Ultrasonic Measurement of Flash Dose Profiles for 13 Mev Electrons In Water

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2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

ABSTRACT

Purpose: To use ultrasonic methods to measure FLASH-beam dose distributions within irradiated water, thereby to validate ultrasonic phase-shift methods for FLASH dosimetry and, ultimately, to differentiate regions where FLASH thresholds are exceeded.

Methods: A 10-L rectangular water tank (15 cm x 15 cm x 45 cm) was irradiated with a narrow beam of 13 MeV electron pulses from a medical linac (6 μs duration, rep rate 120 Hz, ~1-10 Gy/pulse, beam diameter ~0.5 cm). The tank was positioned 33 cm downstream from the linac vacuum window and oriented so that the electron-beam axis coincided with its long axis. Radiation-induced temperature rise was determined at a reference depth of 2.5 cm and at variable depths between 1.9 cm and 7.9 cm by measuring phase-shifts in narrow (~0.5 cm) ultrasonic probe beams oriented along independent transverse cords through the tank. A relative depth-dose profile was obtained from the ratio of phase shift at each depth to that at reference depth and compared with the results of a Monte Carlo simulation.

Results: The relative depth-dose profile obtained by ultrasonic methods shows good agreement with the results of Monte Carlo convolved with a blurring function representing the finite width of the ultrasonic probe beams. Experimental noise in this preliminary data set is elevated by ~100x due to pick up from vibrating machinery and stepper motor scanning system affecting one of the two ultrasonic sensors, for which isolation measures are being developed.

Conclusion: This work demonstrates proof-of-concept for use of ultrasound for calorimetric measurements of dose (and dose-rate distributions) in water for FLASH beams covering an order-of-magnitude variation in dose rate. An expected reduction of vibration noise of 100x will enable much-greater measurement precision and, thereby, a much-enhanced ability to differentiate where within an irradiated volume FLASH conditions are achieved. (Note added later: the work shown here was done after eliminating the mechanical noise.)

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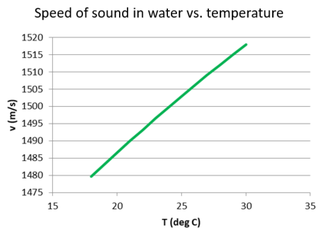
INTRODUCTION

This describes work toward calorimetric imaging of dose distributions in water using ultrasonic thermometry.

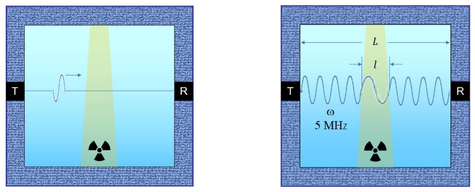
Ultrasonic thermometry is based on temperature dependence of the speed of sound, shown below for water [1], where for clinically relevant doses, temperature changes are quite small:



$$v(T) \cong 1394 + 4.5T, [^oC \rightarrow m/s]$$

$$\Delta T \cong 0.2391 \text{ mK/Gy}$$

For radiation beams of a few cm width in water, effects on ultrasonic probes of temperature are subtle. Shown below are example estimates of changes in pulse time-of-flight (TOF) and phase shift of 5 MHz ultrasound waves:



$TOF \cong 7\ \mu s$ per cm (~2 cm)

$\Delta TOF \cong 10$ ps/Gy

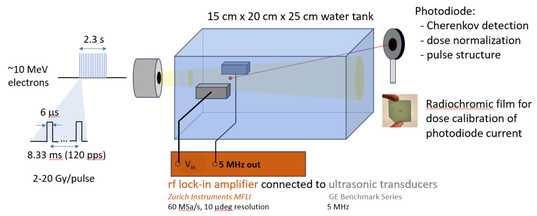
$\Delta\varphi = \Delta(\omega \cdot TOF)$

$\cong \omega \cdot \Delta TOF$

$\cong 18$ mdeg/Gy

Both approaches present technical challenges – sub-ps resolution for TOF; mdeg resolution for phase shift -- but the phase-shift approach is easily done with digital rf lock-in amplifiers (LIAs).

An example implementation is shown below, in which a LIA is connected to a transmitter-receiver pair of ultrasonic transducers that are positioned on opposite sides of a water tank. This produces a narrow ultrasonic beam whose phase is measured by the LIA for purposes of monitoring temperature-induced changes in speed of sound between the transducers.



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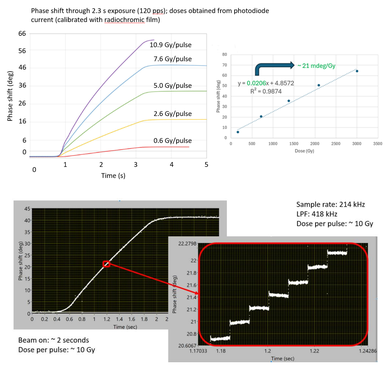
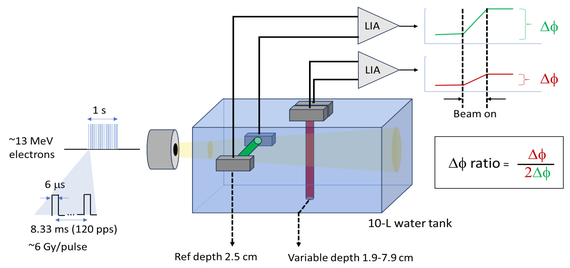
A pulsed radiation beam incident from the left enters the tank and heats the water between the sensors. Phase-shift measurements in earlier work [2] show a linear dependence with dose-per-pulse and a detection sensitivity sufficient to resolve doses from individual linac pulses:



METHODS

For extending the earlier work to obtain dose *profiles* in water, a second TR transducer pair was added, and a two-channel rf LIA (HF2LI, Zurich Instruments) was used to monitor phases of the resulting transverse ultrasonic beams simultaneously, as illustrated below:



Electron pulses from a medical linac (MIRF, NIST; characteristics shown above) were injected into the water. The electron gun was pulsed at 2 s intervals via an external power supply (~240 pulses).

Transducers producing the horizontal (green) ultrasonic beam were fixed at positions corresponding to a water depth of 25 mm (measured from the left wall of the tank), and the corresponding phase shift was used as reference; the other pair, producing the vertical (red) beam, were attached to a translation stage. Measurements were taken at 5 mm increments between 19 mm and 79 mm water depth.

Phase-shifts were obtained as suggested at the upper right of the preceding illustration, using midpoint extrapolation based on least-squares fits to the flat (beam off) segments of each trace. The resulting Δϕ ratios, include a factor of 2 in the denominator to account for extra traversal in the vertical beam, were compared with Monte Carlo depth-dose profiles.*

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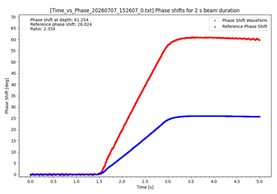
*TOPAS Monte Carlo code was used to model the electron source and experimental geometry. The 13 MeV electron beam exits the accelerator through a 50-micron aluminum vacuum window, impinging on the water tank located on the central axis 33 cm downstream of the vacuum window. The 3.2 mm glass wall is included in the simulation of the water tank. Dose was scored in a cylinder around the central axis whose diameter was the same as the 15 mm transducer beam.

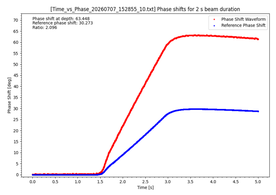
RESULTS

Example single-exposure phase-shift plots at fixed depth:

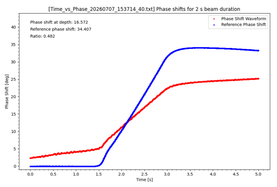
Depth = 19 mm



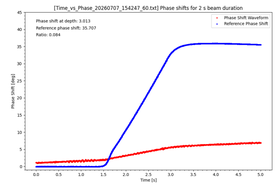
Depth = 29 mm



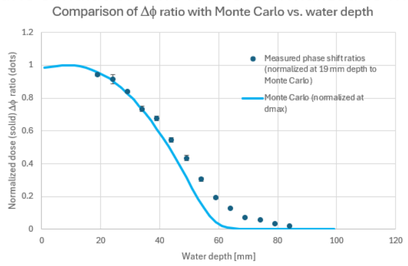
Depth = 59 mm



Depth = 79 mm



Resulting variation of Δϕ ratio vs. depth compared with results of Monte Carlo simulation (the former normalized to MC at 20 mm):



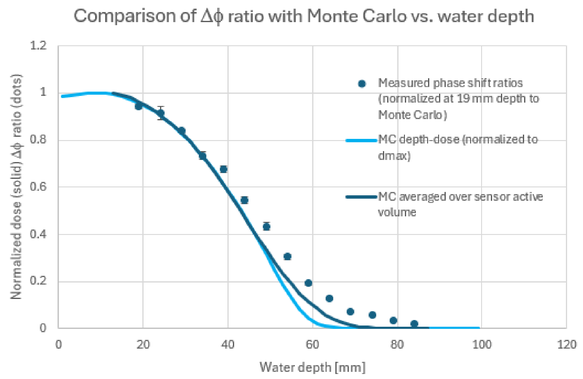
DISCUSSION

The (depth-specific) phase-shift plots exhibit excellent signal-to-noise at all depths scanned. This is unsurprising given the FLASH-level dose-per-pulse values used in this study.

The phase-shift plots also exhibit a small nonlinearity in the beam-on segment, most noticeable at the start of the rise. This is attributable to variations in electron-gun current (hence dose per pulse) at the start of each exposure.

The Δϕ ratios decrease smoothly with depth over nearly two orders of magnitude, indicating that this simple setup is potentially useful for mapping dose distributions arising from FLASH and/or or conventional beams.

Comparison with MC simulation shows a depth-dependent deviation which is currently being studied. Possible causes include simplifications in the MC model (e.g., differences between dose-scoring volume in the model and the water volume sampled by the ultrasound beam) and blurring due to finite dimensions of the sensing region of each transducer. Applying a simple correction for the latter effect (by blurring the MC output rather than deblurring the measurements) decreases the deviation.



CONCLUSIONS

Ultrasonic detection of heating in irradiated water, shown earlier for conventional radiotherapy beams [1], has been used here to obtain depth-dose profiles from water exposed to 13 MeV electrons at FLASH dose rates.

Phase-sensitive detection, rather than TOF methods, are used because of the relative ease with which high-precision measurements can be made with standard, off-the-shelf instruments.

Earlier work [2] has shown a linear relationship between dose and ultrasonic phase shift, which the present work extends for obtaining dose distributions. However, while the results exhibit reasonable agreement with Monte Carlo simulations, we see a depth-dependent systematic deviation of unknown origin.

Future work is planned to resolve the discrepancy with MC simulation and to expand the sensor array to do imaging of dose fields in FLASH beams, with the intention of differentiating regions in which FLASH and sub-FLASH dose rates are present.

REFERENCES

1. Malyarenko EV, Heyman JS, Chen-Mayer HH, Tosh RE. High-resolution ultrasonic thermometer for radiation dosimetry. J Acoust Soc Am. 2008 Dec;124(6):3481-90. doi: 10.1121/1.2997431. PMID: 19206777.
2. Tosh, RE and Bateman FB, "Ultrasonic Detection of Flash-level Dose Pulses from a Medical Linac," oral presentation, 67th Annual Meeting of the American Association of Physicists in Medicine, Washington DC (July 27-30, 2025).

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