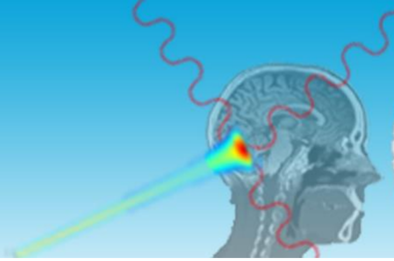
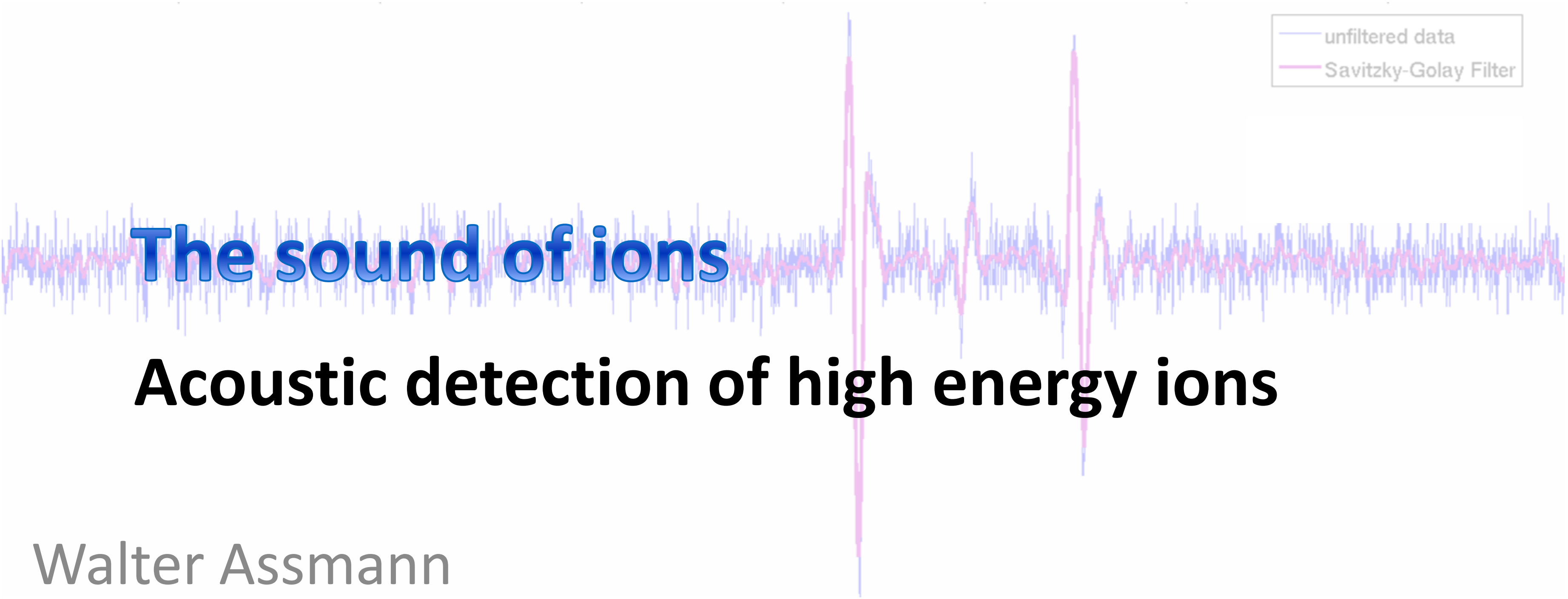




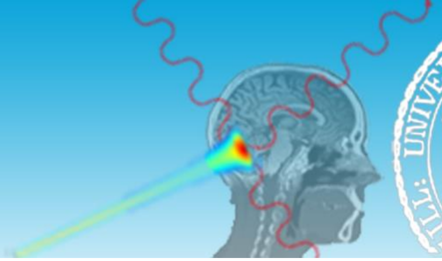
The sound of ions

Acoustic detection of high energy ions

Walter Assmann

Faculty of Physics – Department of Medical Physics,

Ludwig-Maximilians-Universität München, Germany



Old idea …

EXPERIMENTAL STUDIES OF THE ACOUSTIC SIGNATURE OF PROTON BEAMS TRAVERSING FLUID MEDIA*

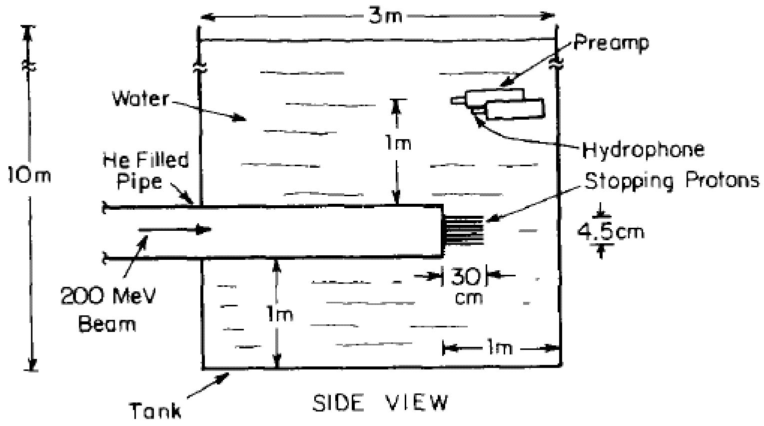
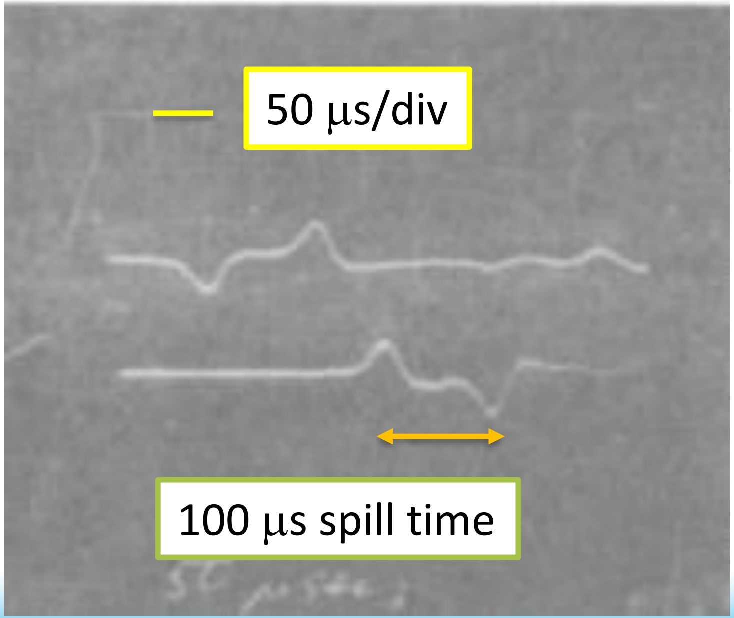


Fig. 3. Detector arrangement for the linac experiment.

6. Conclusions

We have demonstrated that an observable acoustic signal is produced in a single transducer by charged particle depositions $\gtrsim 10^{14}$ eV in fluid media. The source of the signal is dominantly thermal expansion. Applications to beam monitoring, heavy ion experiments, high energy physics and cosmic ray physics are foreseeable.

Sulak et al, NIM 161 (1979), 203-217
see also:
G.A. Askariyan et al, NIM 164 (1979), 267-278



Thermo/Ionoacoustics

Stopping of ions causes **local heating** and **pressure wave**

$$\frac{dV}{V} = -\kappa dp + \beta dT$$

$$p = \frac{\beta}{\kappa \rho C_V} D \quad *$$

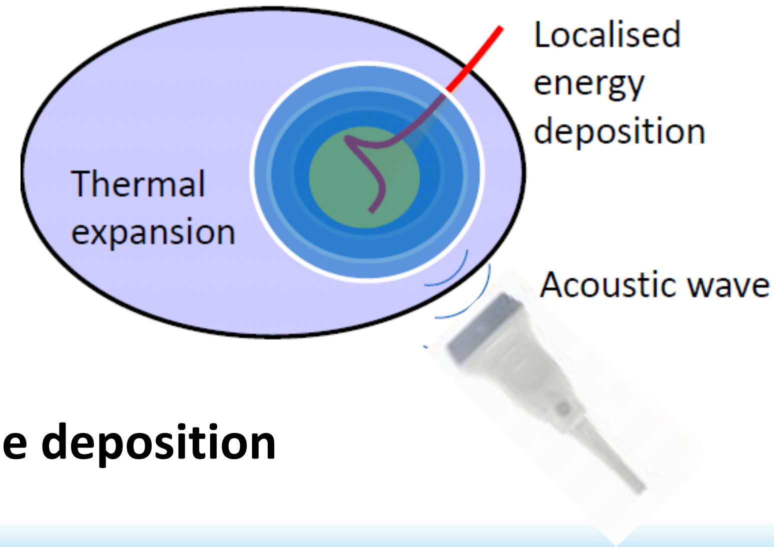
κ isothermal compression
β volume expansion coefficient
D deposited ion dose
* in thermal and stress confinement

thermal confinement:

$t_{\text{ion pulse}} < t_{\text{therm diffusion}}$ (typically < ms)

stress confinement:

$t_{\text{ion pulse}} < t_{\text{stress propagation}}$ ($v_s \sim 1.5$ mm/µs)



→ **p maximal for adiabatic and isochoric dose deposition**
(limits ion pulse length)

Thermo/Ionoacoustics

General thermoacoustic equation :

$$\left(\nabla^2 - \frac{1}{v^2}\frac{\partial^2}{\partial t^2}\right)p(\vec{r},t) = -\frac{\beta}{\kappa {v_s}^2}\frac{\partial^2 T(\vec{r},t)}{\partial t^2}$$

in thermal confinement

$$\rho C_v \frac{\partial T(\vec{r},t)}{\partial t} = H(\vec{r},t)$$

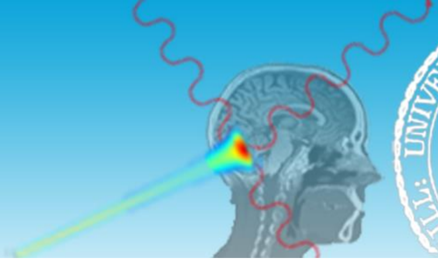
$$\left(\nabla^2 - \frac{1}{v^2}\frac{\partial^2}{\partial t^2}\right)\boxed{p(\vec{r},t)} = -\frac{\beta}{C_p}\boxed{\frac{\partial H(\vec{r},t)}{\partial t}}$$

„Heating function“

$$H(\vec{r},t) = H_s(\vec{r}) \cdot H_t(t)$$ space/time decoupled

Bragg curve

temporal pulse width



Overview

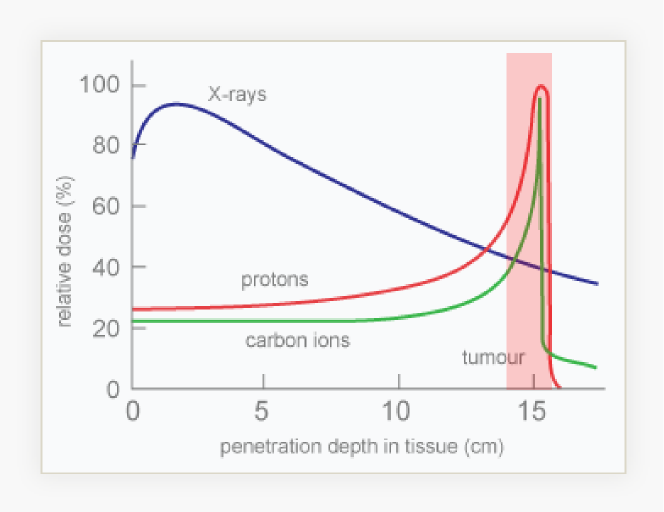
Examples of ionoacoustic applications

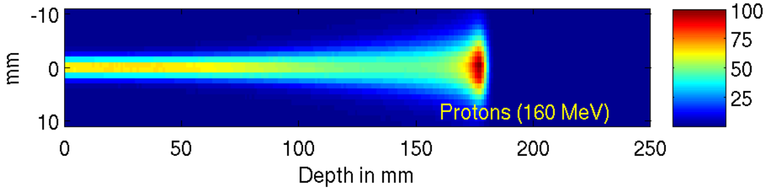
- ***Acoustic ion range determination for particle therapy***
  - proof of principle with 20 MeV protons
  - pre-clinical tests with 230 MeV protons
- ***Acoustic monitor for intense, energetic ion bunches***
  - GeV ions at FAIR/GSI
  - laser accelerated MeV protons

Short introduction to particle therapy

Particle therapy: radiation therapy using ions instead of photons

Dose distribution: photons vs. ions





Advantages of particle therapy:

- ***Finite range*** of ions
- ***Maximum*** dose deposition at end of range (***Bragg Peak, BP***)

→ highly conformal irradiation

- ***Minimum*** dose in healthy tissue

Problem of particle therapy:

- ***Range uncertainty*** of ions

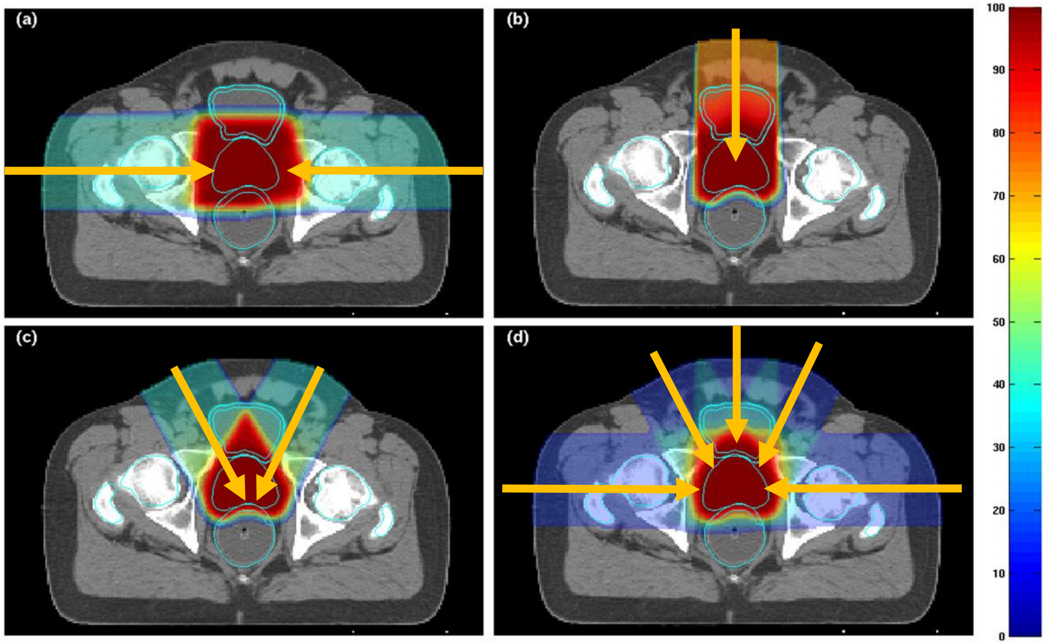
→ missing dose in tumor

→ severe damage in healthy tissue

Wilson, R.R., "Radiological use of fast protons", Radiology 47, 487-91 (1946)

Range uncertainty

Reasons: Calibration errors CT/HU to ion stopping power, CT artefacts, patient and tumor movement, anatomical changes during therapy, positioning error, …



S. Tang et al., Int J Rad Oncol Biol Phys, 83(1), 408 (2012)

Example: *Prostate tumor*

present dose planning

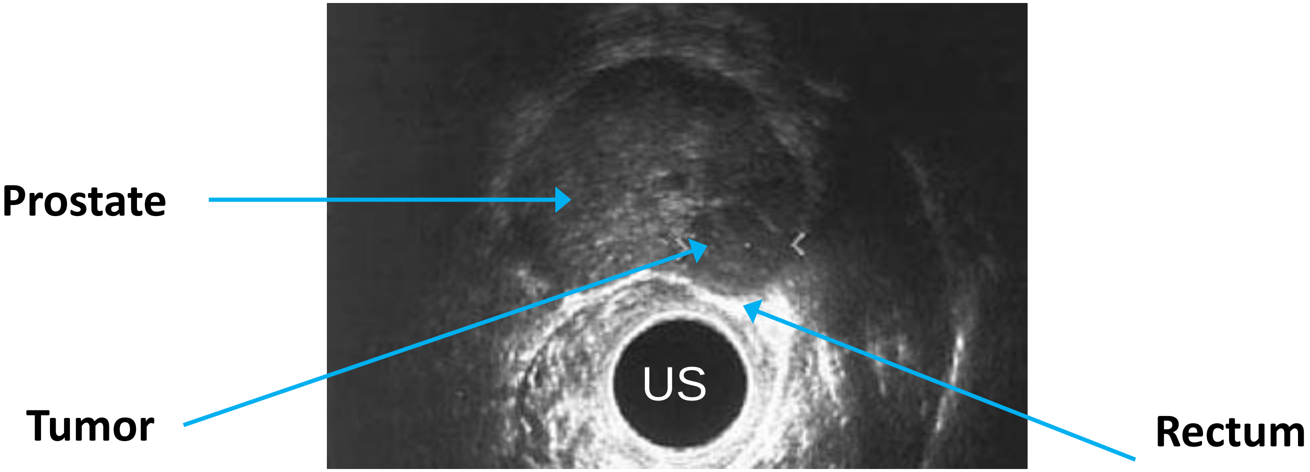
(a) **suboptimal lateral** dose delivery with unnecessary dose deposition in healthy tissue (not better than advanced photon IMRT!)

possible dose delivery

(b-d) **optimal anterior** dose delivery sparing best healthy tissue and organs-at-risk (rectum, bladder), but needs ***in-vivo* range verification** with ≤ 1 mm precision

Grand goal

Co-registration of ultrasound imaging with ionoacoustic Bragg peak signal

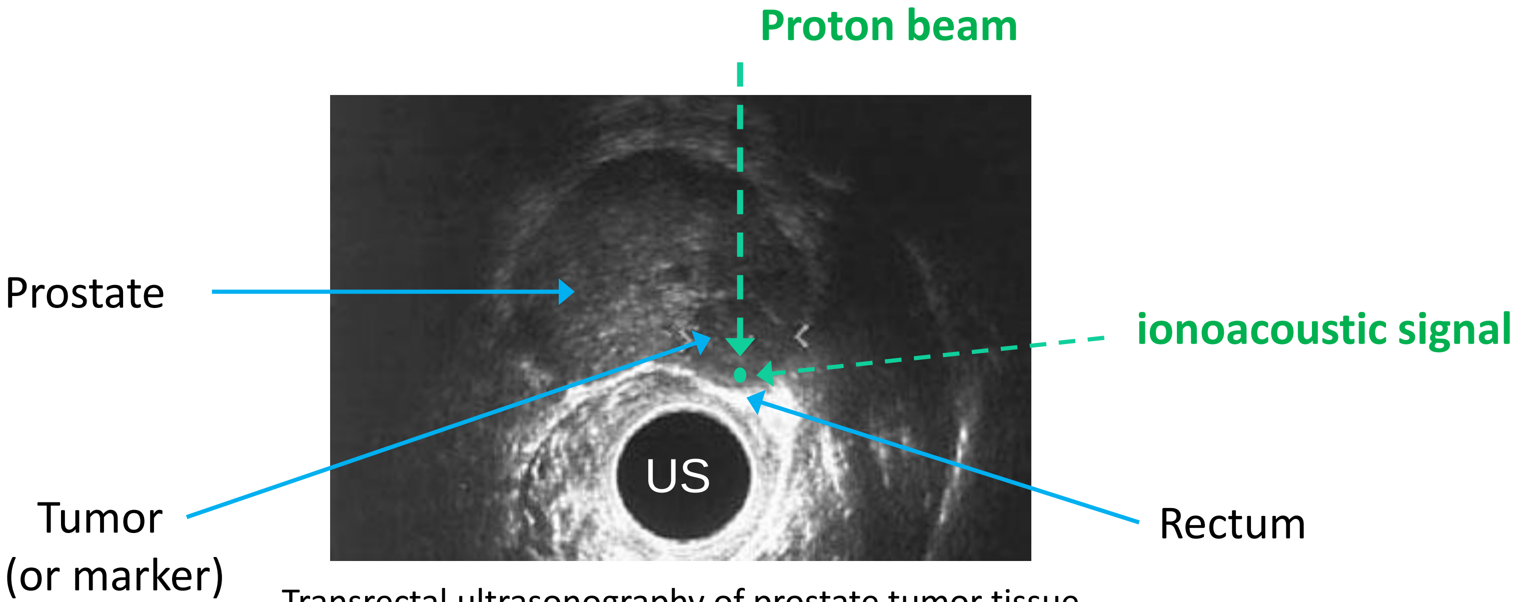


Transrectal ultrasonography of prostate tumor tissue

Range uncertainty!

Grand goal

Co-registration of ultrasound imaging with ionoacoustic Bragg peak signal



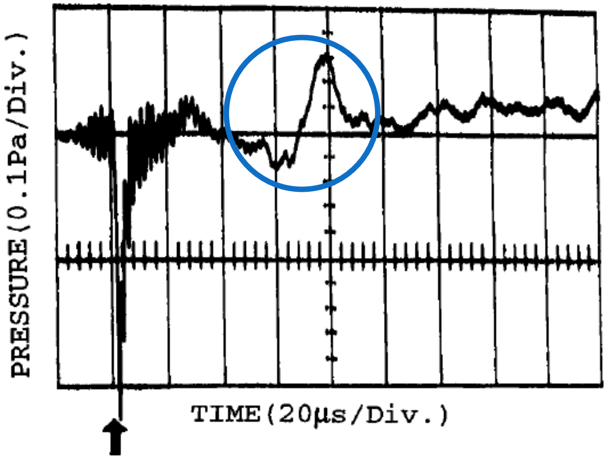
Transrectal ultrasonography of prostate tumor tissue

Both methods use ultrasound: *no tissue inhomogeneity problem,*
only relative distance determination

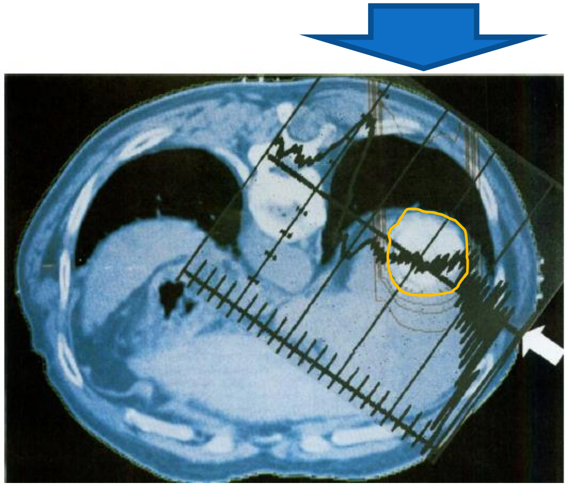
Early attempts

Acoustic Pulse Generated in a Patient During Treatment by Pulsed Proton Radiation Beam

Y. Hayakawa et al, Rad. Onc. Invest., 3, (1995), 42-45



proton beam



Hydrophone

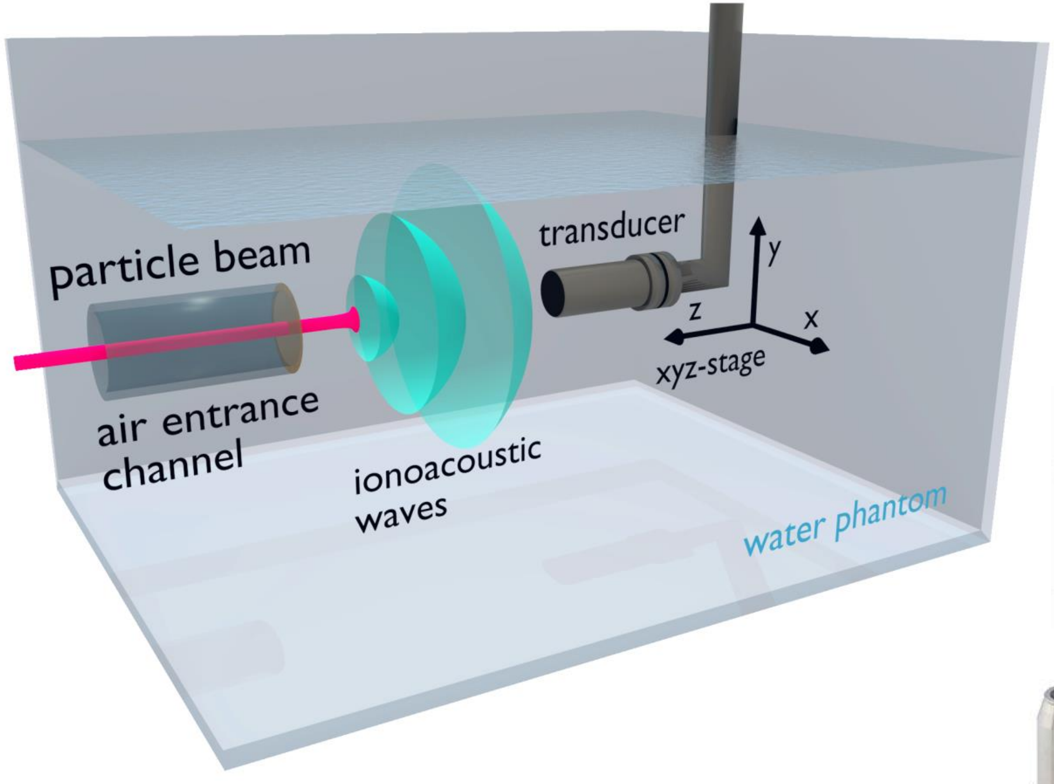
Hepatic cancer treatment

online monitoring of Bragg peak position during irradiation possible?

→ **(weak) US signal successfully detected,** but no progress since then…

@GSI: Köhler, Peiffer (1995) World Congress on Ultrasonics

Ionoacoustic test setup



„Axial geometry“

PZT transducer
(simple and cheap)

OLYMPUS

TRANSDUCER DESCRIPTION

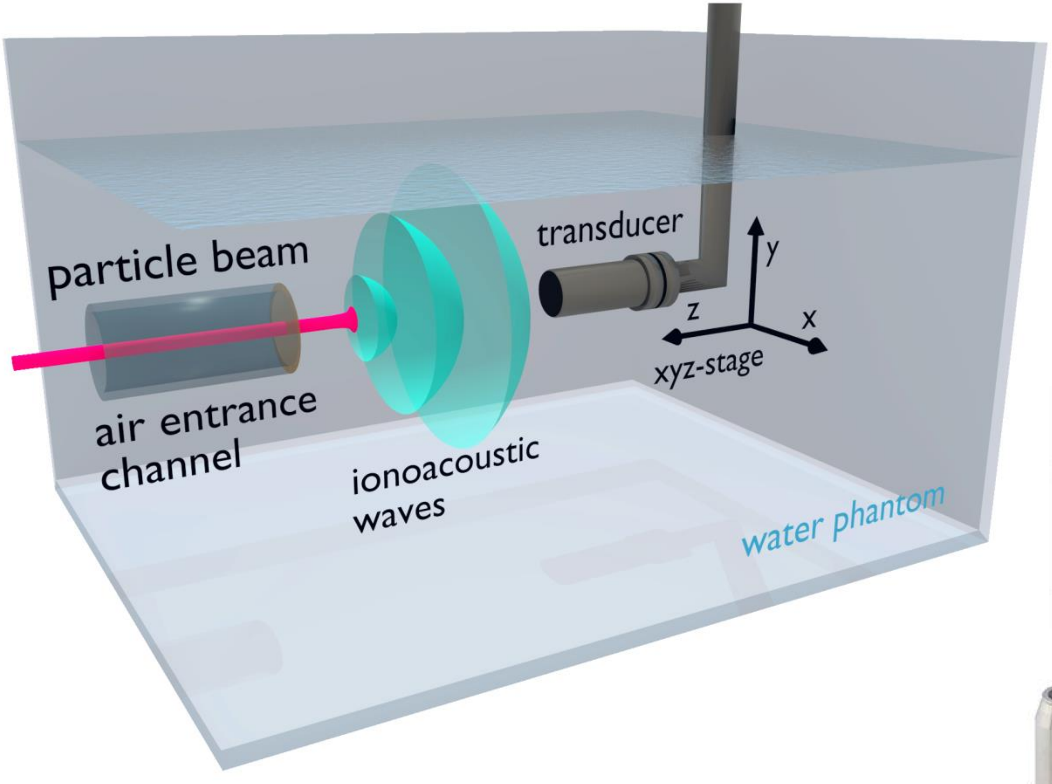
PART NO.: A133S
SERIAL NO.: 262671
DESIGNATION: CONTACT
FREQUENCY: 2.25 MHz
ELEMENT SIZE: .25 in. DIA.

TEST INSTRUMENTATION

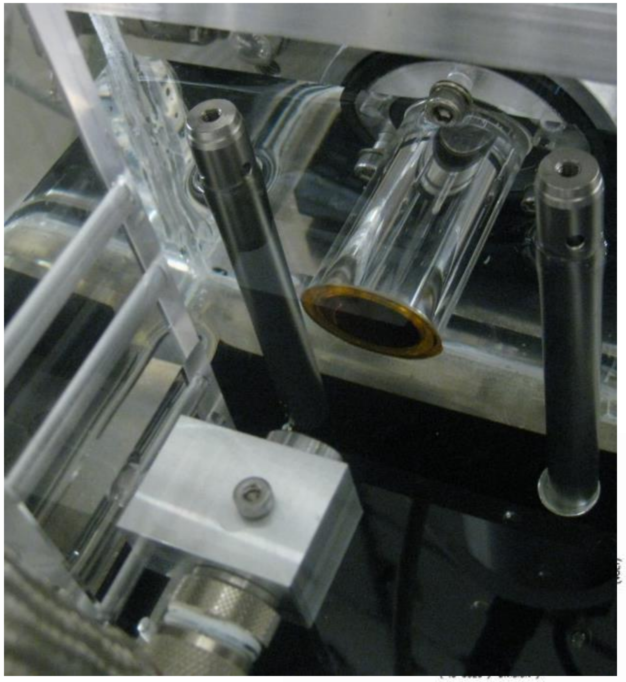
PULSER/RECEIVER: PANAMETRICS 5052 UA #4
DIGITAL OSCILLOSCOPE: LECROY 9400 – V 2.08FT 3E0323
TEST PROGRAM: TP103-1 VER. 102A0E SETUP: DWG. #5979
CABLE: RG-174/U LENGTH: 4 FT.

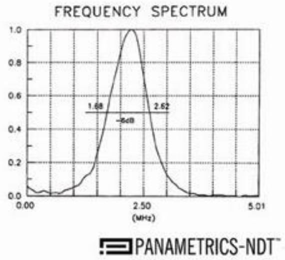
TEST CONDITIONS

Ionoacoustic test setup

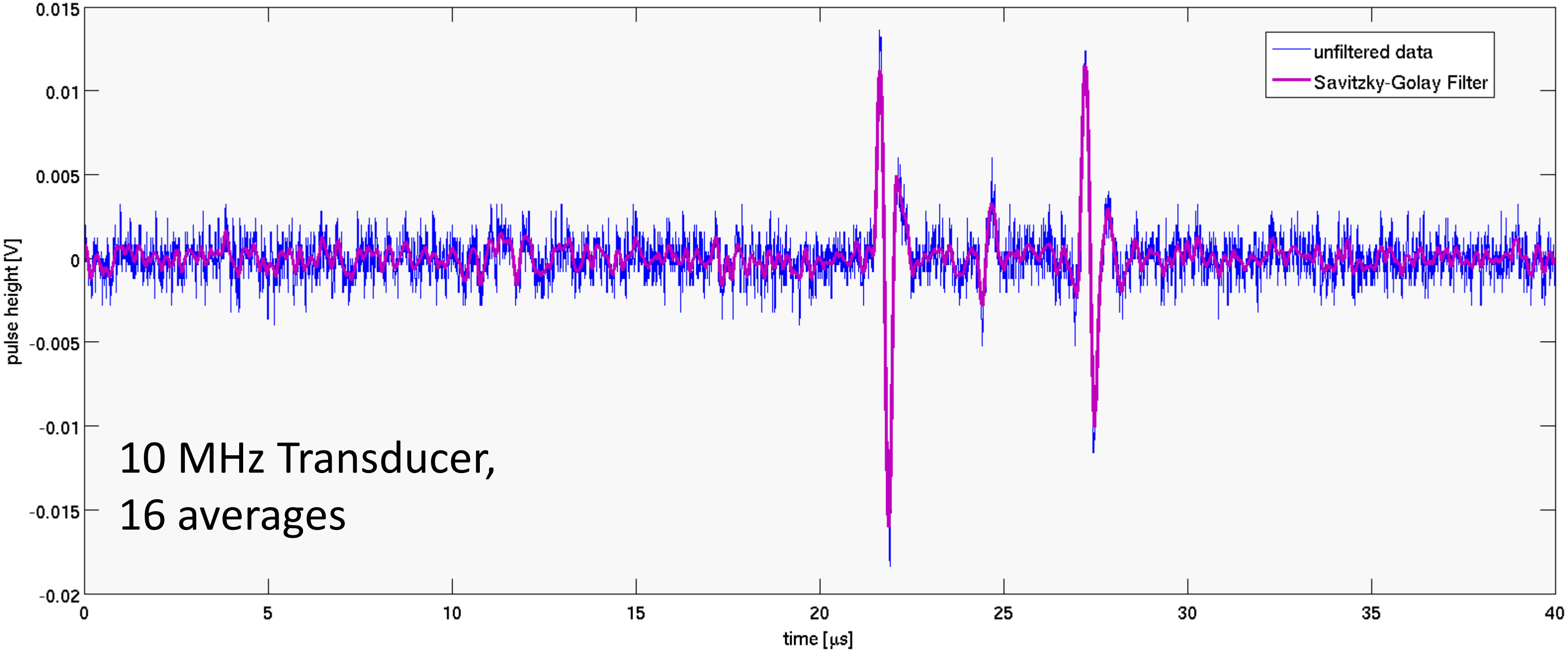


„Axial geometry“





Test with 20 MeV p



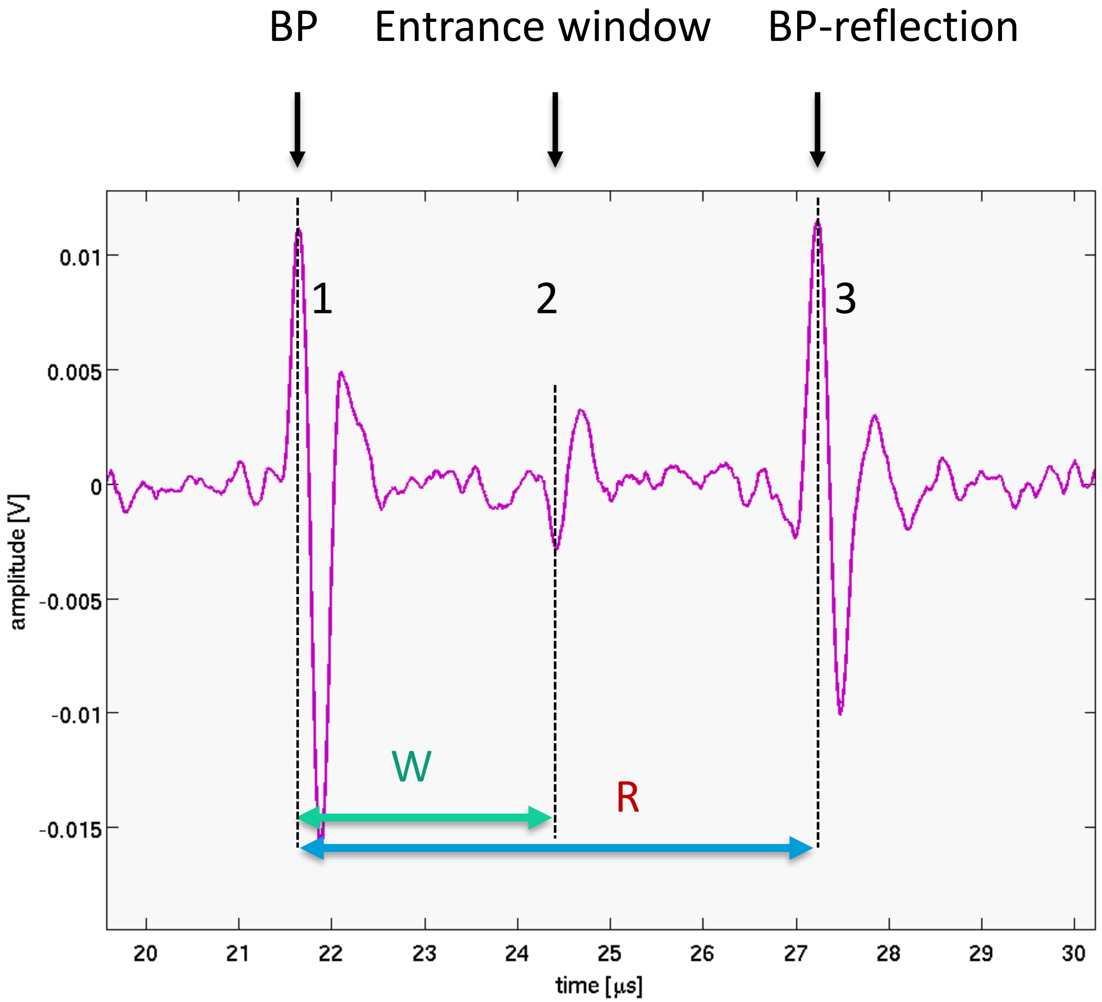
10 MHz Transducer,
16 averages

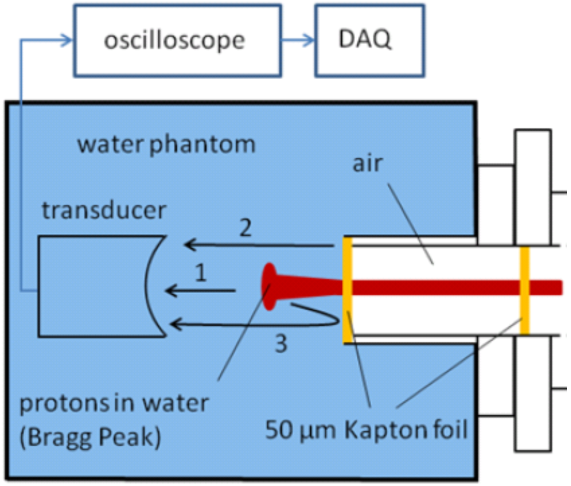
12 MV Tandem, 280 ns pulse width, 63 dB amplifier, ~ 15 mV signal

OoM estimate: $2 \cdot 10^6$ p per pulse → 2 μJ → 0.5 mK → **4 mbar**

→ **weak signal with low signal-to-noise ratio (SNR)**

Ionoacoustic signal





1 Bragg Peak (BP)
2 Entrance window (W)
3 Reflection (R)

Speed of sound:
1520 m/s (H_2O, 35 ^{0}C)
or **1.52 mm/µs**

Range accuracy

Vacuum window	Kapton	Titanium	Titanium
Proton energy [MeV]	**20**	**20**	**21**
Experiment [µm] Bragg peak – window Bragg peak – reflection	 3990 +- 40 4020 +- 20	 4090 +- 40 4060 +- 20	 4490 +- 40 4460 +- 20
Geant4 simulation [µm]	4040 +- 30	4070 +- 30	4450 +- 30
Difference beween simulation and exp [µm]	**-50** **-20**	**+20** **-10**	**+40** **+10**

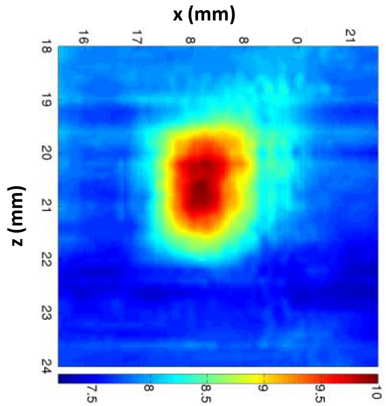
< 1%

Uncertainty of Geant4 simulation: mean excitation energy parameter
best agreement with **I = 78 eV** > confirming ICRU recommendation

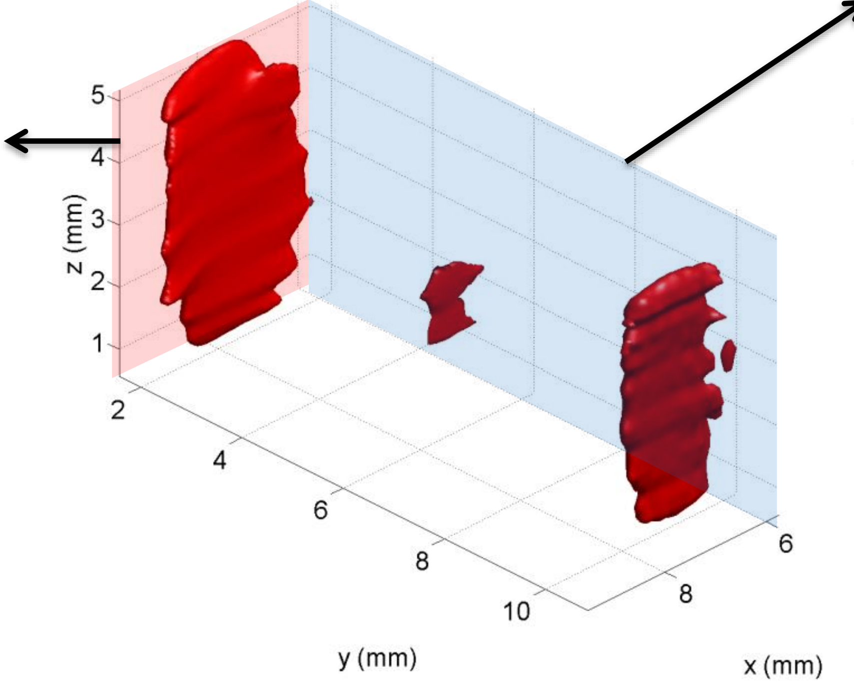
→ **most simple and accurate** method for mm-range determination in water

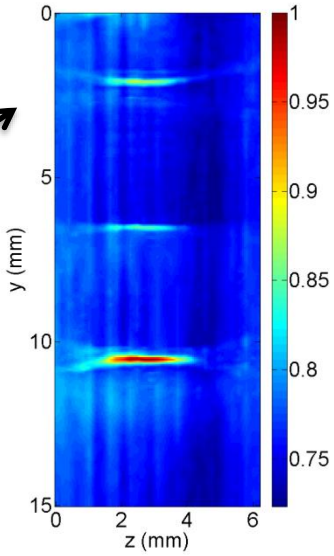
W. Assmann et al. (2015) Med Phys

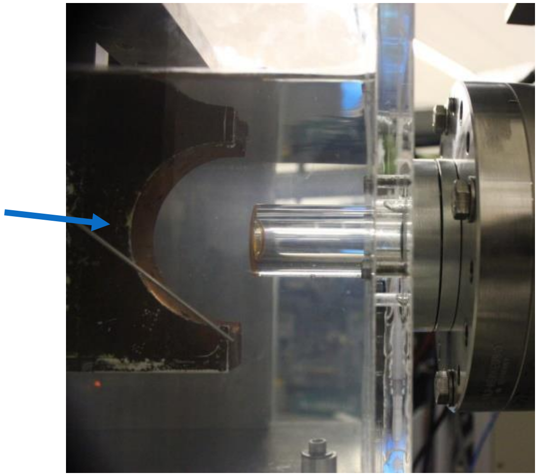
Ionoacoustic tomography



3D → 2D







64-channel transducer-array

3D and 2D image reconstruction

Iono/Optoacoustics with Ultrasound Imaging

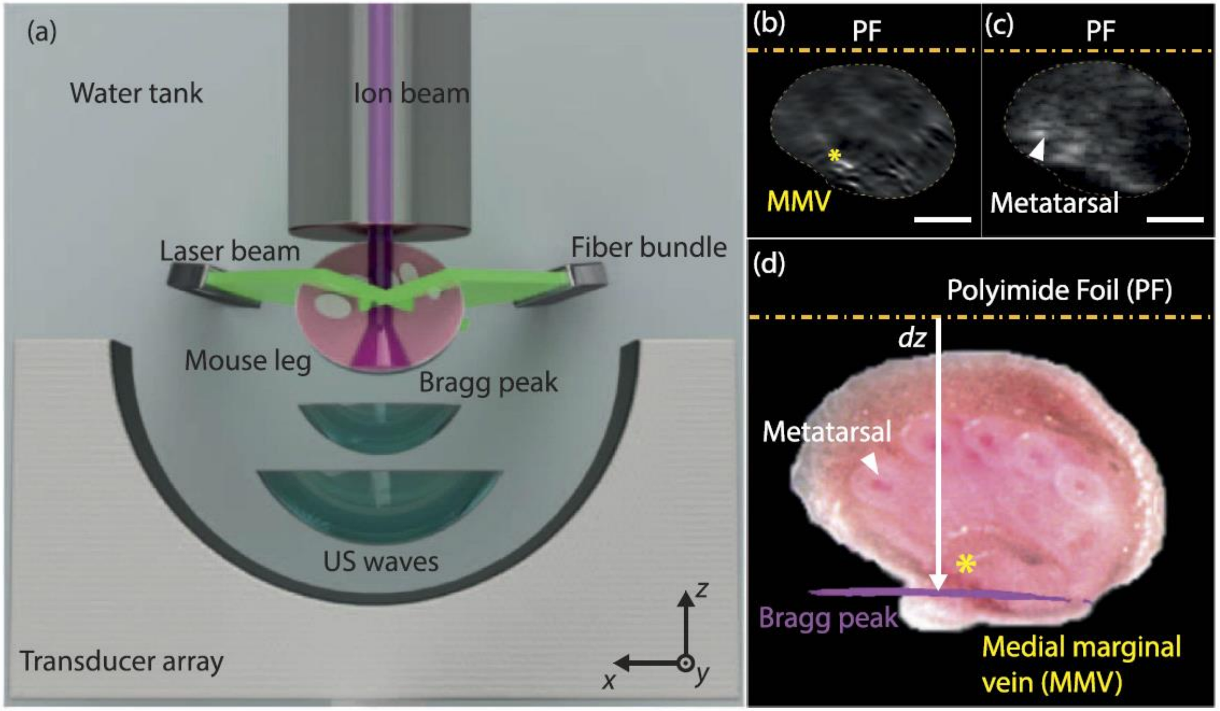
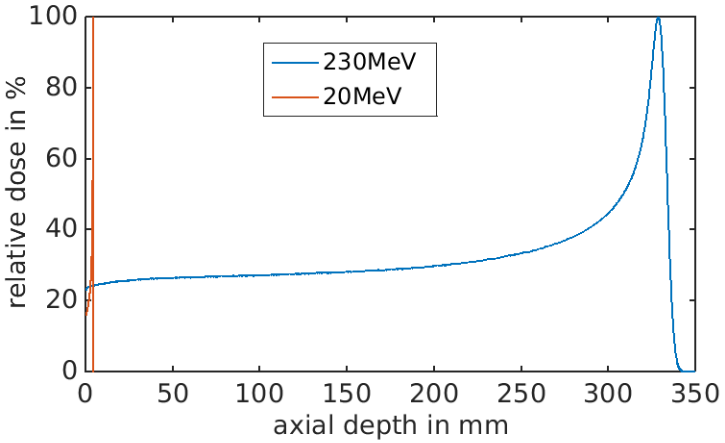


Figure 3. Triple-modality imaging of a mouse leg using optoacoustics, ionoacoustics, and ultrasonography. (**a**) Schematic of the opto- and ionoacoustic experiment. For ultrasonography we replaced the curved array with a linear US-array (picture not shown). (**b**) Optoacoustic reconstruction of a mouse leg positioned in the proton beam line (scale bar represents 2 mm, star marks the medial marginal vein). (**c**) Ultrasonography of the mouse leg, showing metatarsal bones (scale bar represents 2 mm). (**d**) Cryoslice of a mouse leg with the ionoacoustic reconstruction (magenta color) co-registered to the optical image, displaying the Bragg peak at the distal end of the leg with a proton range $dz = 4.7 \pm 0.2$ mm (star marks the medial marginal vein).

S. Kellnberger, W. Assmann et al. Nature Sci. Rep. 6 (2016) 29305

from 20 MeV to 230 MeV

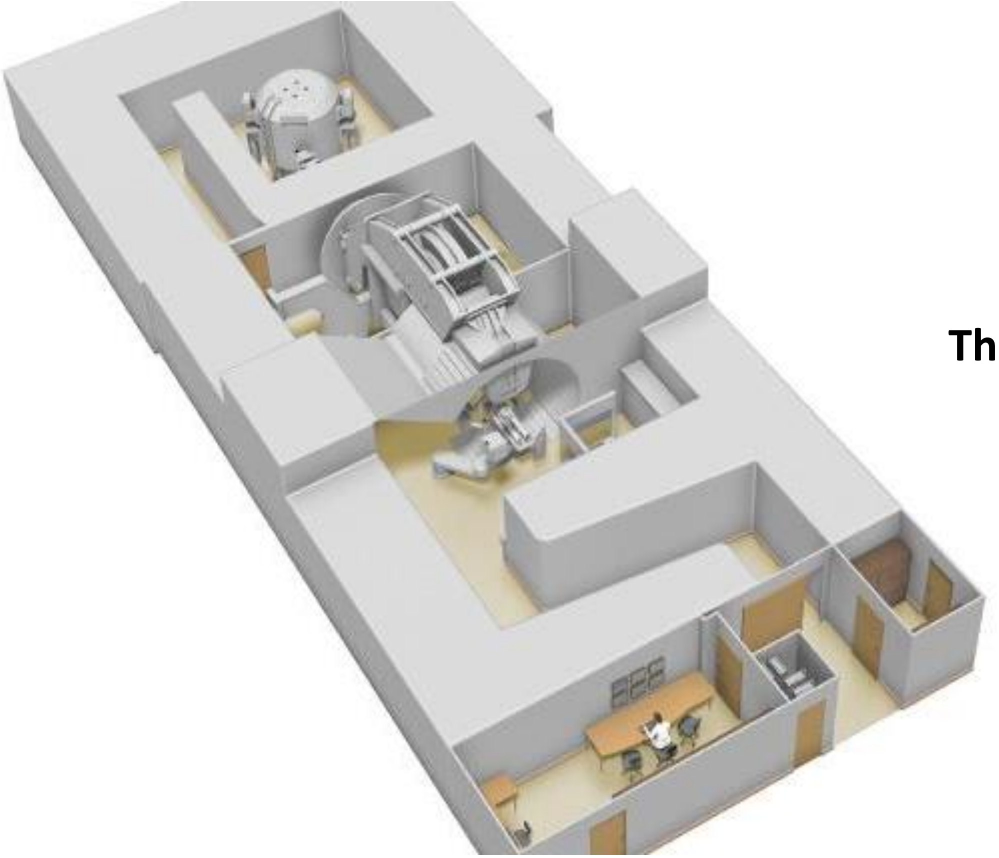


Bragg curve with Geant4 Simulation

- Bragg peak width at 120 – 230 MeV: **5 - 20 mm** (20 MeV: 300 μm)
- stress confinement condition: **5 -15 μsec** (20 MeV: < 200 ns)
- ultrasound frequencies: **10 - 50 kHz** (20 MeV: 2 MHz)
- ionoacoustic pressure (simulation): **μbar** (20 MeV: mbar)

→ **Hydrophone detector, even more averaging, ….**

230 MeV proton therapy unit



Synchro-cyclotron

Gantry

Therapy

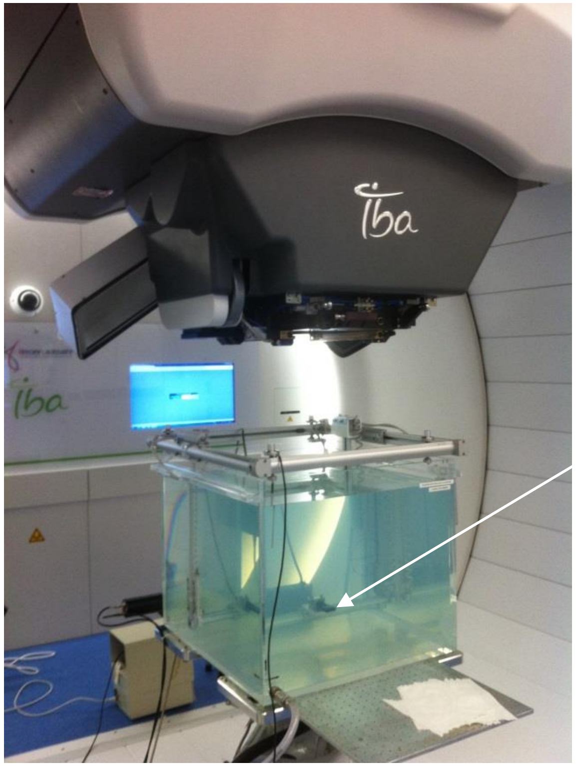
Control

iba

Proteus®ONE

First test at IBA synchrocyclotron

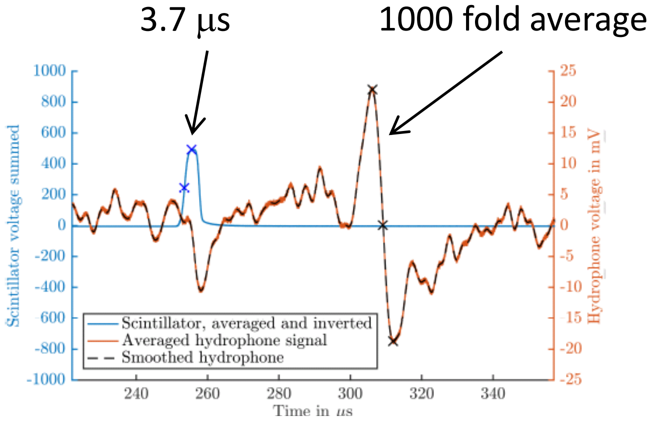
Test experiments with 145 - 227 MeV p

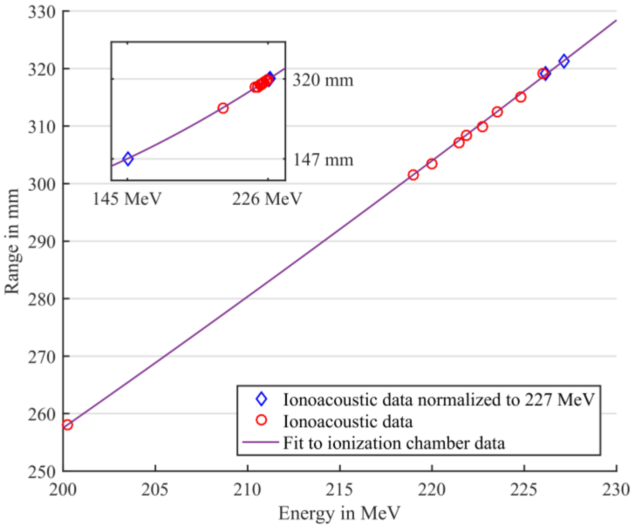


IBA 230 MeV S2C2 @ CAL (Nice)

Submillimeter accuracy & precision
for ≈ 300 mm range

Acoustic pressure
≈ µbar





K. Jones et al. (2015) Med Phys **S. Lehrack et al. (2016) Phys Med Biol Lett** **S. Patch et al. (2016) Phys Med Biol**

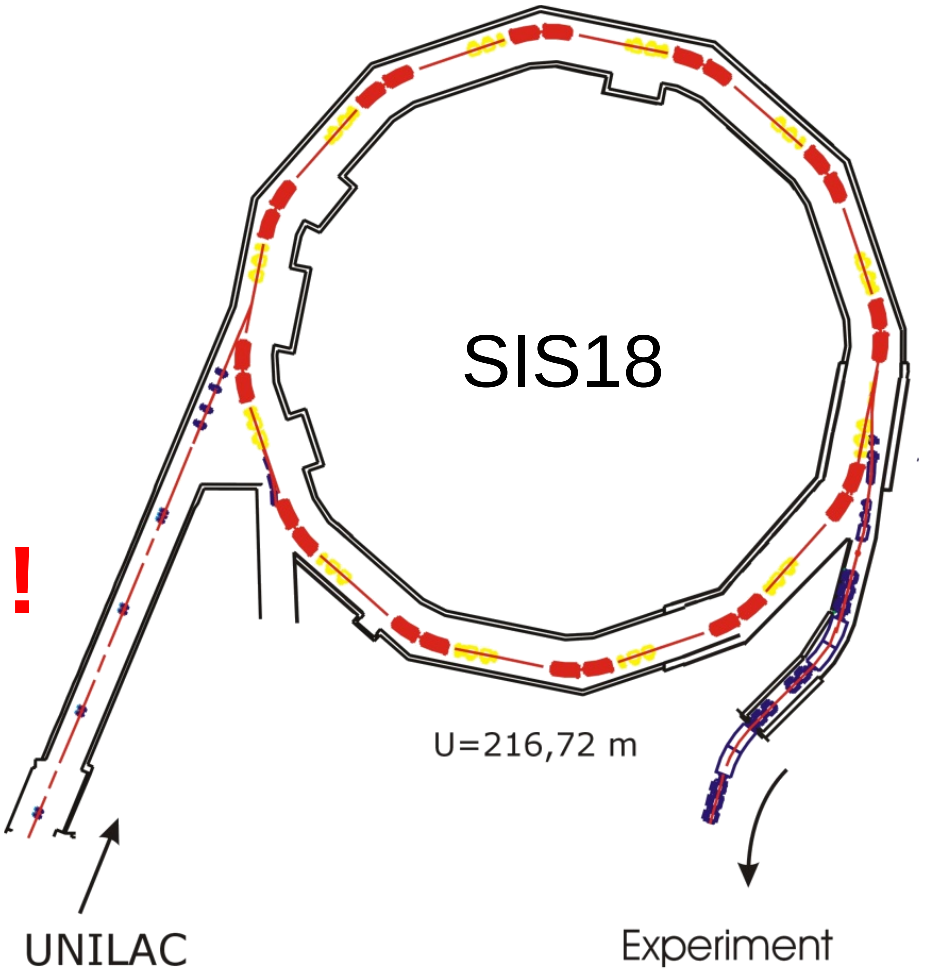
Beam intensity upgrade for FAIR

SIS18 upgrade →

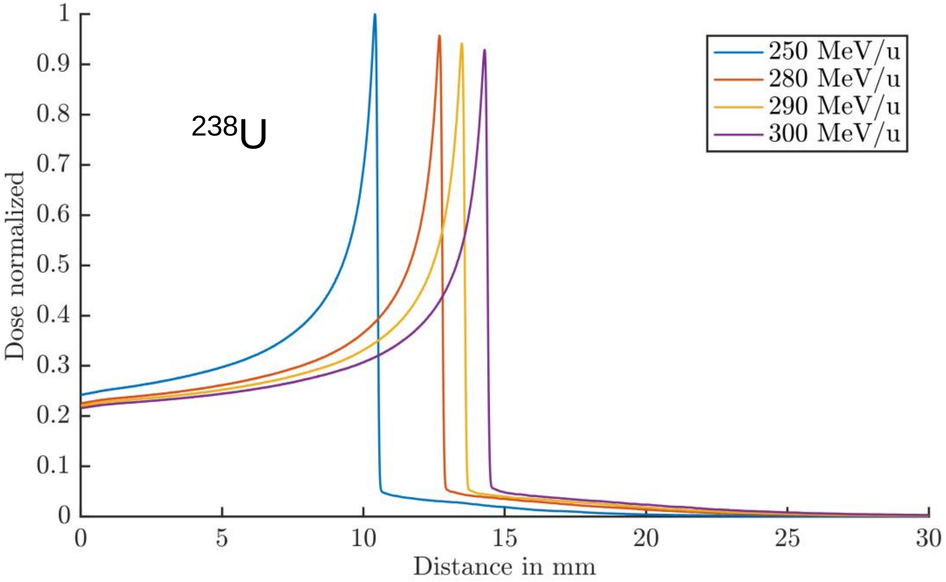
	Today	FAIR Booster
Reference Ion	U^{73+}	U^{28+}
Maximum Energy	1 GeV/u	0.2 GeV/u
Maximum Intensity	4x10^{9}	1.5x10^{11}
Repetition Rate	0.3 - 1 Hz	2.7 Hz

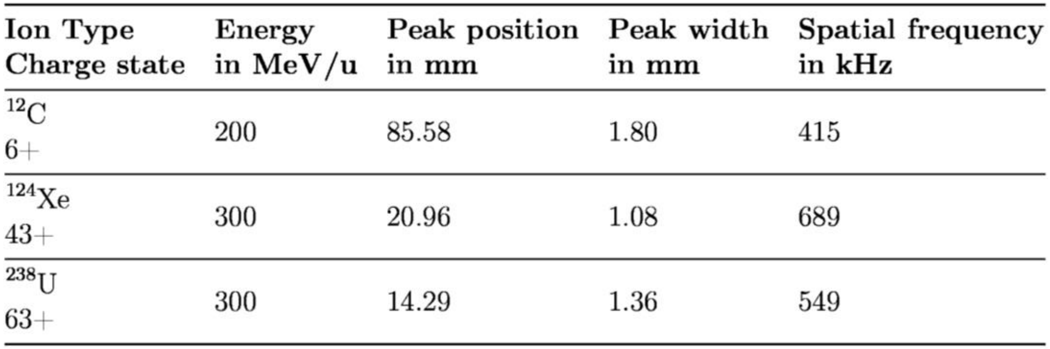
!

→ ***Detector problems***



Geant4 simulation:
Bragg peak in water

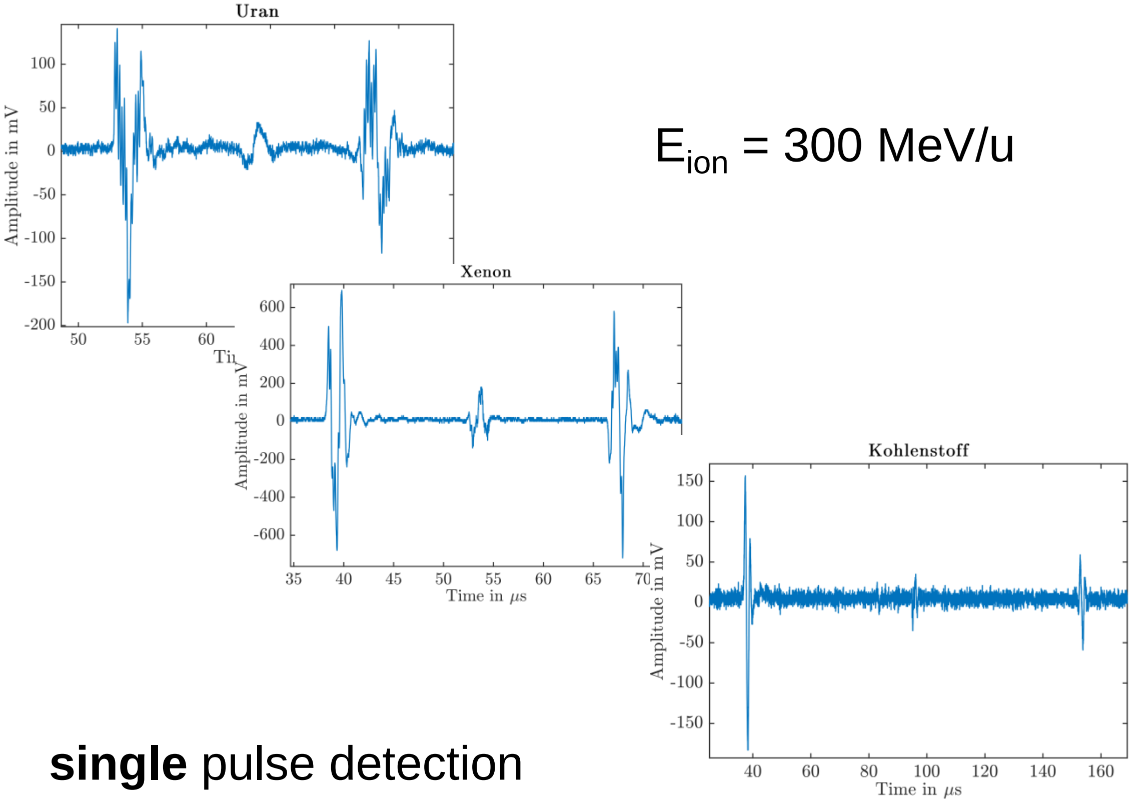




Ion Type **Charge state**	**Energy in MeV/u**	**Peak position in mm**	**Peak width in mm**	**Spatial frequency in kHz**
^{12}C 6+	200	85.58	1.80	415
^{124}Xe 43+	300	20.96	1.08	689
^{238}U 63+	300	14.29	1.36	549

Ionoacoustic monitor for GeV ions

Test setup at GSI

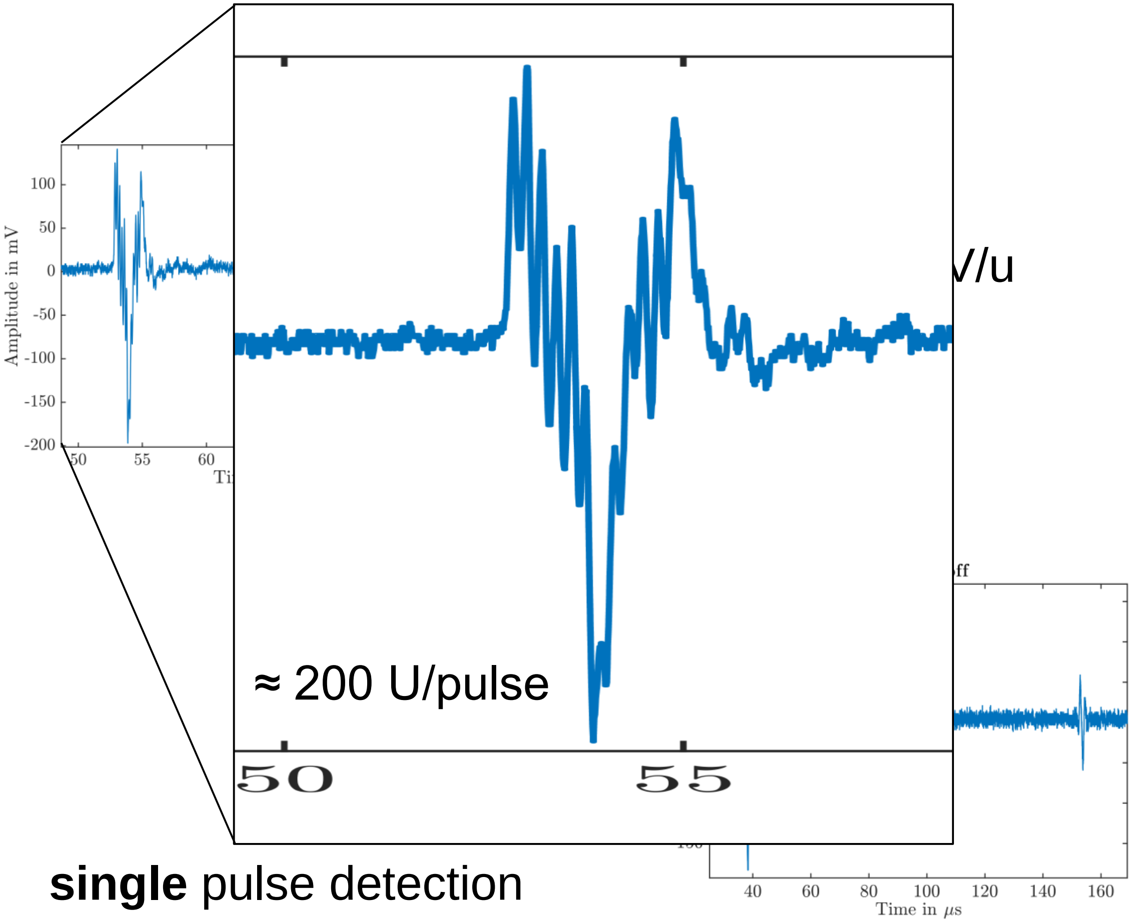


E_{ion} = 300 MeV/u

single pulse detection
(no averaging!)

Ionoacoustic monitor for GeV ions

Test setup at GSI



V/u

≈ 200 U/pulse

single pulse detection
(no averaging!)

GSI results: comparison to Geant4

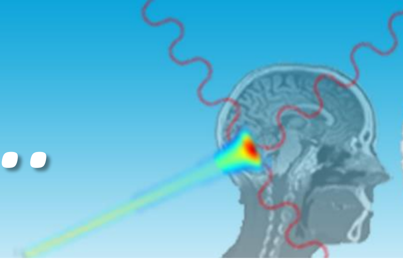
Ion Type	Energy in MeV/u	Ionoacoustic in mm	ΔR in µm	Geant4 in mm	ΔGeant4 in µm	ΔE in keV/u
^{12}C	180	70.83	7.8	70.75	82	11.5
	200	85.28	59.4	85.58	297	80.8
	220	100.70	55.8	100.84	143	70.9
	240	116.75	7.6	117.07	315	9.1
^{124}Xe	280	18.60	4.6	18.60	1	40.1
	290	19.75	4.9	19.78	30	42.0
	300	20.92	8.4	20.96	38	70.0
	310	22.12	4.1	22.18	62	33.3
	320	23.33	4.3	23.41	81	34.1
^{238}U	250	10.48	8.3	10.41	65	113.9
	280	12.73	14.7	12.69	35	185.9
	290	13.50	6.4	13.48	17	78.8
	300	14.24	74.5	14.29	55	134.8

agreement < 1%

Conclusion

- Ionoacoustic range determination is a **simple and precise** technique and a promising approach to overcome the range uncertainty problem in proton therapy
- Ionoacoustic detection of (intense) energetic ion bunches is an alternative to electonic detectors with larger **dynamic range** and less **EMP sensitivity**
- **Radiation resistant** 1-dim to 3-dim beam monitor

Thanks to .....



IBMI, Helmholtz-Zentrum München

S. Kellnberger, M. Omar, **V. Ntziachristos**

Universität der Bundeswehr München

M. Moser, C. Greubel, **G. Dollinger**

GSI Helmholtz-Zentrum für Schwerionenforschung, Darmstadt

M. Bender, **Chr. Trautmann**

LMU München, *Department für Medizinische Physik*

S. Lehrack, A. Maaß, S. Reinhardt, P. Thirolf,
D. Haffa, **J. Schreiber, K. Parodi**

Recent review: K. Parodi and W. Assmann, Mod Phys Lett A 30, 17 (2015) 1540025

The end

Thanks for your attention!