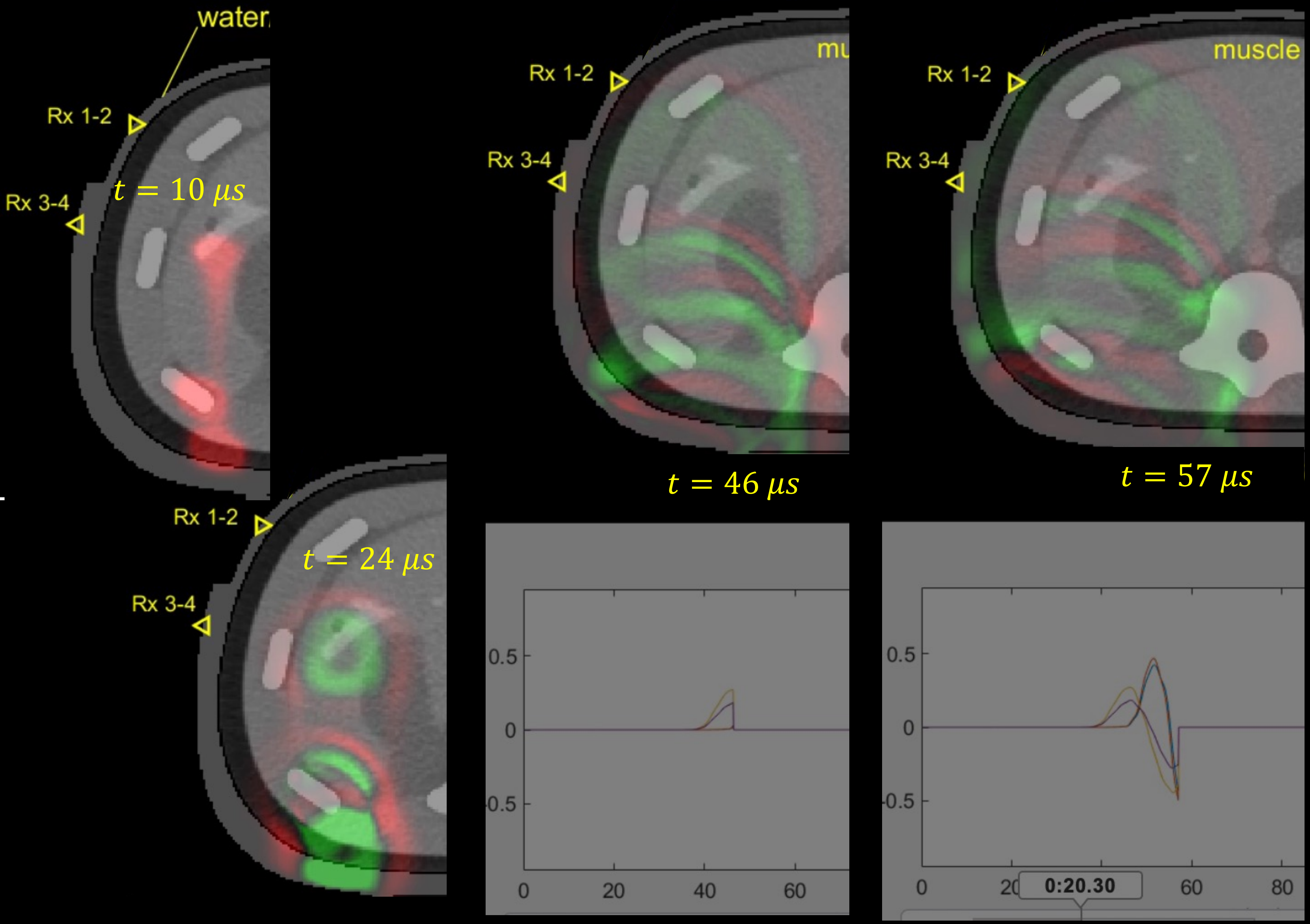


Ionoacoustics for Proton Range Verification

SK Patch, Acoustic Range Estimates

Y Hao, Washington University in St Louis

AAPM

July 2022

Thermoacoustic Signal Chain

I. Energy deposited by particle beam

II. tissue heats & increases pressure

III. thermoacoustic pulses propagate away

IV. acoustic receivers somehow detect pressure changes

V. data processing, *i.e. math*: image reconstruction, Bragg peak localization . .

I. Energy deposited by particle beam

a) Units: [E/V] = J/m³ = N/m² = Pascal

parameter Γ controls conversion efficiency

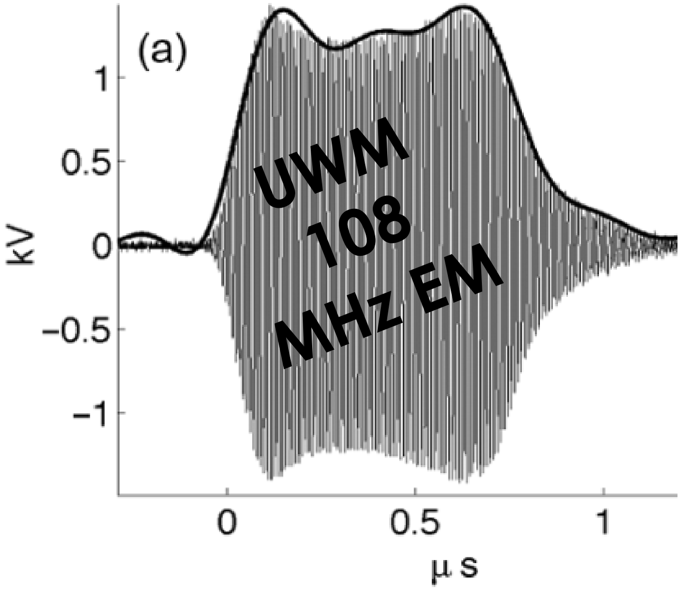
b) Deposition rate

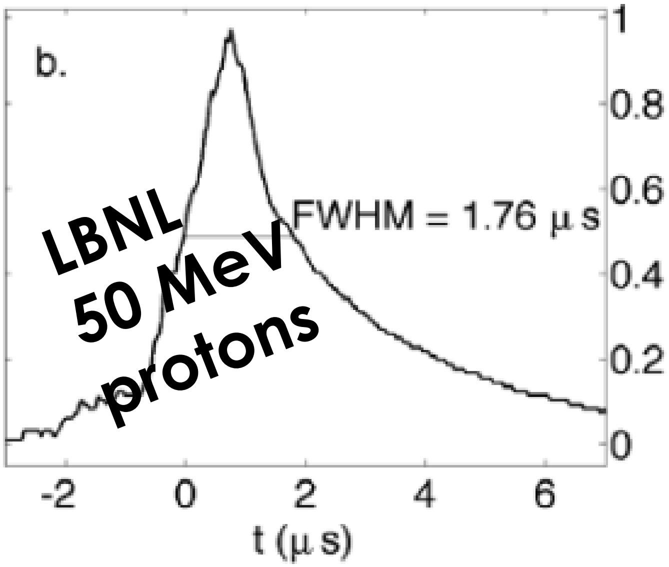
micro: 1 proton stops from O($10^8\, m/s$) within just a few ns

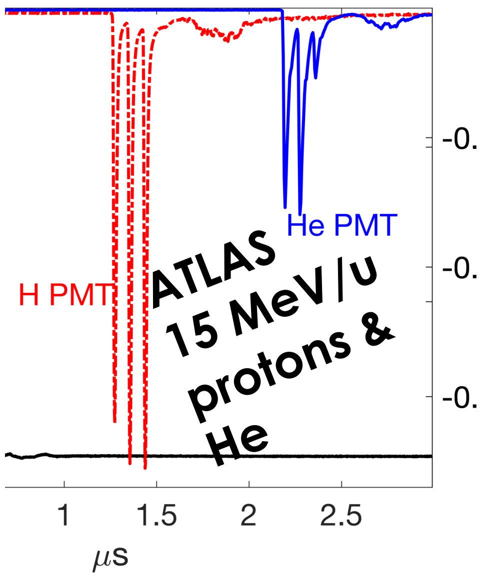
macro: many protons in pulse w/envelope *I* (hardware limited)

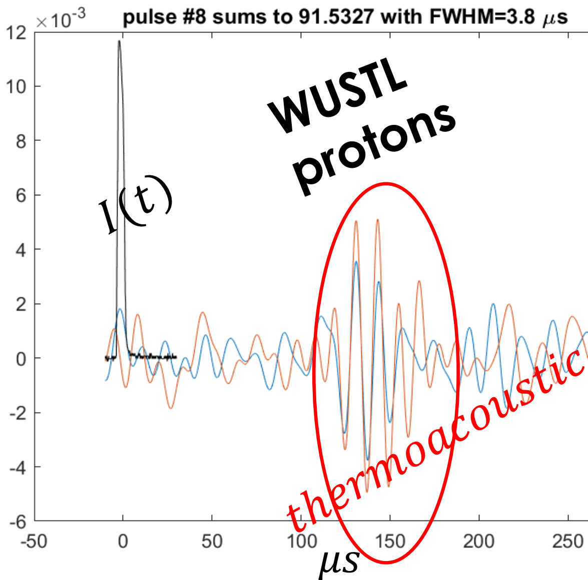
Various pulse envelopes, $I(t)$, with FWHM from 250 ns to 4-5 μs.

(generally) stress-confined. . .





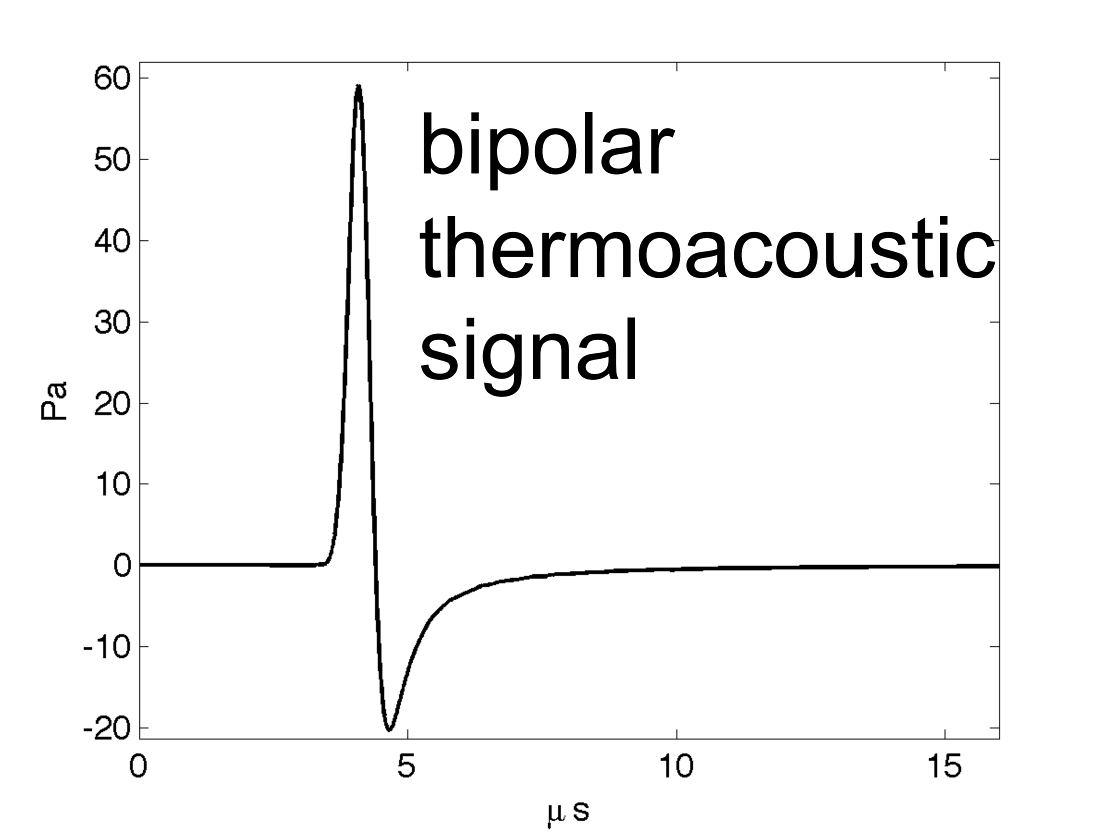


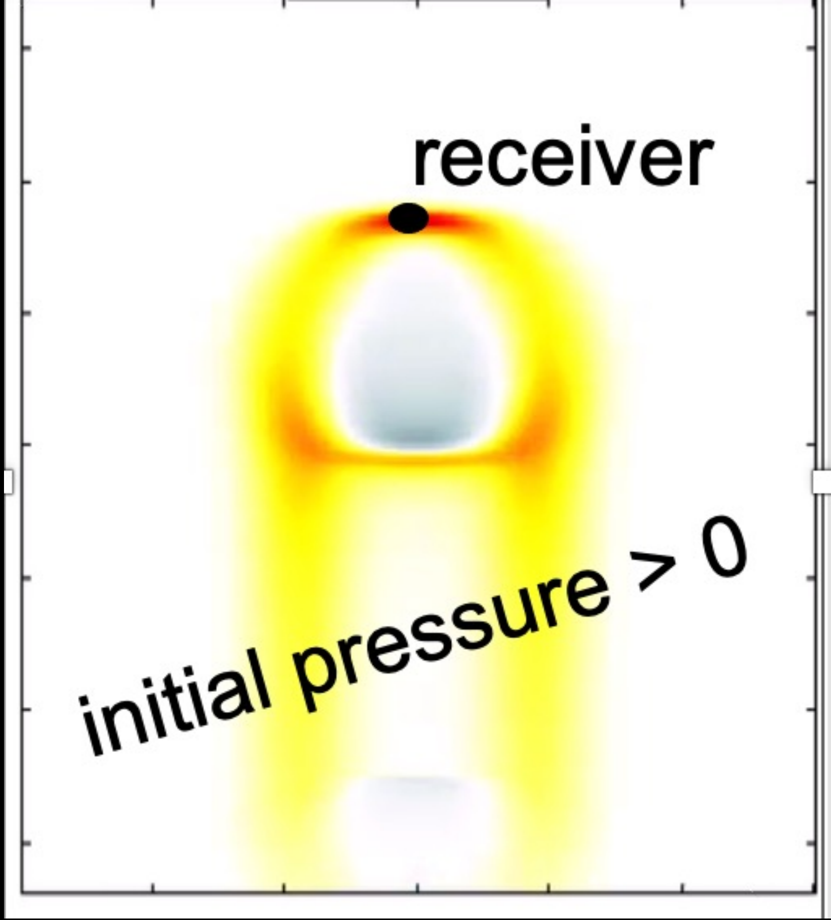


Importance of Stress Confinement

Positive (compression) followed by weak negative (rarefaction)

49 MeV, 4 pC single-turn extraction



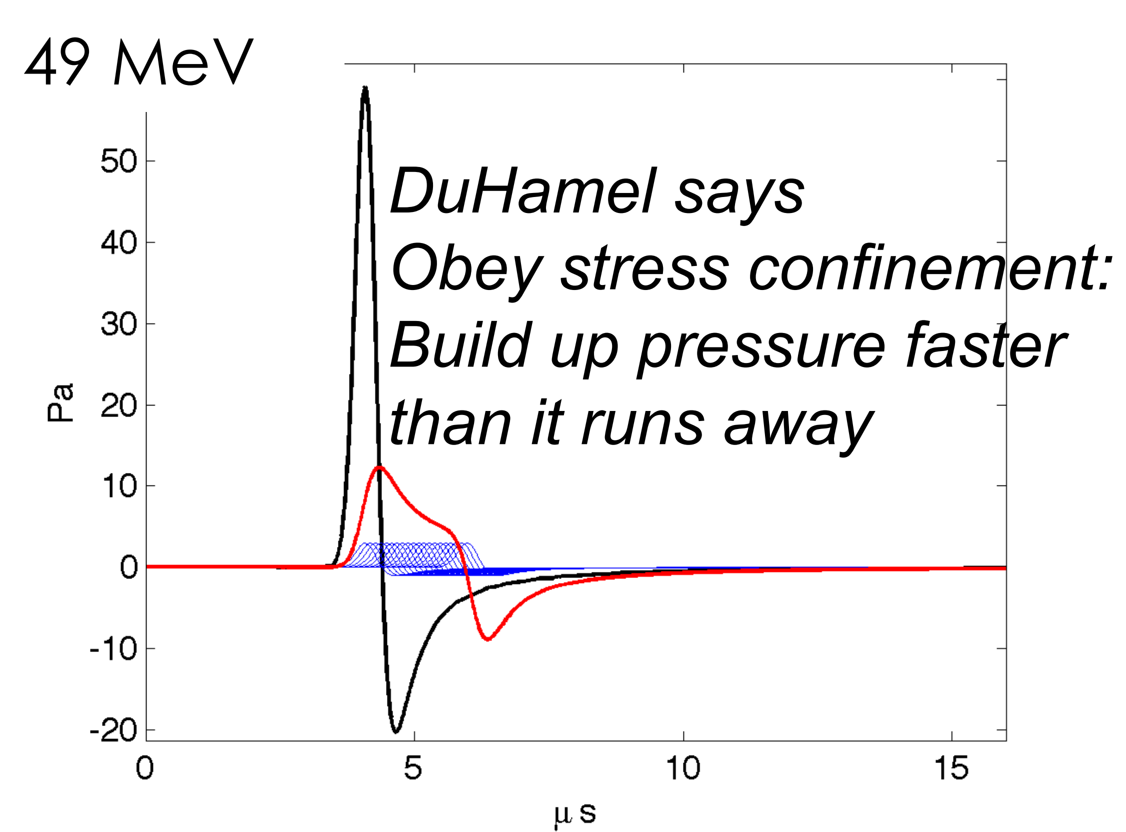


Importance of Stress Confinement

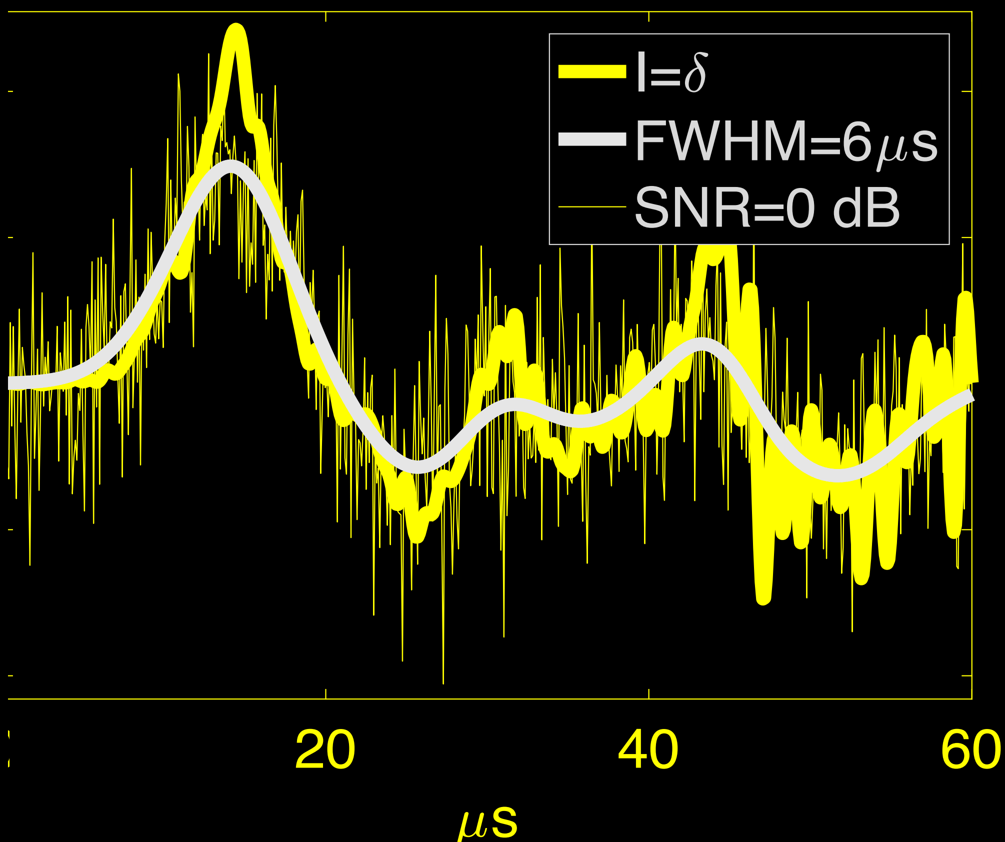
- straggle of degraded clinical beam broadens Bragg curve

Destructive interference when stress confinement fails.

4 pC over 2 μs @ 10 MHz



degraded 227 MeV in 6 μs



I. Energy deposited by EM photons or charged particles

a) Units: [E/V] = J/m^3 = N/m^2 = Pascal

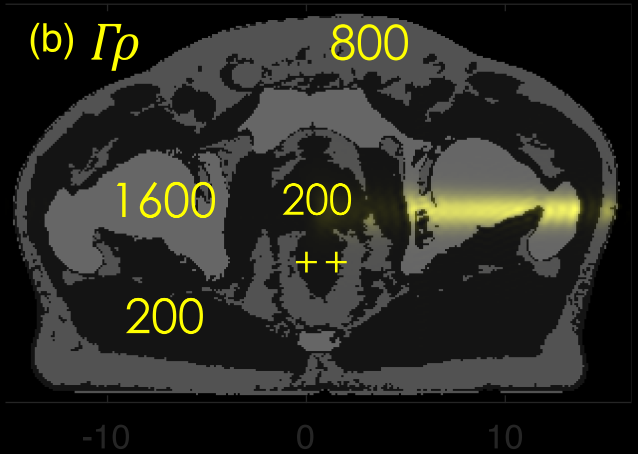
b) Deposition rate

OBEY STRESS CONFINEMENT – HIGH INSTANTANEOUS DOSE RATE BEST

c) Spatial variations – due to *unknown* tissue parameter, Γ

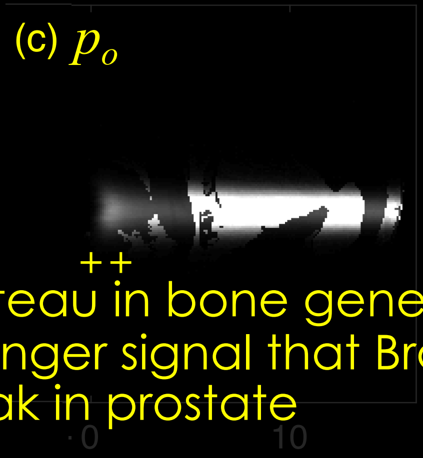
$p_o = \Gamma\, E/V$ where Γ is conversion efficiency (E density to pressure)

$p_o = \Gamma\, \rho D$ where D = dose in Gy



Tissue	HU range	SOS (m/s)	Γ	ρ (kg/m^3)
air	(-1000, -200)	343	0.376	1.2
fat	(-200, -50)	1480	0.877	920
muscle, organ	(-50, 100)	1540	0.208	1040
bone	(100,+1000)	3200	0.788	2000

Med Phys, ***45***(2), pp. 783-93, 2018.

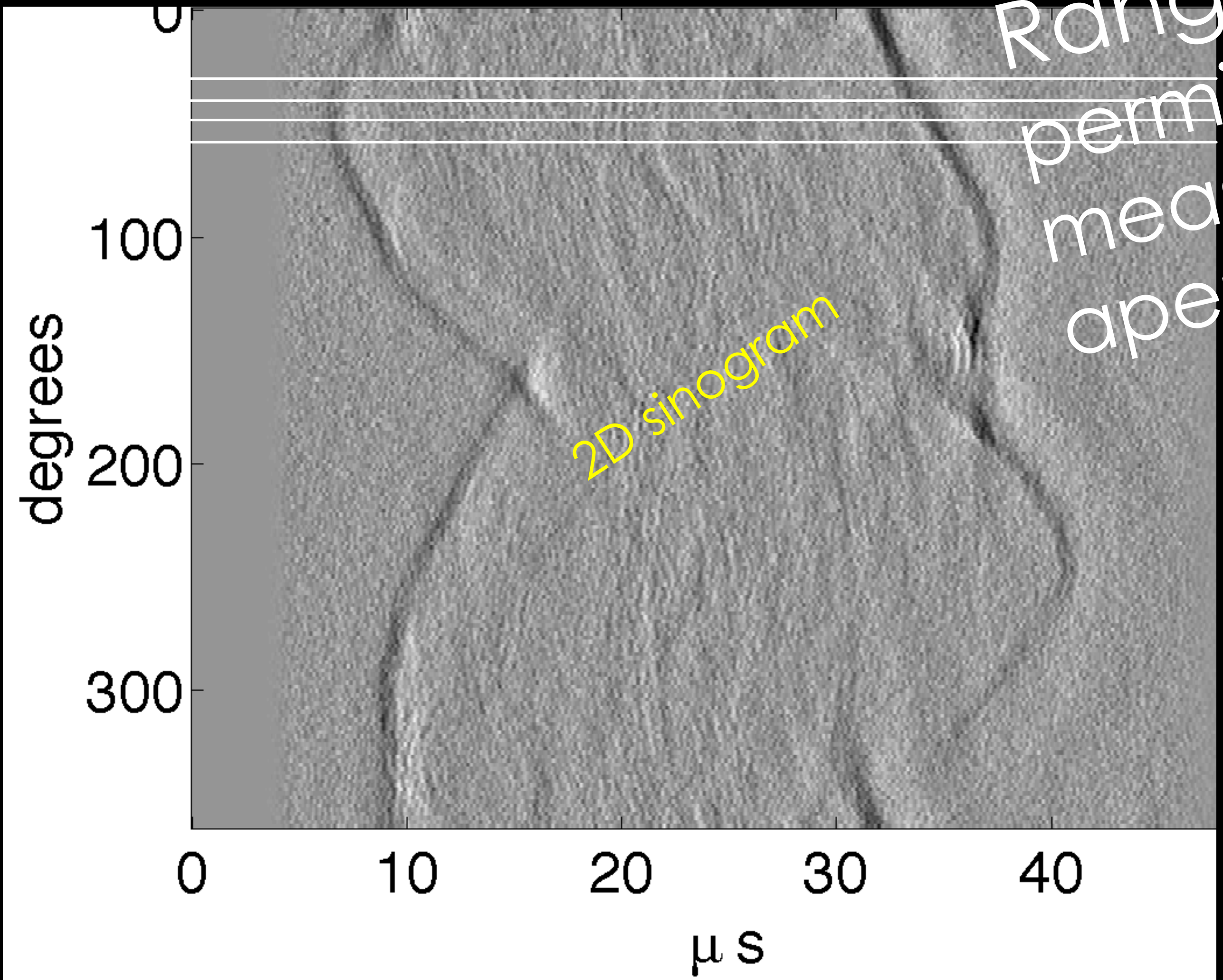


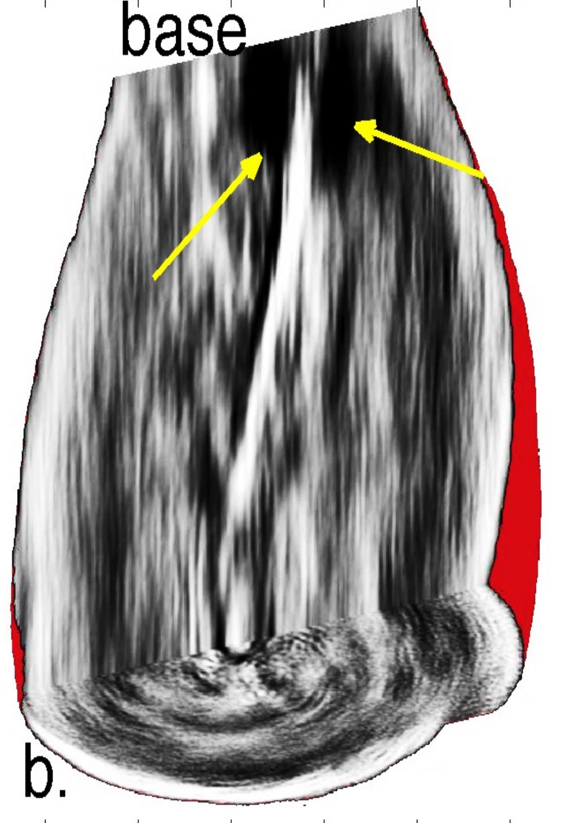
Plateau in bone generates stronger signal that Bragg peak in prostate

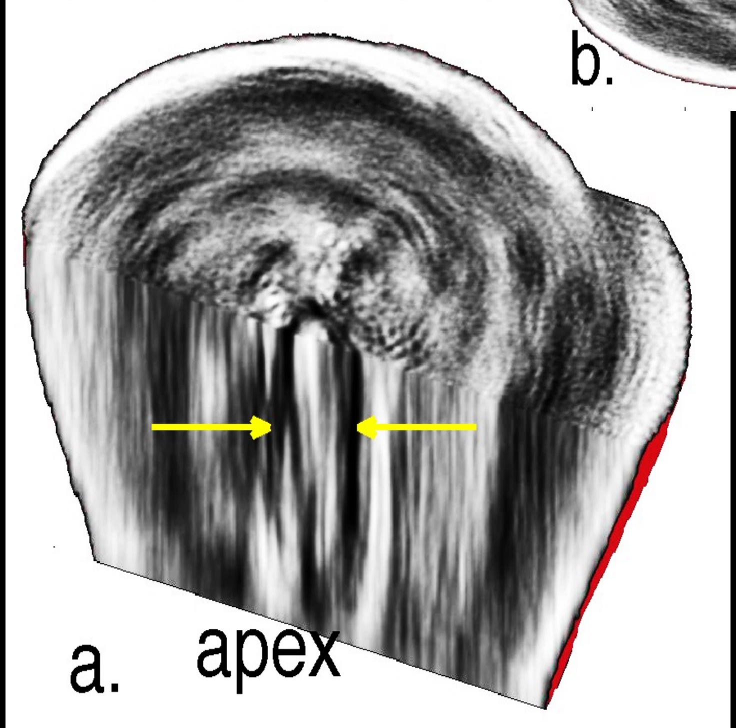
Analysis: Thermoacoustic *Tomography*

Measurement aperture surrounds object

Range Verification permits only limited measurement aperture.







stacks of 2D reconstructions TUFFC **63**(2), (2016)

Brief History of Thermoacoustic Range Verification

1979 - early work at National Labs (US & USSR)

- Sulak L, Armstrong T, Baranger H, Bregman M, Levi M, Mael D, Strait J, Bowen T, Pifer A, Polakos P, Bradner H, Parvulescu A, Jones W, Learned J, 1979 Experimental studies of the acoustic signature of proton beams traversing fluid media Nucl. Instrum. Methods 161 203–17
- Askariyan GA, Dolgoshein BA, Kalinovsky AN, Mokhov NV. Acoustic detection of high energy particle showers in water. Nucl Instrum Methods. 1979;164:267–278.

1990s – fast extraction synchrotron studies in Japan

- Hayakawa, Y. et al. Acoustic pulse generation in excised muscle by pulsed proton beam irradiation and the possibility of clinical application to radiation therapy. J. Acoust. Soc. Jpn. (E) 9, 255–257 (1988).
- Hayakawa, Y. et al. Acoustic pulse generation in water by pulsed proton beam irradiation and its possible application to radiation therapy. Jpn. J. Appl. Phys. 28, 217–219 (1989).
- Tada, J. et al. Time resolved properties of acoustic pulses generated in water and in soft tissue by pulsed proton beam irradiation—a possibility of doses distribution monitoring in proton radiation therapy. Med. Phys. 18, 1100–1104 (1991).
- Tada J, Hayakawa Y, Hosono K and Inada T 1991 Time resolved properties of acoustic pulses generated in water and in soft tissue by pulsed proton beam irradiation—a possibility of doses distribution monitoring in proton radiation therapy Med. Phys. 18 1100–4
- Hayakawa Y, Tada J, Arai N, Hosono K, Sato M, Wagai T, Tsuji H **1995 Acoustic pulse generated in a patient** nerated in a patient during treatment by pulsed proton radiation beam Radiat. Oncol. Investig. 3 42-

Background on Thermoacoustic Range Verification

21st century - renewed interest

2007 Terunuma, T. et al. Waveform simulation based on 3D dose distribution for acoustic wave generated by proton beam irradiation. Med. Phys. 34, 3642–3648

2014 Jones, K. C. et al. Proton beam characterization by proton-induced acoustic emission: simulation studies. Phys. Med. Biol. 59, 6549–6563 (2014).

2015

- Assmann W et al, Ionoacoustic characterization of the proton Bragg peak with submillimeter accuracy Med. Phys. 42
- Alsanea F, Moskvin V and Stantz K M Feasibility of RACT for 3D dose measurement and range verification in a water phantom Med. Phys. 42
- Ahmad, M. et al. Theoretical detection threshold of the proton-acoustic range verification technique. Med. Phys. 42
- Jones, K. C. et al. Experimental observation of acoustic emissions generated by a pulsed proton beam from a hospital-based clinical cyclotron. Med. Phys. 42
-
- Patch lab (LBNL 2016, WUSTL 2018, ANL 2019)

high dose in research mode delivery to water

Recent experimental results generated by clinical synchrocyclotrons

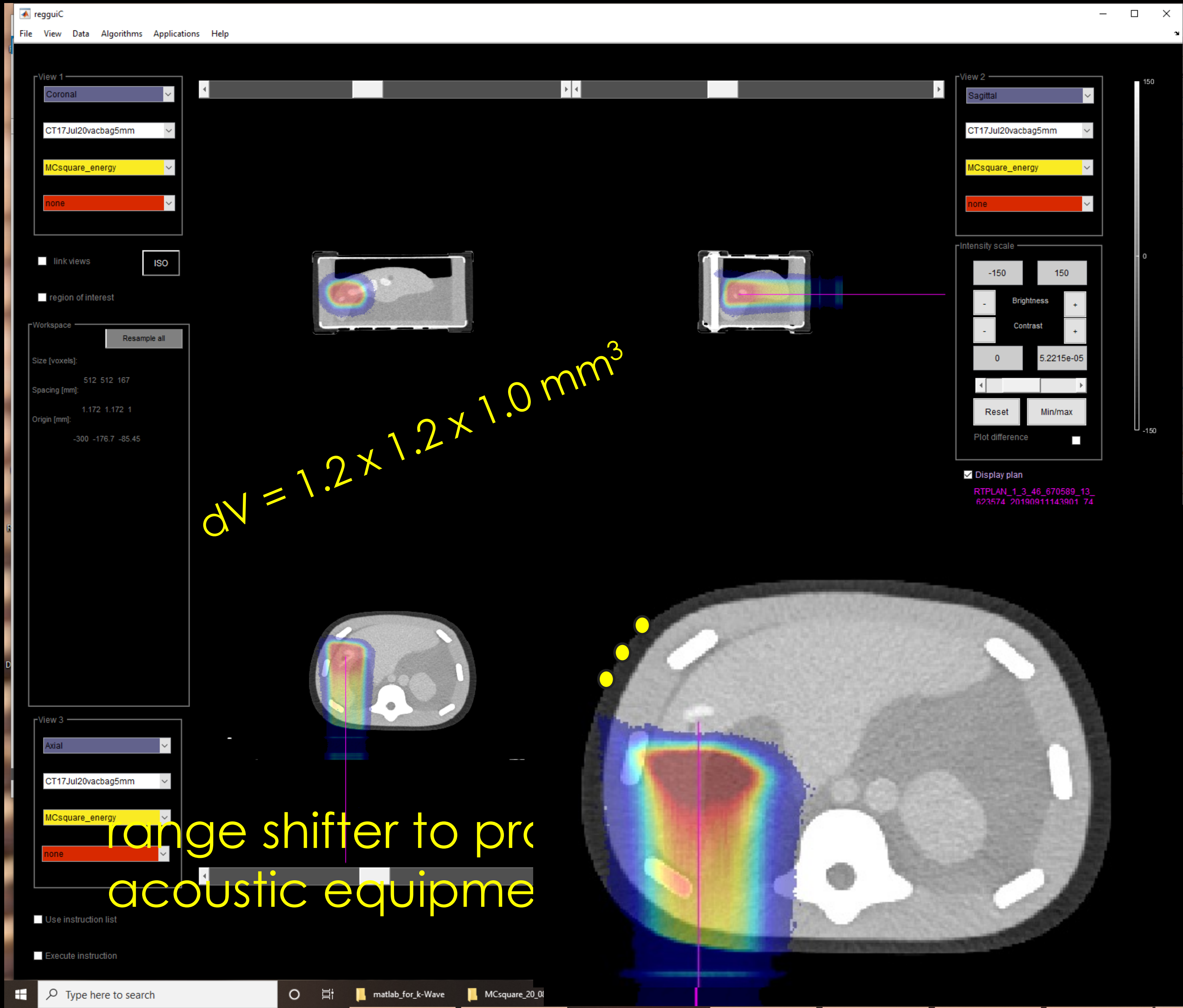
- Lehrack, Submillimeter ionoacoustic range determination for protons in water at a clinical synchrocyclotron. Phys Med Biol. 2017
- Patch, et al, Thermoacoustic range verification during pencil beam delivery of a clinical plan, *Radiother & Oncology*, 2021
-
- more and more. . .

hypofractionated 6 Gy clinical delivery to anthropomorphic hydrogel phantom

Rutherford Newcastle Sept 2019

- 12-layer, single field RT plan
- 6 Gy/fraction to liver
- hydrogel imaging phantom (CIRS 057a)
- IBA ProteusOne w/S2C2, paused between layers
- remote readout via digital scope (Siglent)
- 4 TA receivers + US array

Dose close to acoustic hardware,

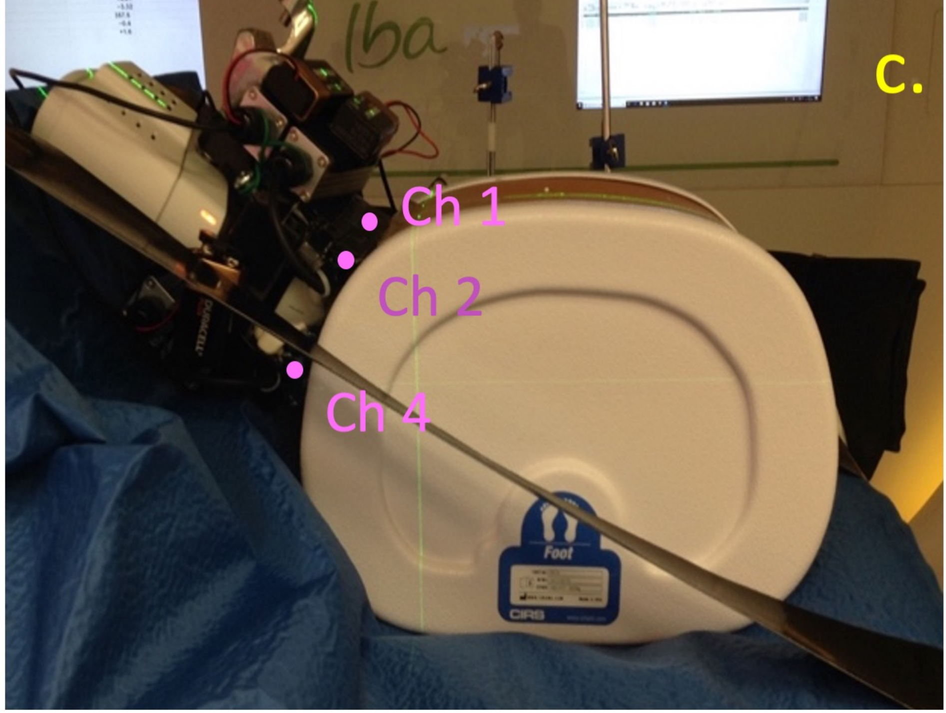


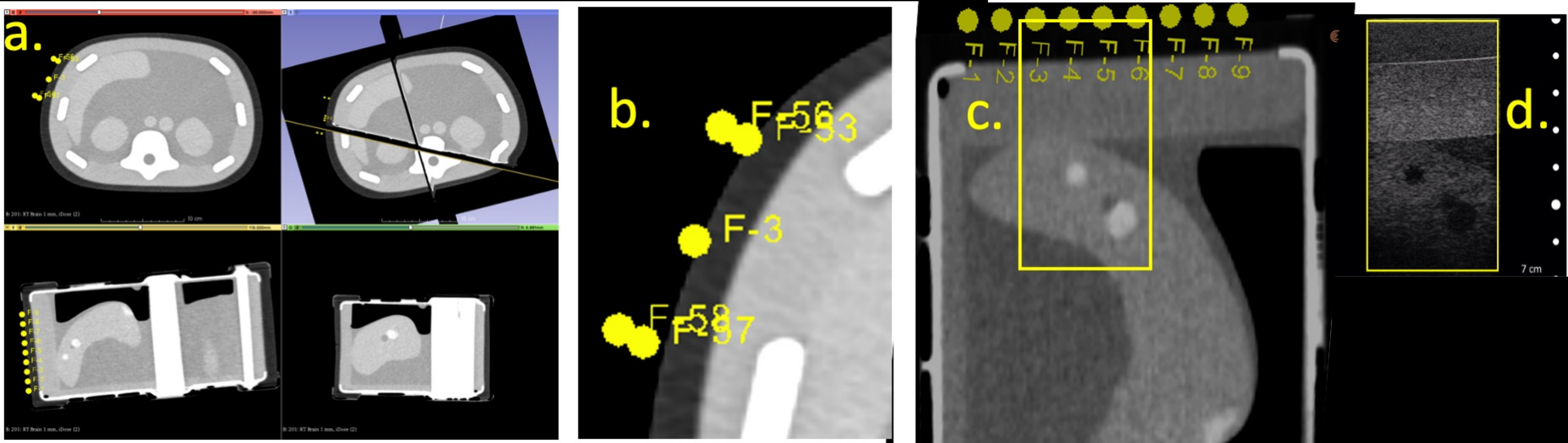
Pinpoint Receiver Locations

by manual co-reg in 3D Slicer

Multiplanar reformat by tipping coronal to match ultrasound image.

Fiducials placed to mark
- center of ultrasound array (F3)
- centers of thermoacoustic receivers (F53, F56)



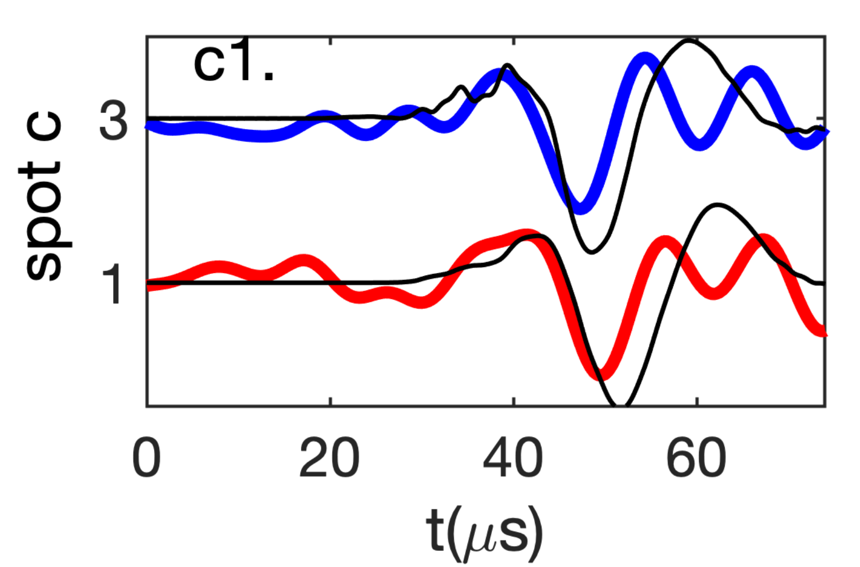


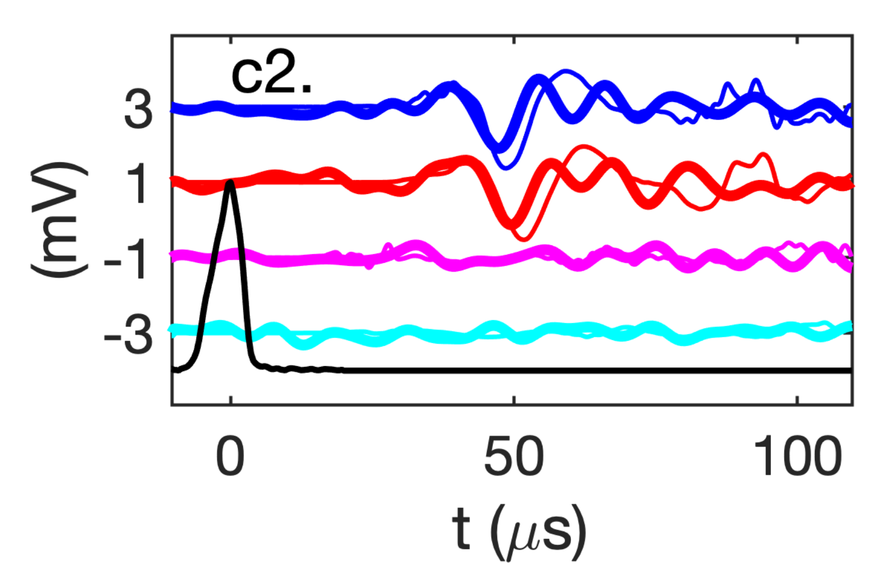
Thermoacoustic Simulations – combines Monte Carlo energy density maps w/acoustic software

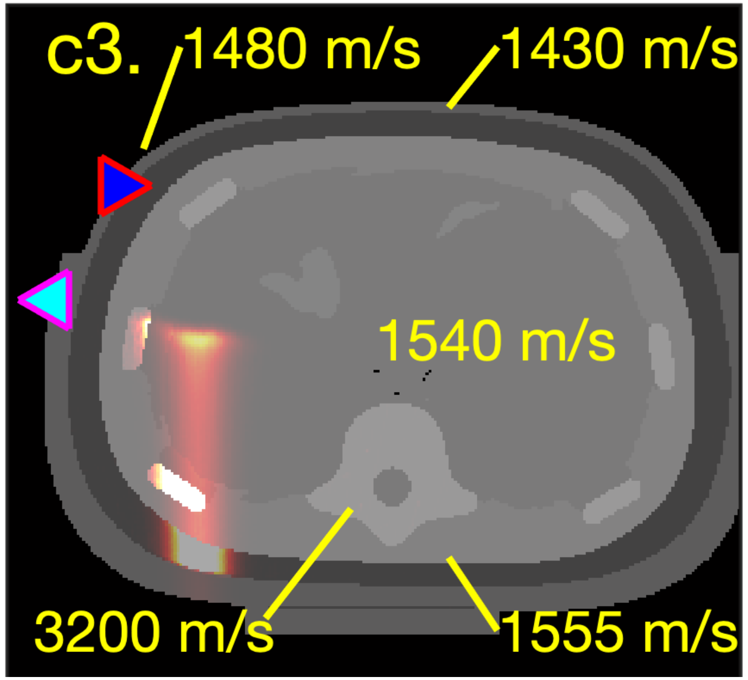
Monte Carlo by MC2 package in OpenReggui
- inputs: planning CT, RT plan, CT and beam calibrations (M Cohilis)
- model energy density actually delivered by using system log files
- accounted for range shifter (K Souris)

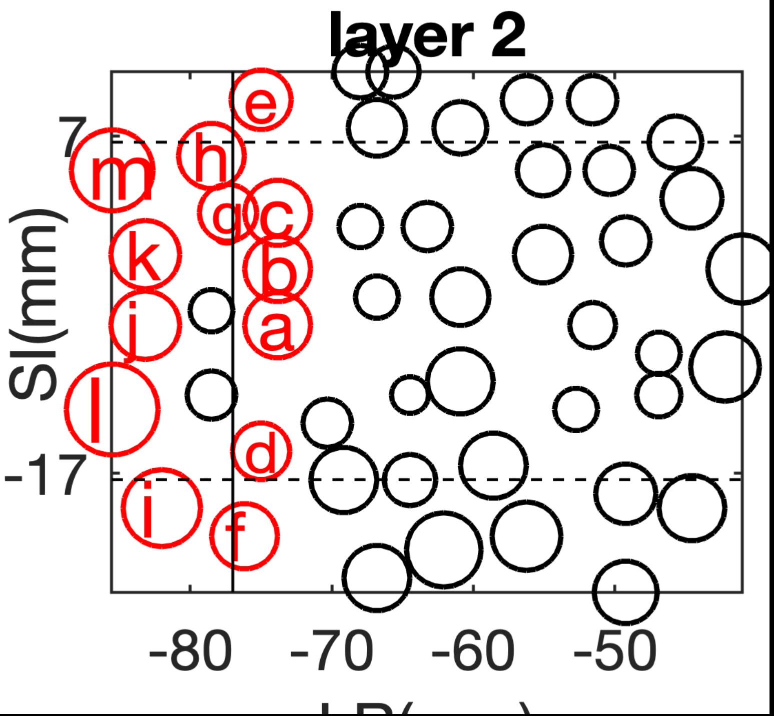
k-Wave acoustic software (key features)
- custom script takes inputs: RT plan, beamlet energy maps, planning CT, HU ranges for tissue types, receiver locations, tissue properties (soundspeed, density, Grüneisen), *planning MRI & US should be used also*
- accounts for proton pulse envelope, measured by gamma detector
- segments tissue based upon CT and assigns soundspeed, Grüneisen, and density
- records thermoacoustic signals at receiver locations, can make movie

2nd layer results. 148.5 MeV –
measured in thick, simulated thin









Path from Spot A to receivers:
- clear to Rx 1 & 2 (red & blue)
- obstructed to Rx 3 & 4 (cyan & magenta)

Notes for Ch 1-2 signals:
- simulated is zero until arrival of “N” from Bragg Pk

Table 2. Time shifts between measured and simulated data in abdominal phantom.

layer	spot	#pul	LR (mm)	p_0 (Pa)	δx (mm)
2	A	23.0	-74	5.0	-1.0
	B	23.0	-74	5.1	-0.4
	C	23.0	-74	5.0	-0.3
	D	20.0	-75	10.1	-0.2
	E	21.0	-75	8.5	1.2
	F	23.0	-76	10.3	-0.2

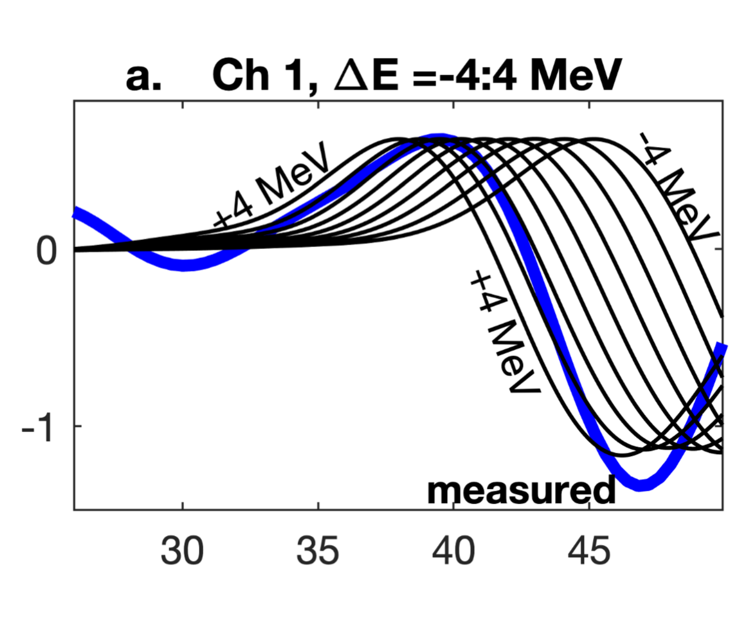
-0.2 ± 0.7 *mm*

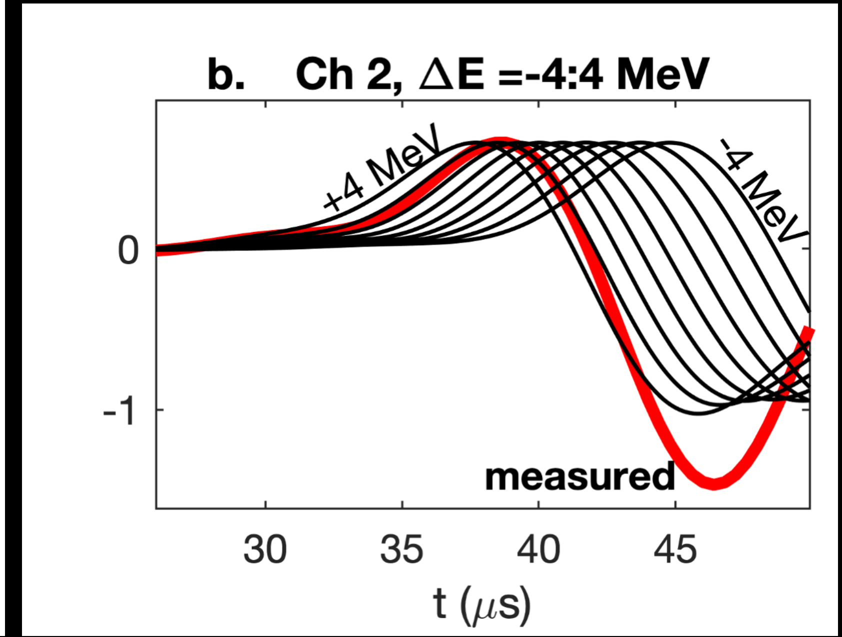
$\sigma = 0.7$ *mm* < 1.19 *mm*

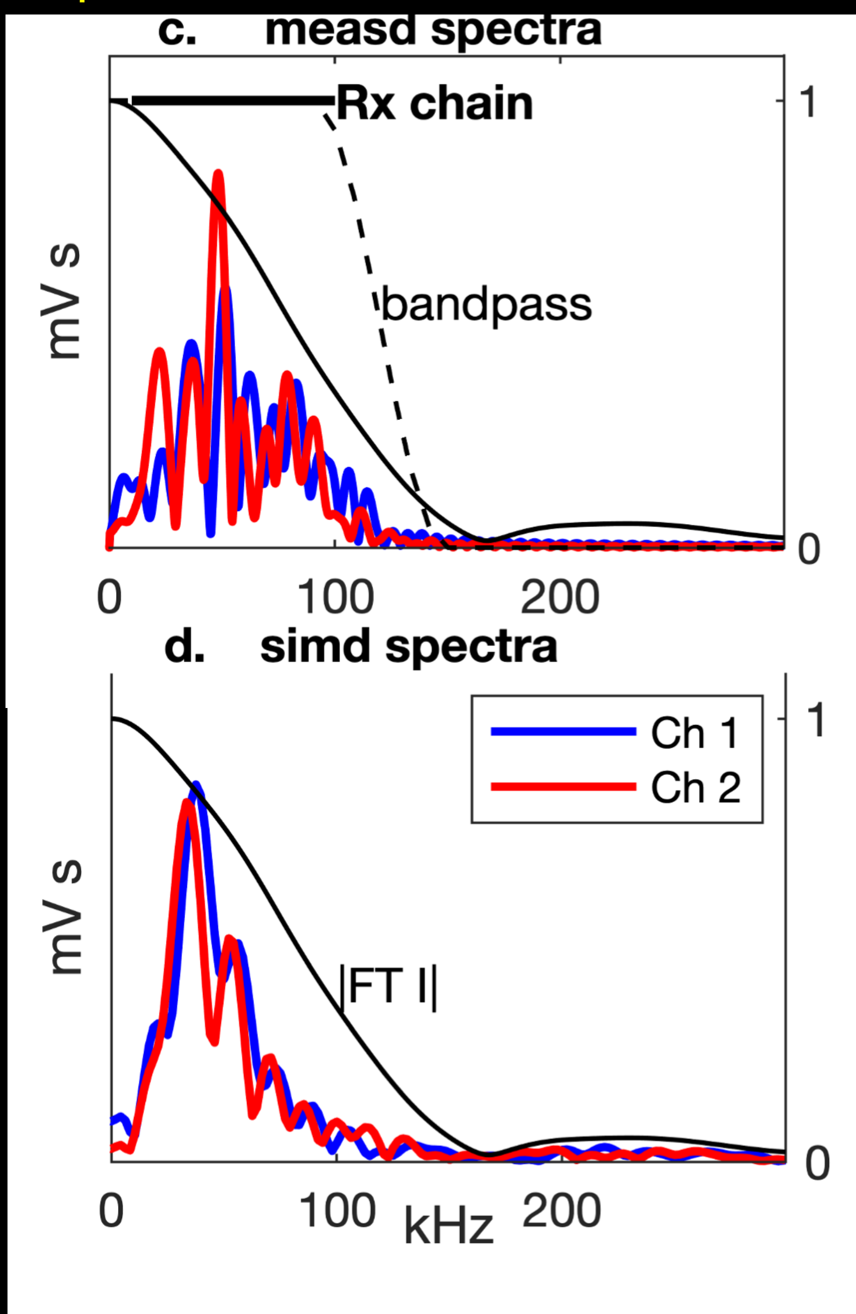
Radiother & Oncol 2021

simplified "2-step" method

Med Phys 2018

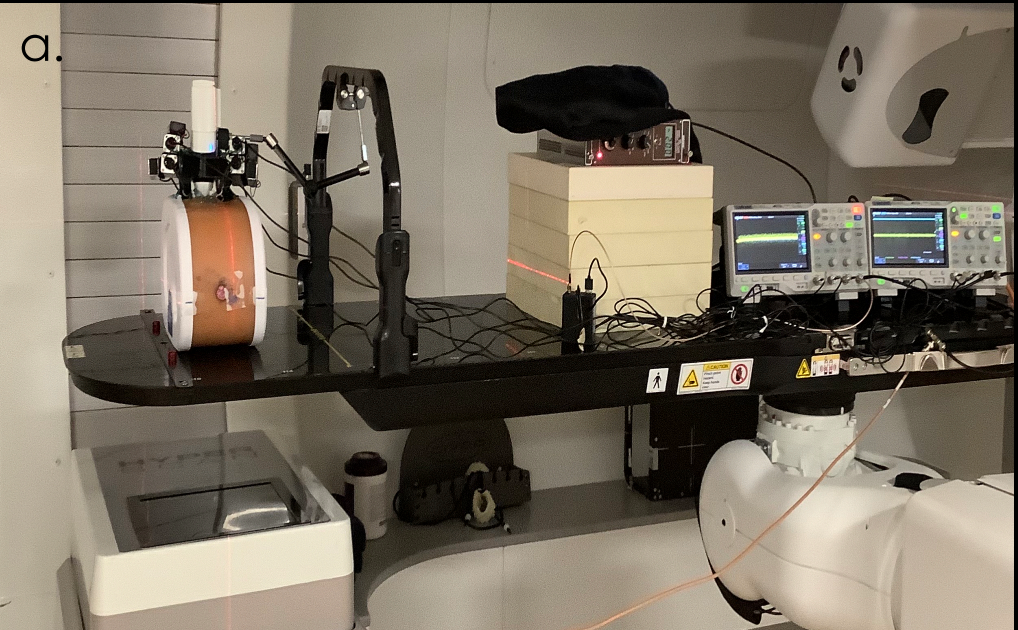


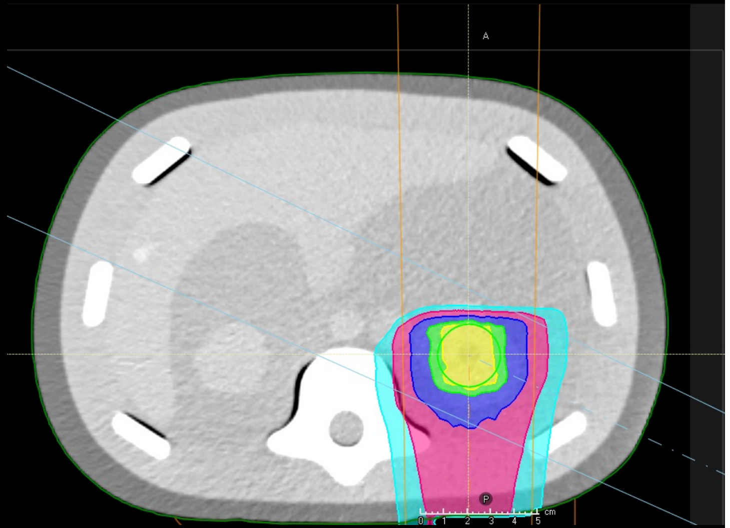


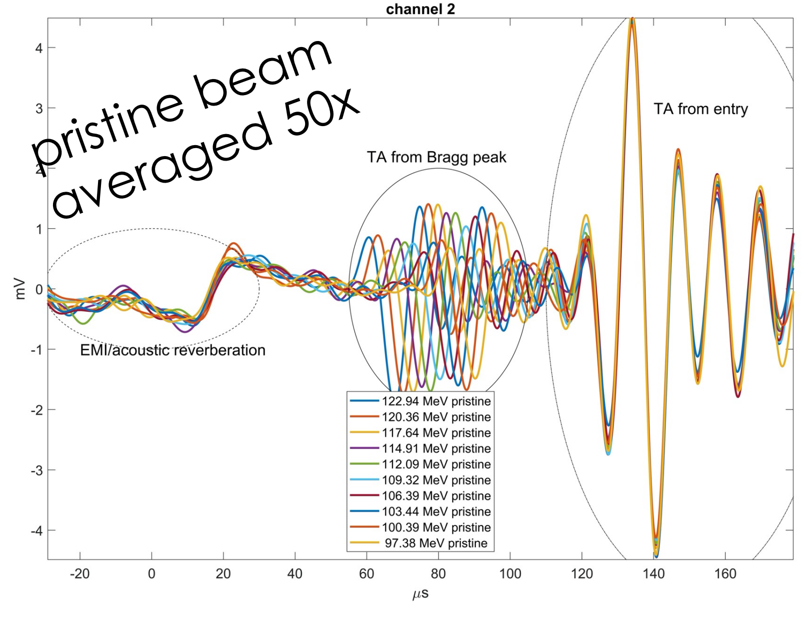


High dose rate therapy may enable pulse-by-pulse verification

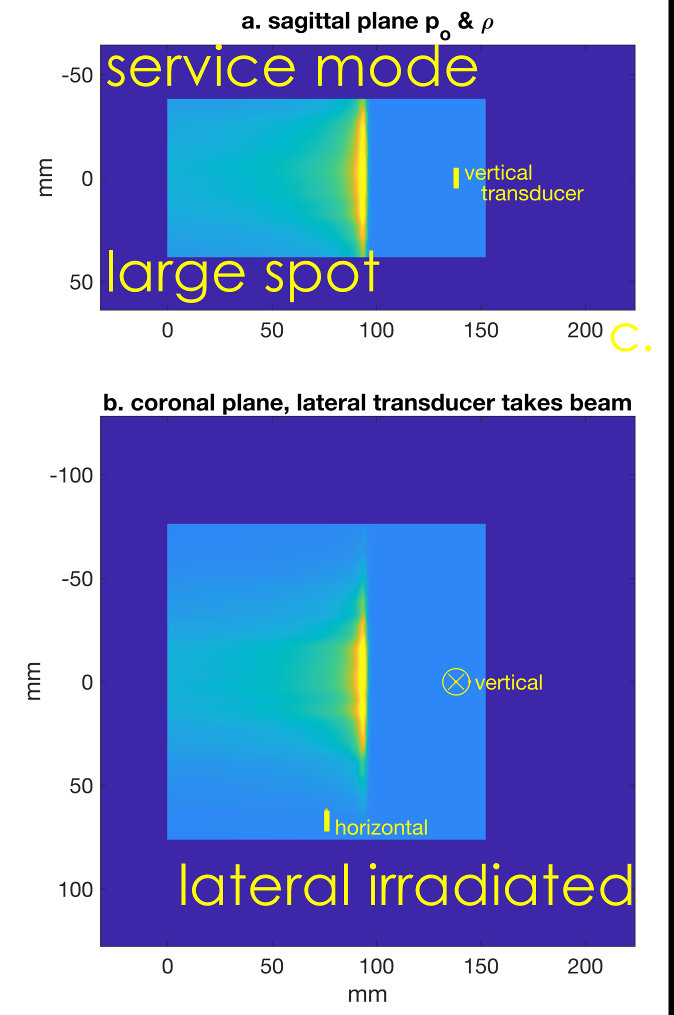
ion	E (MeV)	PW (us)	q/pulse (pC)	# pulses	target	accuracy (mm)	notes
p	148-156	4-5	O(1)	20-23	CIRS gel	-0.2+/-0.7	*Green J*, **159**, pp. 224-230, (2021). S2C2 synchrocyclotron delivered clinical plan; custom receivers to oscilloscopes
p	97-123	4-5	8	1-50	CIRS gel	WIP	synchrocyclotron @ WUSTL, custom ARE to oscilloscopes *limited Monte Carlo capability to quantify accuracy*
	99-122		15-20	1	Lexan	WIP	
	194.5		15-20	1	water	WIP	wireless data acquisition, 500 ksps only

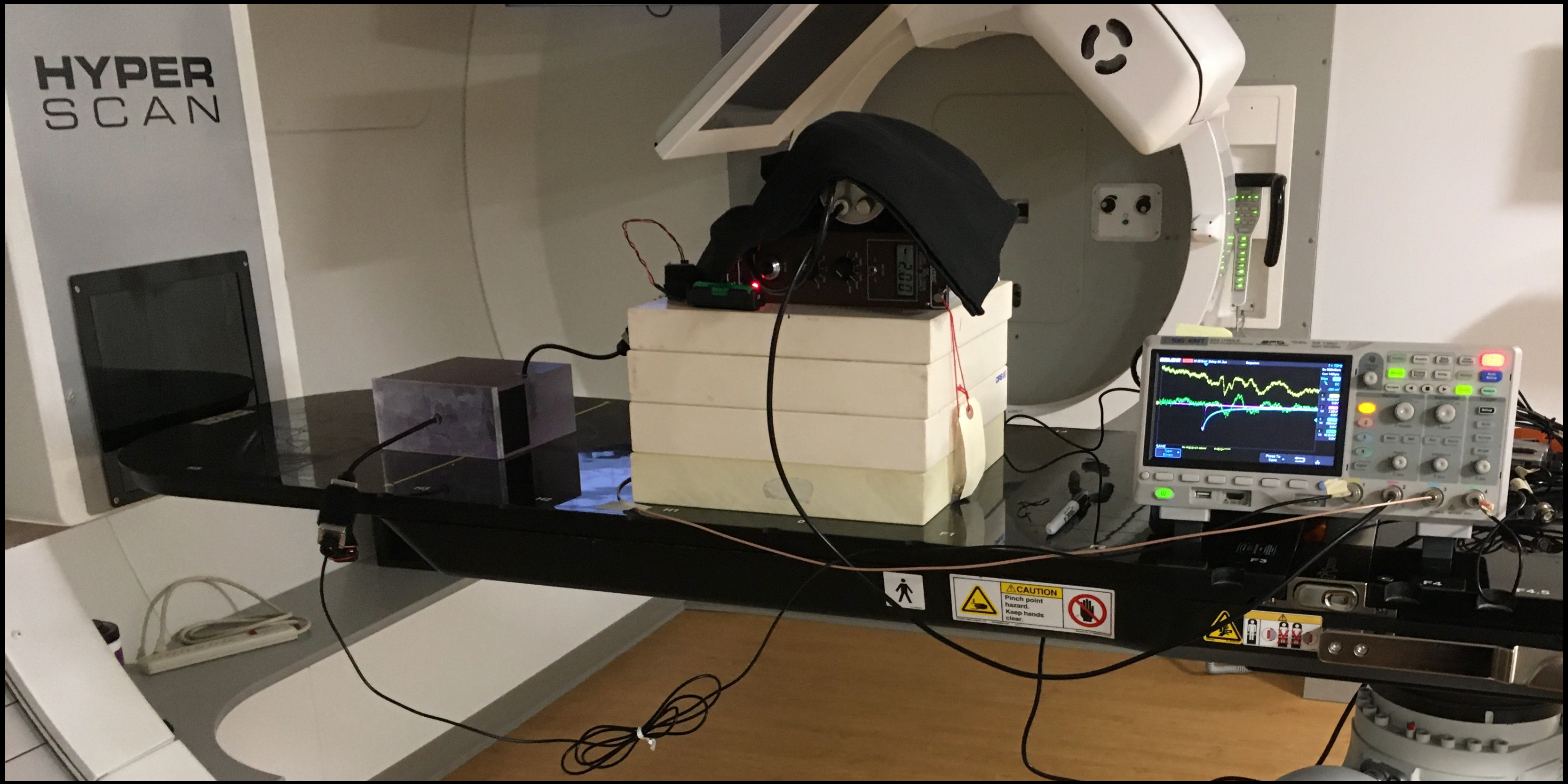






CONFORMAL & HIGH DOSE RATE (15-20 pC/pulse)

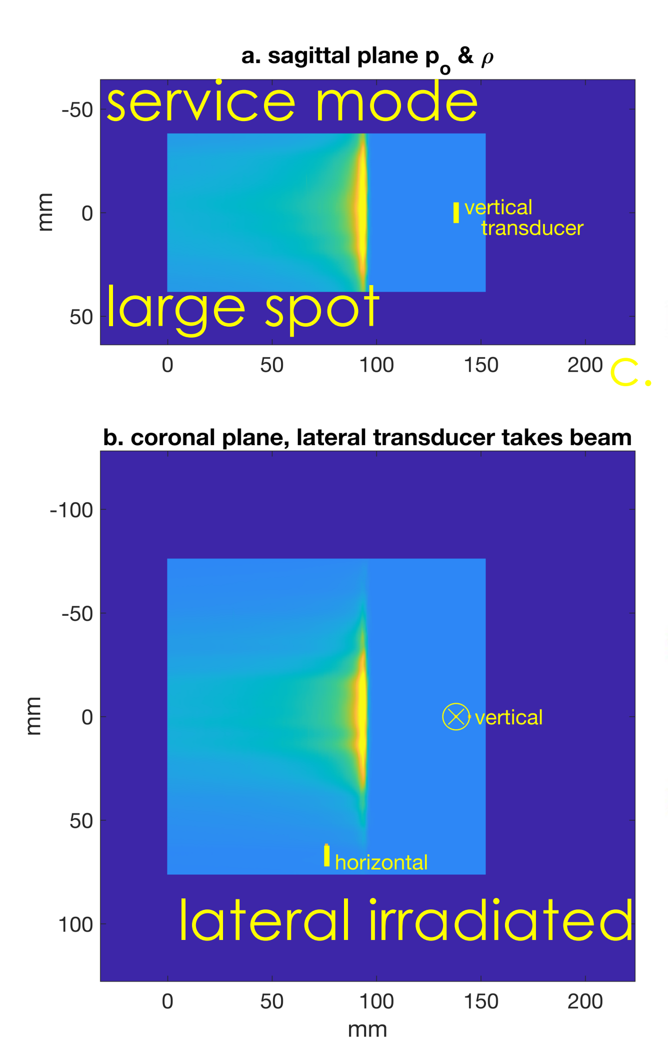


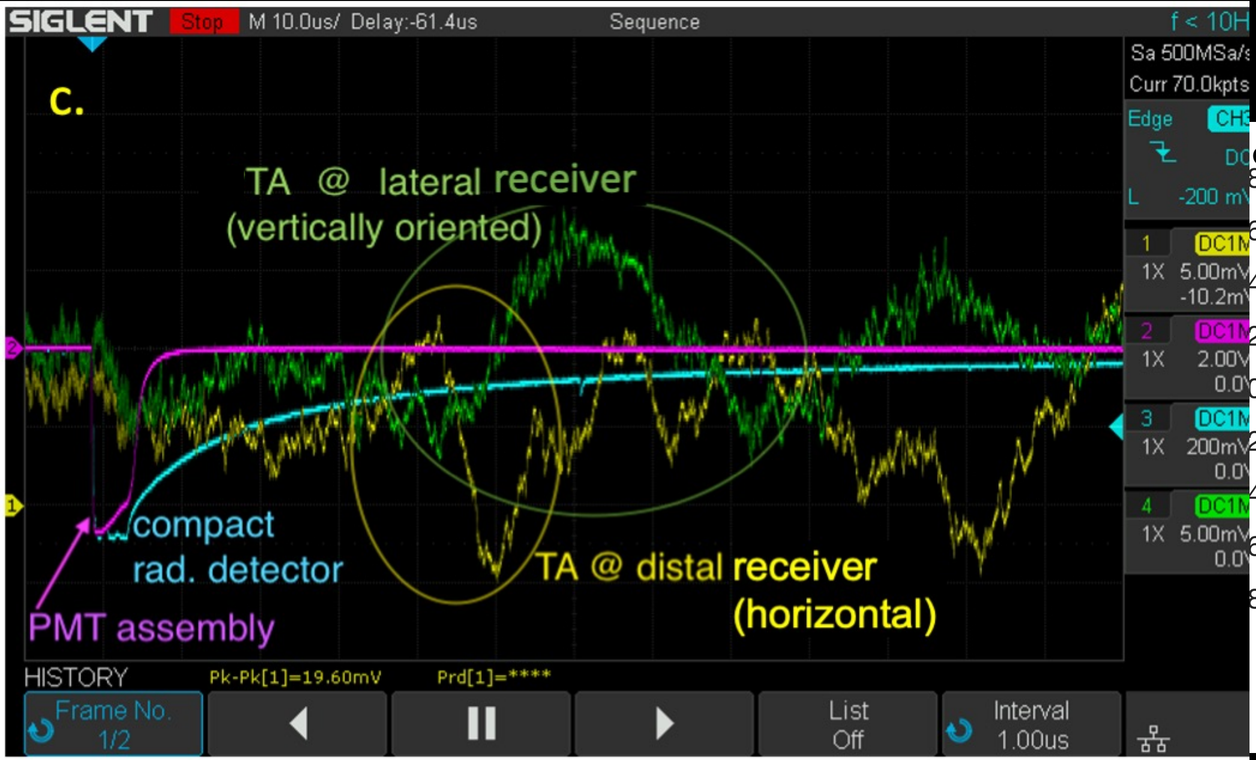


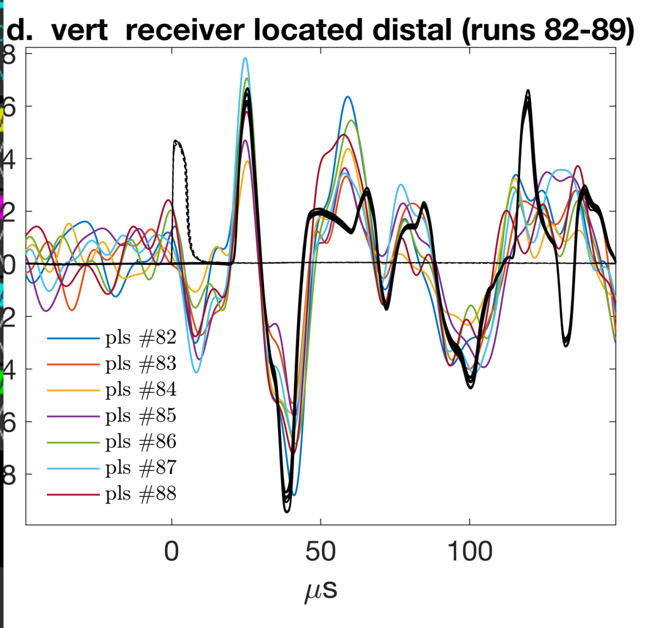
CONFORMAL & HIGH DOSE RATE (15-20 pC/pulse)

color ~ measured
black ~ simulations

assume
- constant charge/pulse
- 2035 m/s soundspeed







CONCLUSIONS

1. Obey stress confinement – clinical synchrocyclotrons great

2. *Quantifying* dose difficult due to
   i. limited angle data (experimental constraint)
   ii. unknown tissue parameter, Γ (*fundamental* constraint)

3. Can pinpoint the Bragg peak, which could perhaps
   - better inform adaptive planning
   - provide confidence for hypofractionation

4. Based upon current hardware,
   - averaging required for conventional dose rates
   - single shot may be sufficient for high dose rates
     safety interlock - should be possible to halt within 1 pulse

Funding: NIH-NCI SBIR Award #R44CA243764