.8 mm(vertical), 5.6 mm(horizontal)

Experimental setup

Measurement of the ionoacoustic wave generated from proton beams was carried out using the experimental setup shown in Figs. 2 and 3. A hydrophone was placed at 20 mm downstream of the BP in water phantom. A plastic scintillator measures the secondary particles generated by nuclei activated by the proton beam; its signal was converted to particle per pulse by the independent measurement using the Faraday cup. Signals were amplified with a 46 dB amplifier and stored with a digital oscilloscope at 50 MS/s sampling rate after averaging of 50 events. A low-pass filter with the cutoff frequency of 1 MHz was applied for filtering out the RF noise occurred at 8 MHz. To shift the Bragg peak, acrylic plates (4-20 mm) were set in front of the water phantom.

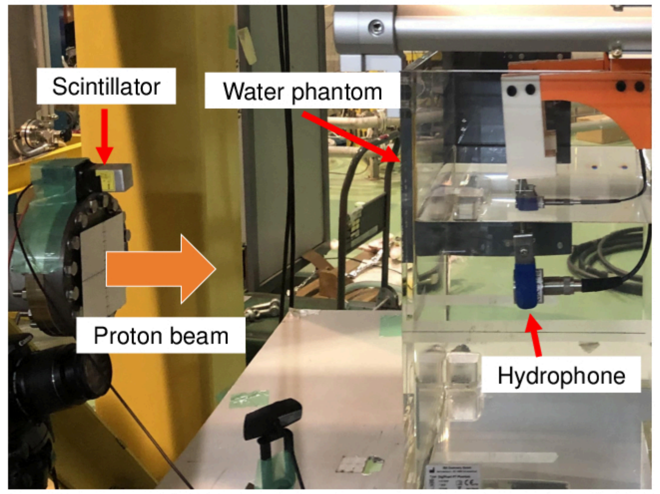

Figure 2. Photo of the experimental setup.

Simulation

With the wave transport simulation code k-Wave [4], we estimated the range accuracy expected to be achieved by relative TOF metrics. 3D dose distribution calculated by using Geant4 Monte Carlo code (ver.9.3) [5] was used as the input of the wave simulation. Hydrophone was modelled as a point sensor with a flat frequency response.

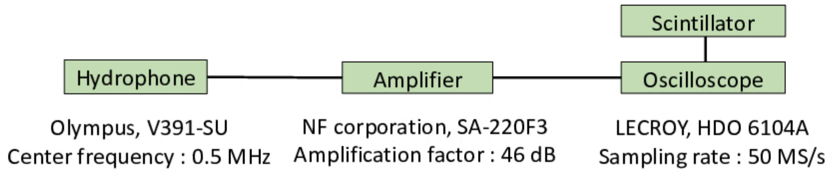

Figure 3. Data acquisition flow

RESULTS

Fig.4 shows the example of the observed acoustic waveform, averaged over 50 measurements.
Four characteristic signals were measured:
(A) Direct wave from the Bragg peak
(B) Resonance wave arising from the energy loss at the acrylic wall
(C) Wave reflected at the water-acrylic-wall boundary
(D) Wave reflected at the acrylic-wall-air boundary.

To avoid the influence of hydrophone positioning error as well as the frequency dependent delay inherent to hydrophone, following two types of relative TOF metrics were examined:
(1) TOF between the negative peak of (A) and (C)
(2) TOF between the negative peak of (A) and positive peak of (D)

As shown in the upper raw of Table 2, according to the simulation results, these two metrics were expected to predict the Bragg peak position within submillimeter accuracy.

The range values derived from the measured relative TOF metrics were summarized in the lower raw of Table 2. As shown, these values agreed well with the BP position estimated from the depth dose measurement to better than 1 mm.

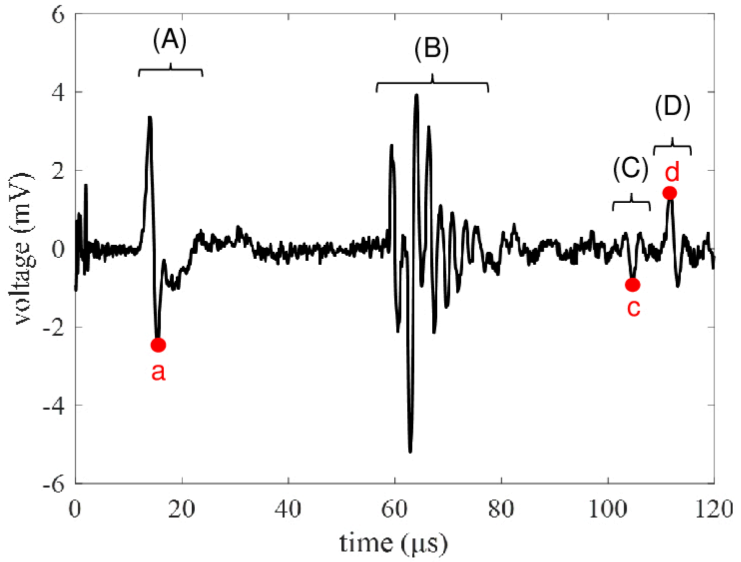

Figure 4. Example of the observed acoustic waveform

Table 2. Comparison of the BP positions obtained from depth dose profile and relative TOF of acoustic wave peaks

	Peak of depth dose profile	Acoustic waveform ※)	
		C - A	D - A
Simulation	78.6 mm	78.22 mm	78.21 mm
Experiments	77.6 ± 0.5 mm	78.16 ± 0.01 mm	78.15 ± 0.01 mm

※) Standard error was derived from 100 independent measurements (each measurement consists of 50 events).

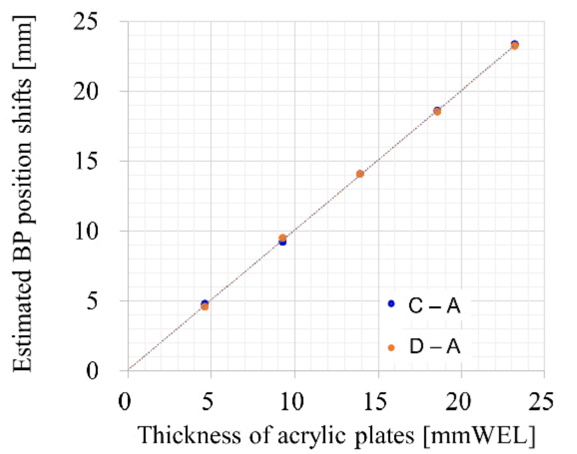

Figure 5. BP position shifts estimated by two relative TOF metrics vs. thickness of acrylic plates

Fig.5 shows the linear relationship of the thickness of the acrylic plates and the shift of BP positions estimated from the relative TOF metrics. Both data suggest that by using the ionoacoustic technique, BP shift can be estimated with submillimeter accuracy.

Further work is underway to improve the signal to noise ratio by employing the hydrophone which has larger frequency response at around 100 kHz, where the main spectral component of the acoustic waves are centered.

CONCLUSIONS

The range value determined by relative TOF metrics through ionoacoustic measurement agreed well with the value estimated from depth dose measurement to better than 1 mm. However, to apply this technique in a clinical setting, the SNR needs to be improved.

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