

# Measurement of Acoustic Emissions Generated by a Pulsed Proton Beam from a Hospital-Based Clinical Cyclotron

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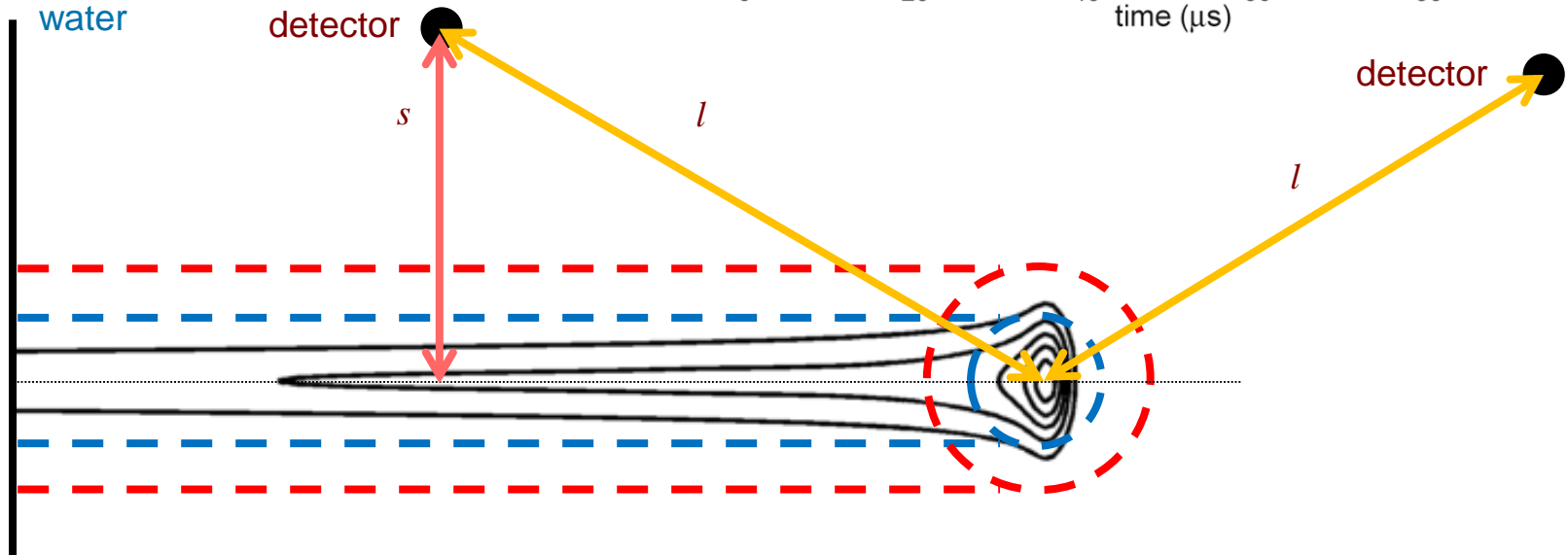
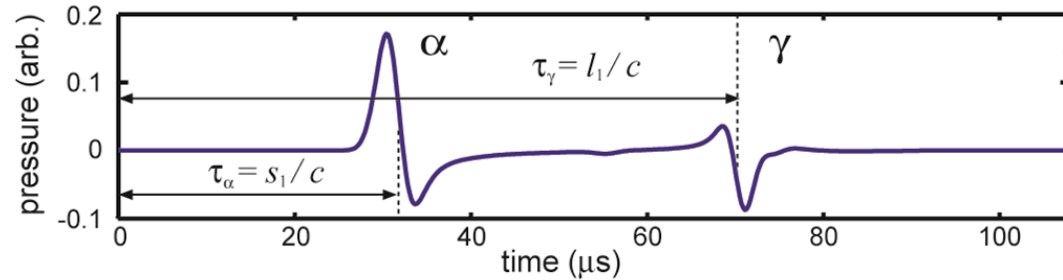
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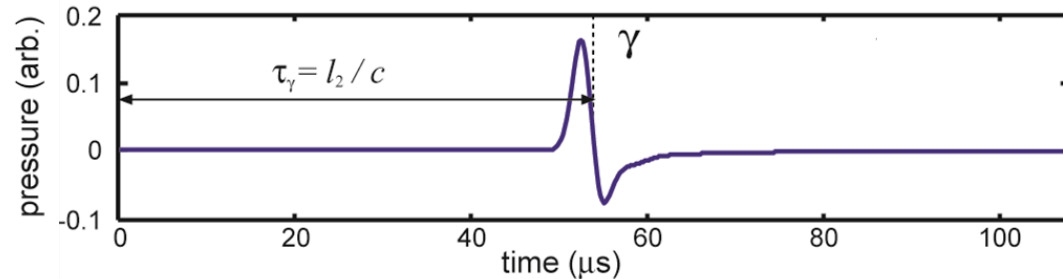
# Protoacoustic Range Verification Potential

The arrival time,  $\tau$ , of pressure waves reports on distance between dose deposition and detector.



Time-of-flight (TOF) hypothesis:

$$\tau = l/c$$



# Data Acquisition

Roberts Proton Center, IBA C230  
University of Pennsylvania



Function Generator

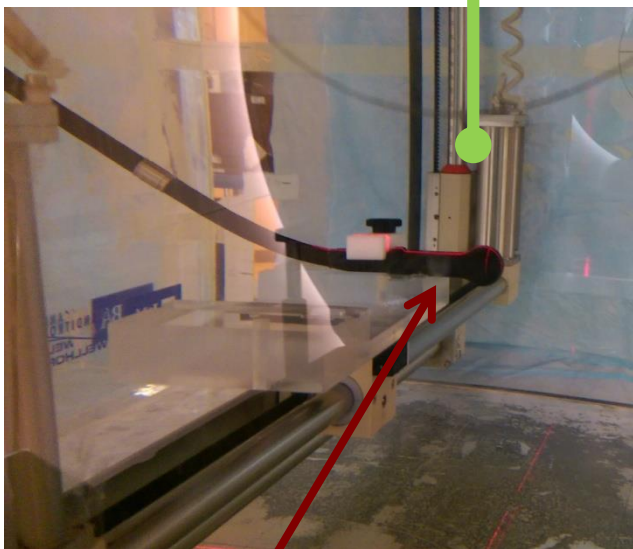
Modulates the cyclotron  
proton source

17-19  $\mu\text{s}$  proton pulses FWHM  
up to 790 nA proton current ( $1.2 \times 10^8$  protons/pulse)

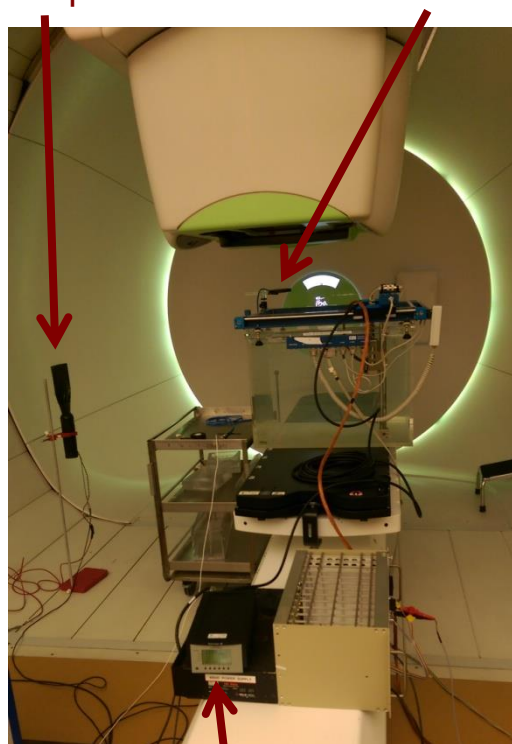
Plastic Scintillator +  
Photomultiplier Tube

Bragg Peak  
Ionization Cham

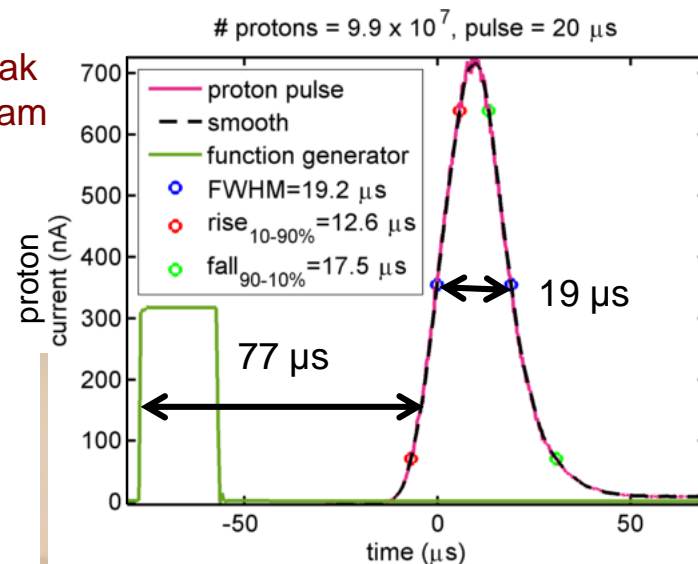
Beam



Brüel & Kjaer 8105  
Hydrophone

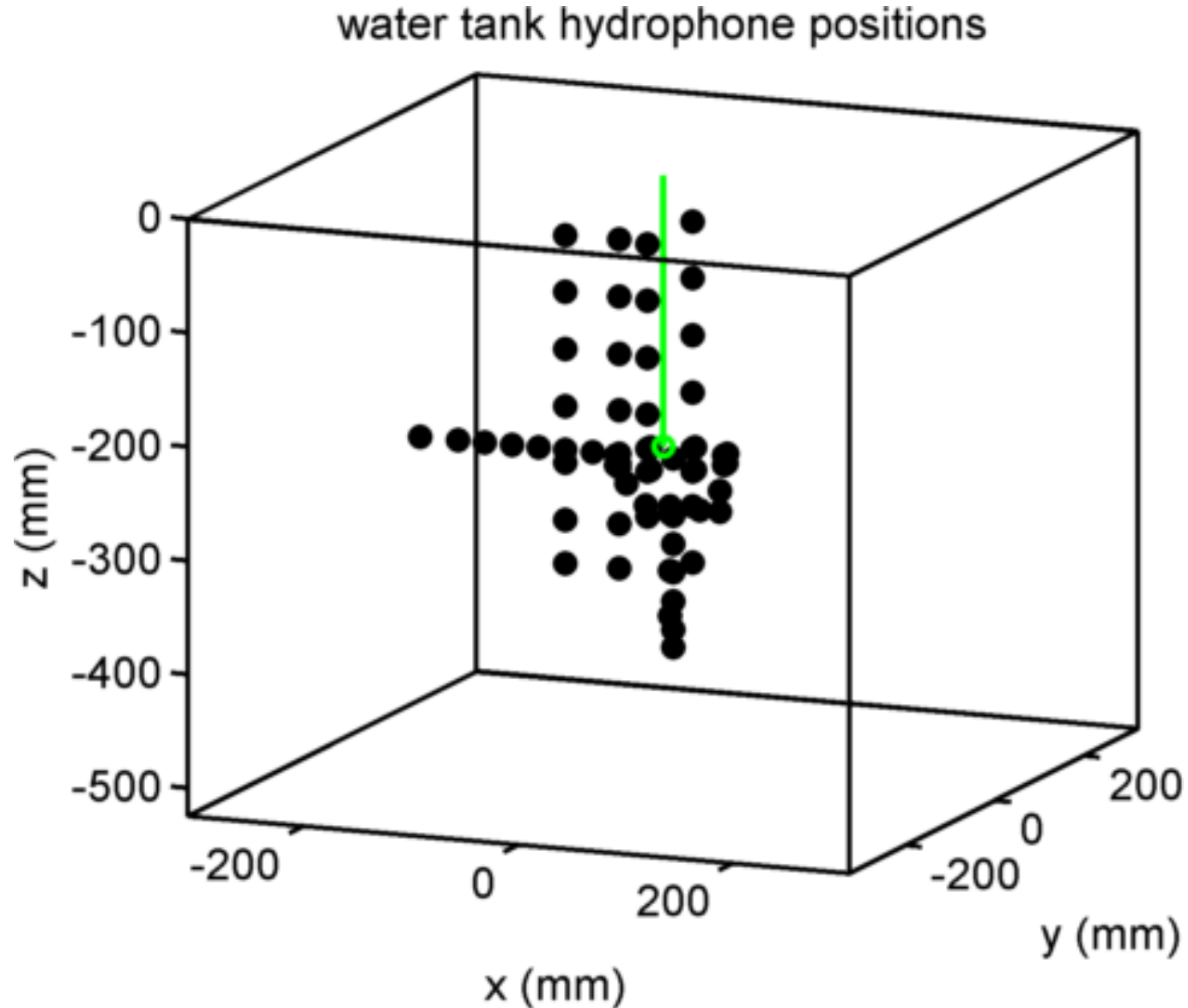


65 dB (x1780 gain) amplifier



Oscilloscope for Data  
Acquisition

# Data Collection: Hydrophone Positions

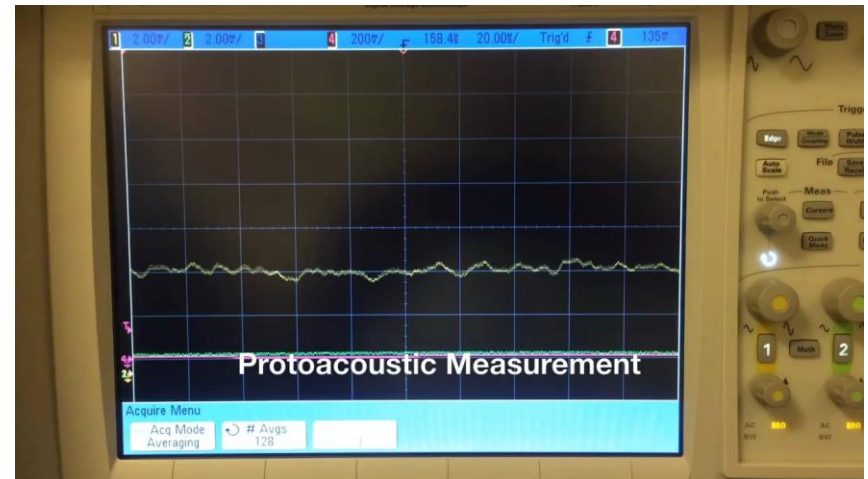


# Protoacoustic Measurements

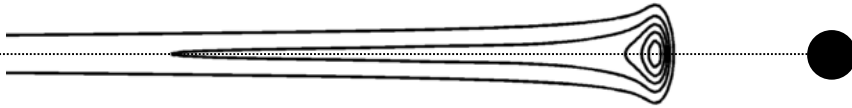
## Water Tank



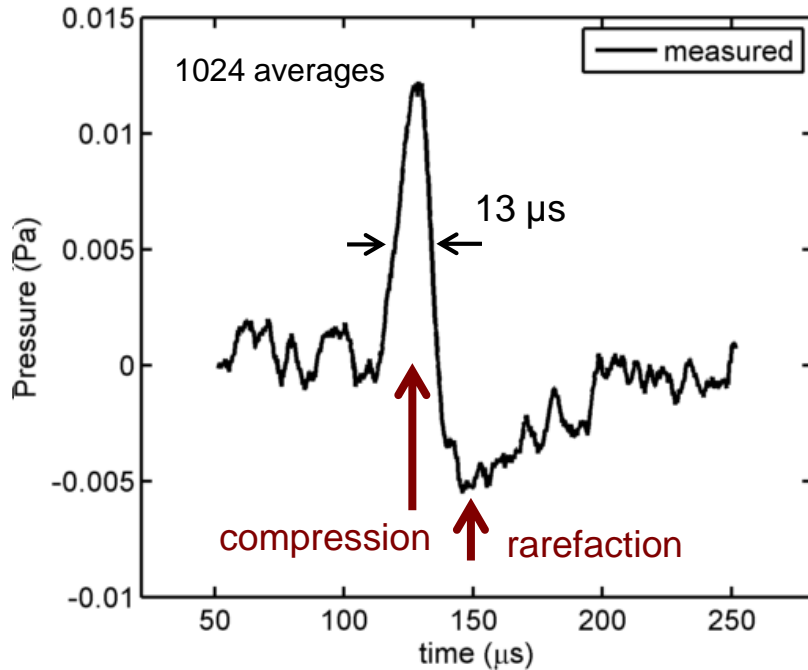
## Oscilloscope



# Characteristic Acoustic Signal



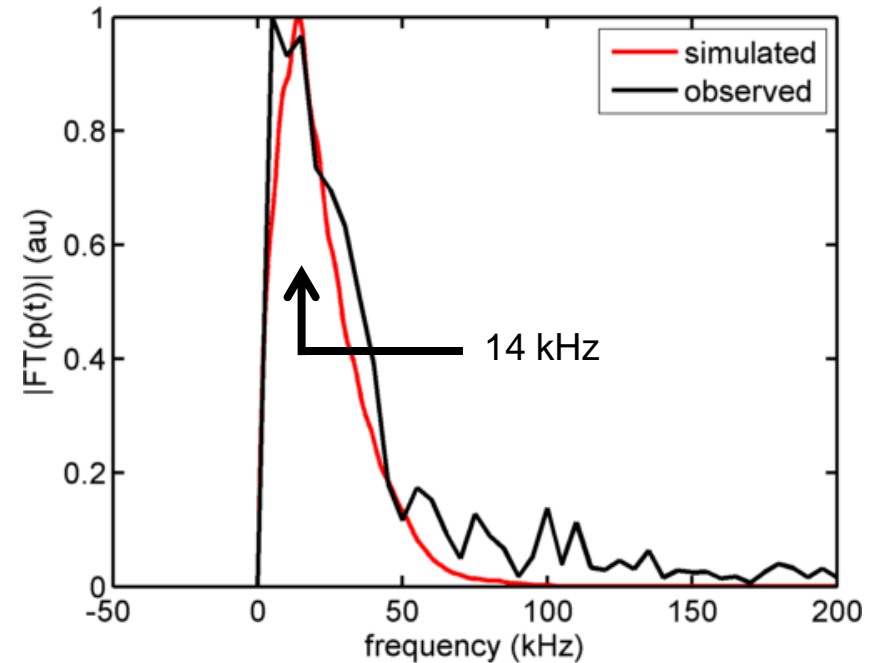
Time domain



FT

A double-headed arrow pointing left and right, with 'FT' written above it, indicating the Fourier Transform relationship between the time and frequency domains.

Frequency domain



6 cm from Bragg peak  $\rightarrow$   $\sim$ 15 mPa of pressure ( $3 \times 10^7$  protons, 4.8 cGy)

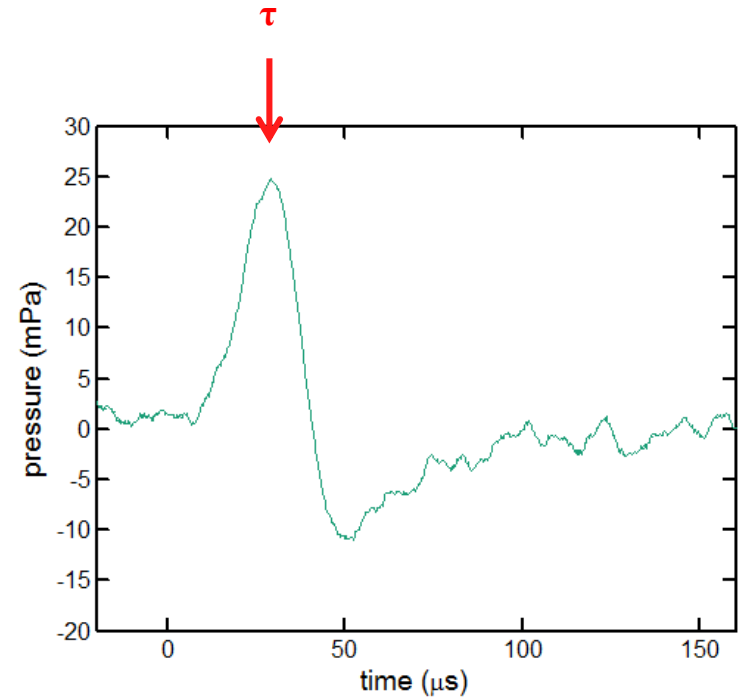
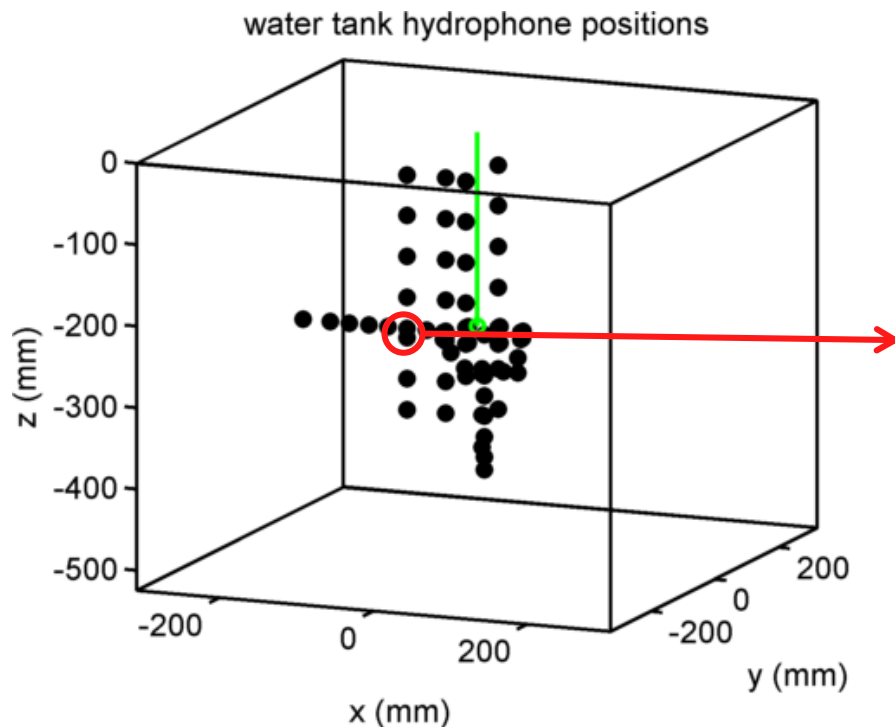
# Data Collection: Precision

$$\tau = l/c \longrightarrow \tau = \frac{1}{c} \left[ l + \sigma_{noise} \right]$$

## Questions:

1) What is the precision/reproducibility of the arrival time measurement?

- protoacoustic peak FWHM is  $\sim 13 \mu\text{s}$
- $1 \mu\text{s}$  error in measuring arrival time  $\rightarrow 1.5 \text{ mm}$  distance error
- *In ultrasound*: spatial resolution  $\sim \lambda/2 = (c/v)/2 = (1487 \text{ m s}^{-1} / 100 \text{ kHz})/2 = 7.4 \text{ mm}$

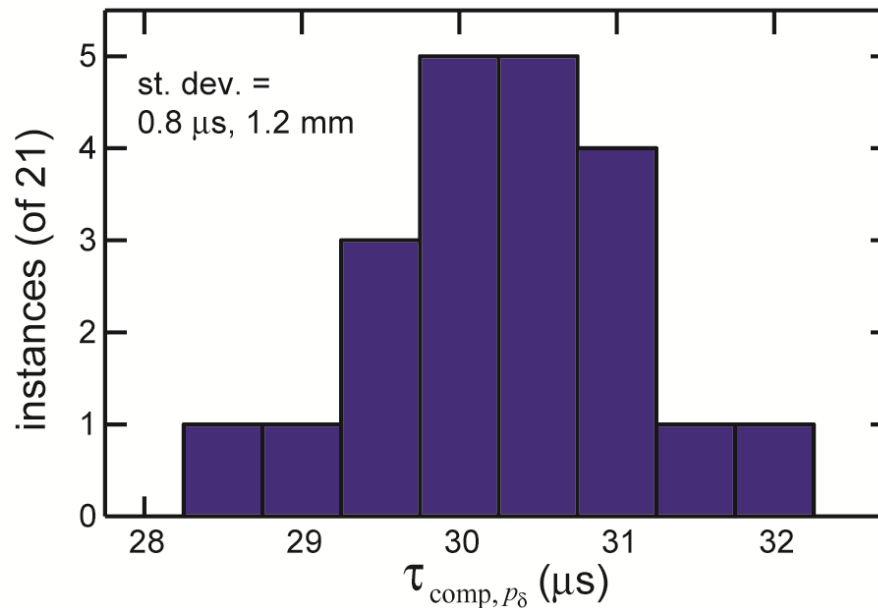




# Precision (reproducibility) of measurement

$$\tau = \frac{1}{c} \left[ l + \boxed{\sigma_{noise}} \right]$$

1.2 mm



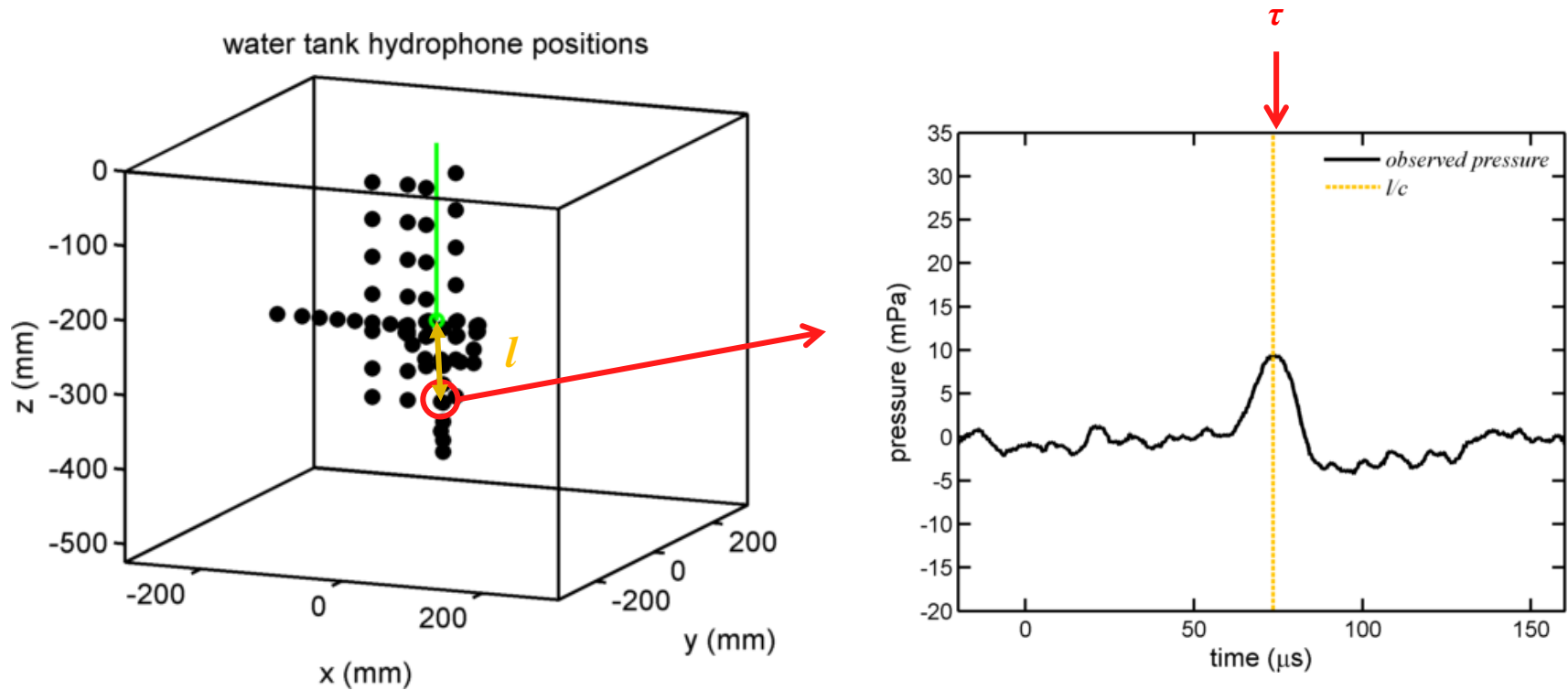
- Arrival time is measured with a standard deviation of 1.2 mm (at high SNR = 21).
- Given the ideal conditions (high SNR, homogeneous water medium), this represents the “best case” precision for this system.



# Data Collection: Range Verification Error

## Questions:

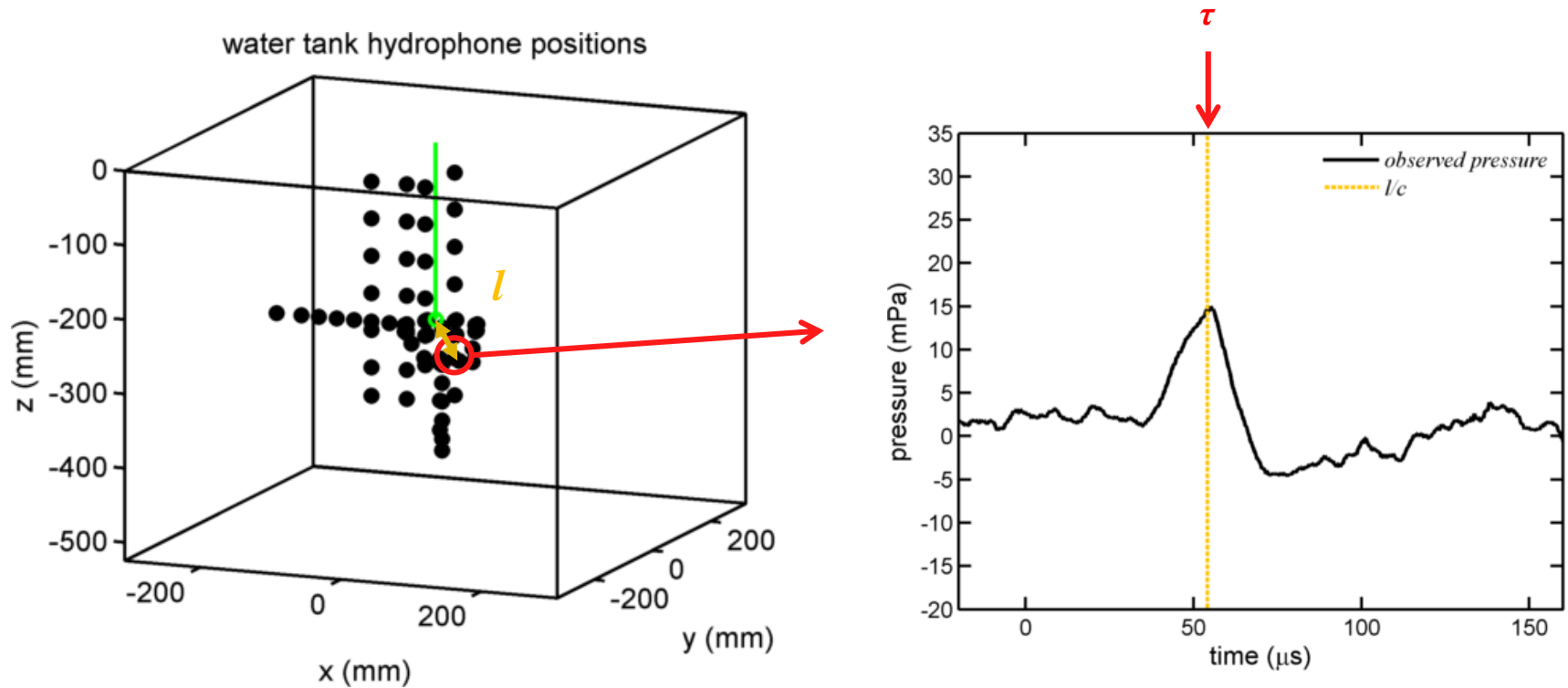
- 1) What is the precision/reproducibility of the arrival time measurement?
- 2) What is the range verification error?
  - error =  $\tau * c - l$



# Data Collection: Range Verification Error

## Questions:

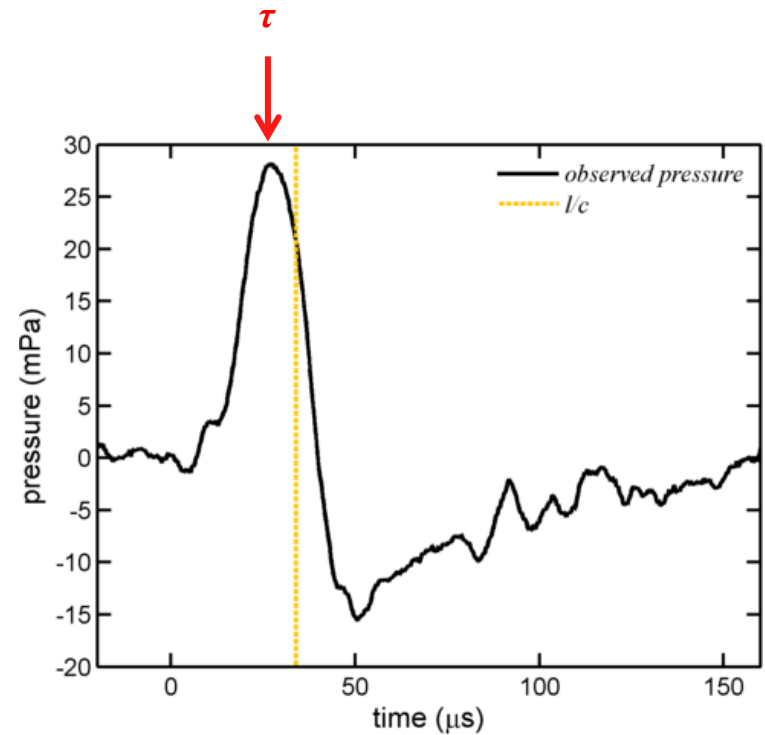
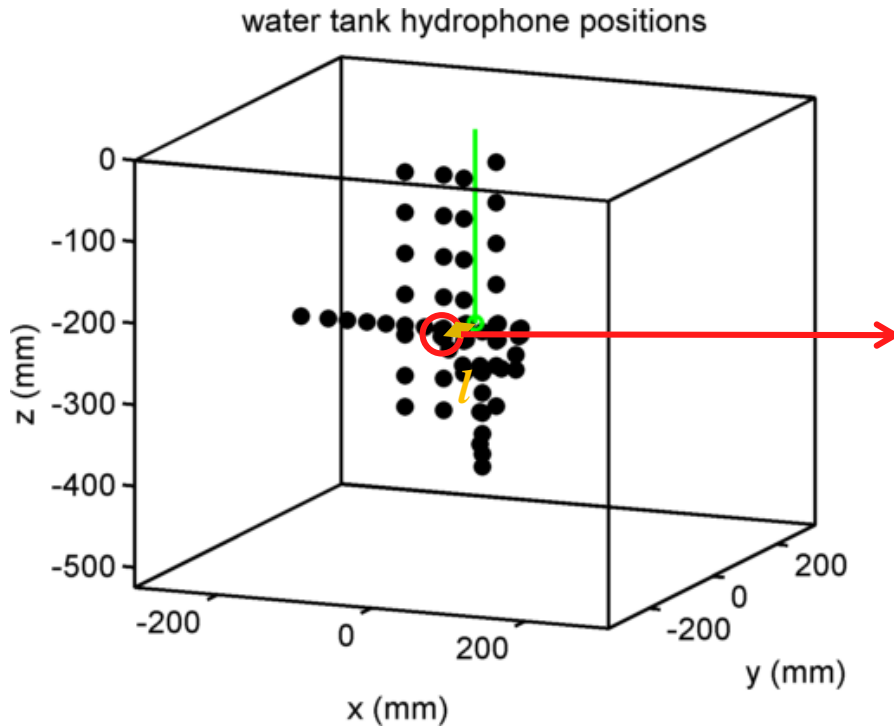
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# Data Collection: Range Verification Error

## Questions:

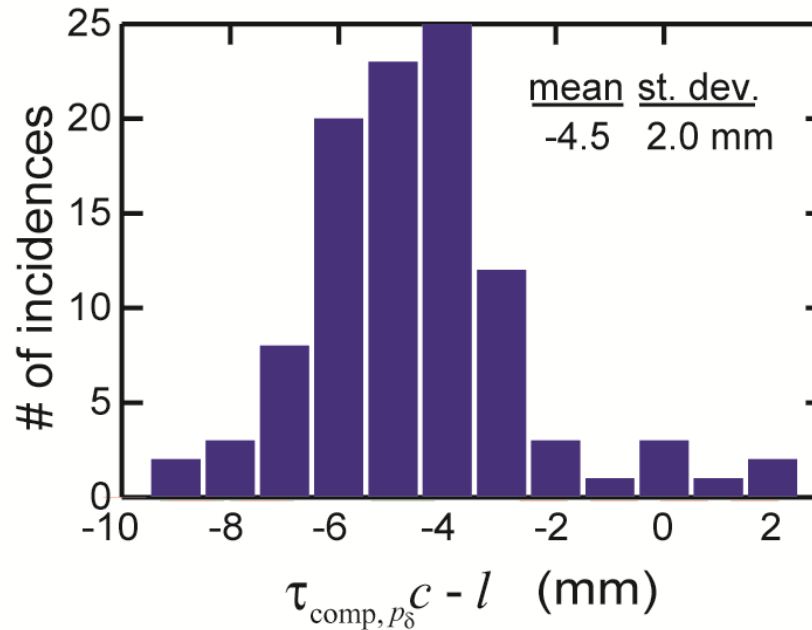
- 1) What is the precision/reproducibility of the arrival time measurement?
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  - error =  $\tau * c - l$



# Range verification error

$$\tau = \frac{1}{c} [l + \sigma_{noise} + S]$$

$$\tau * c - l = \sigma_{noise} + S \rightarrow -4.5 \text{ mm, st. dev.} = 2.0 \text{ mm}$$



- Error in measuring the Bragg peak position from a single acoustic measurement has a standard deviation of 2.0 mm.
- Calibration is necessary to account for systematic errors ( $S$ )

# Required dose

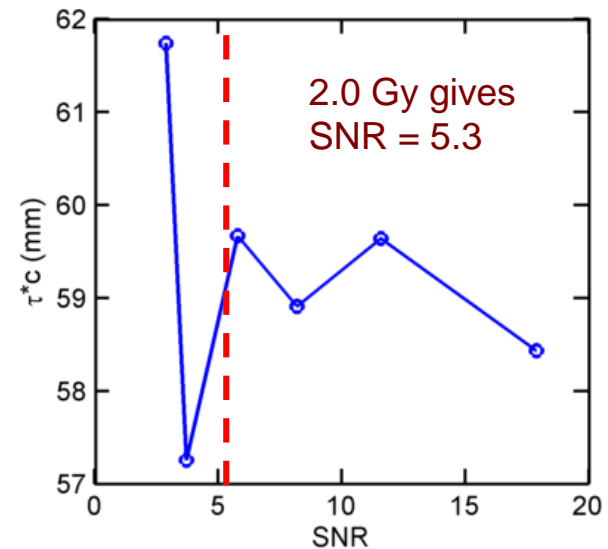
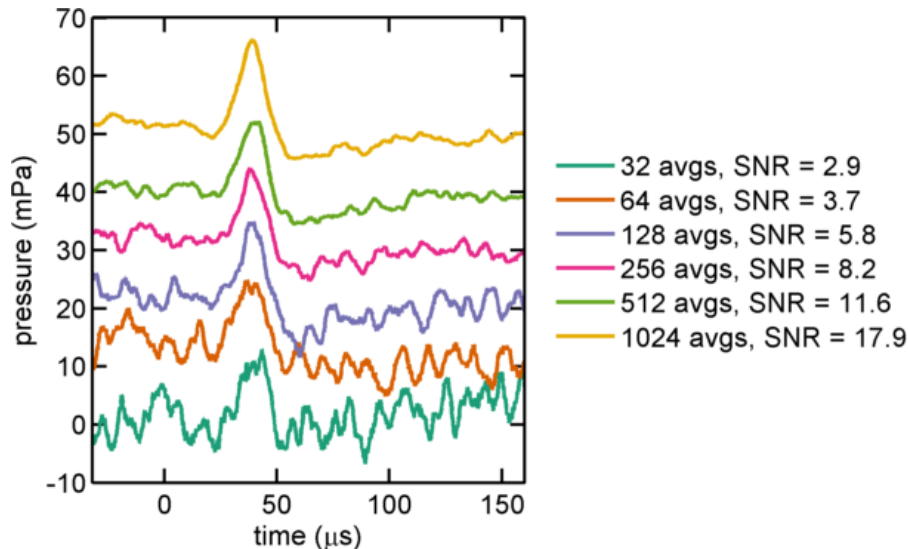
## Questions:

- 1) What is the precision/reproducibility of the arrival time measurement?
- 2) What is the range verification error?
- 3) What dose is required?
  - The presented data was collected at SNR ~21 = dose of 20-120 Gy at Bragg peak

$$SNR = \sqrt{n} \frac{P_{max}}{N}$$

$$n = \frac{D_{total}^{BP}}{D_{single}^{BP}}$$

$P_{max}$  : At 5 cm,  $p_{max} = 5.2 \text{ mPa} / 1 \times 10^7 \text{ protons}$  (1.6 cGy at Bragg peak)  
 $N$  : noise is 27 mPa  
 $n$  : averages



# Conclusions

- ◆ Proton pulses generated by a hospital-based, clinical cyclotron induce the emission of measurable acoustic waves.
- ◆ Acoustic monitoring is a potential proton range verification technique with accuracy of 2 mm (standard deviation, SNR=21) in water, but calibration is required to account for systematic error.
- ◆ In water, 2 Gy of deposited dose will generate a protoacoustic SNR of 5.3.

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