Ionoacoustic imaging for particle range verification

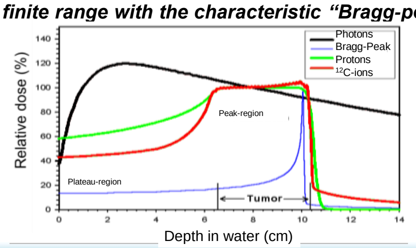
Katia Parodi, Ph.D.
Ludwig-Maximilians-Universität München,
Dept. of Experimental Medical Physics, Munich, Germany

Joint AAPM-ESTRO Symposium:
Advances in Experimental Medical Physics

Washington D.C., 01.08.2016

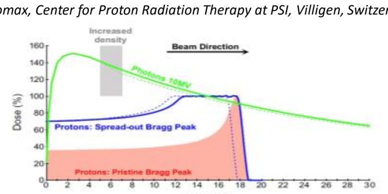
The physical advantages of ion beams

The finite range with the characteristic "Bragg-peak"



The challenges of ion beams in clinical practice

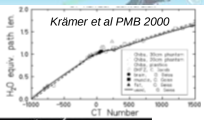
"The advantage of protons is that they stop.
The disadvantage of protons is that we don't always know where."
(Prof. Dr. AJ Lomax, Center for Proton Radiation Therapy at PSI, Villigen, Switzerland)

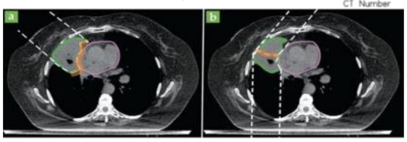


M. Engelsman et al, Seminars Rad. Onc. 2013

The need of in-vivo range verification

Calibration of X-ray CT into water equivalent length and positional / anatomical uncertainties are large sources of range uncertainty, causing usage of safety margins (a) and suboptimal choice of beam angles (b)

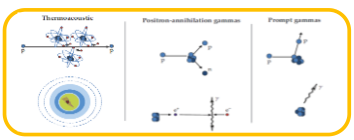




Polf and Parodi, Phys Today 2015

Make the invisible visible

Different emission mechanisms



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

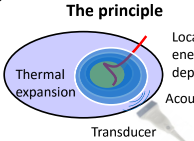
$$\frac{dV}{V} = -\kappa dp + \beta dT$$

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

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

"Ionoacoustic" range verification

The principle



But:

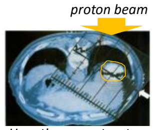
1 Gy dose → 0.25 mK ΔT → 2 mbar Δp

Detectability?

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



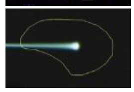
Hepatic cancer treatment

(Weak) acoustic signal observed for **passive delivery** of **50 ns pulsed *p* beam**

Time for a new attempt?

Passively scattered irradiation of whole **tumor volume *at once***
- → ***diffuse*** local dose deposition
- → ***small*** ionoacoustic signal amplitude
- → ***complex*** range information

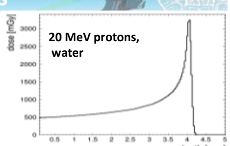
Sequential tumor irradiation by **pencil beam scanning**
- → highly *localized* dose deposition
- → *enhanced* ionoacoustic signal amplitude
- → *direct* range information



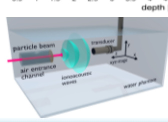
Trends of ***higher pulse intensity*** for **new accelerators**
like synchro-cyclotrons (6-7 µs FMHW, up to ~5pC/pulse @ 1kHz)

Systematic studies at low beam energies

Experimental setup at the MLL Tandem accelerator
- 20 MeV protons stopped in a water phantom
- 1 – 10 MHz PZT detector, remotely controlled
- 8 ns – 4 ms beam pulse width at 3 ns rise time
- 10^4 – 10^8 protons per pulse



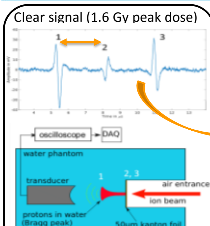
Systematic "ionoacoustic" investigations under ideal conditions

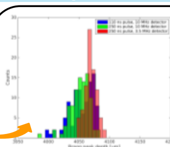


W. Assmann et al Med Phys 2015

Range determination: Reproducibility & accuracy

Clear signal (1.6 Gy peak dose)





	BP (mm)
Geant4	4070
10 MHz	4055 ± 20
10 MHz	4050 ± 15
3.5 MHz	4070 ± 10

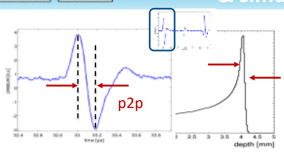
BP position accuracy and precision **< 100 µm**
(≈ frequency independent)

Model	focus	f_c [MHz]
V-303*	spherical	1
V-382*	planar	3.5
V-311*	spherical	10
Array	cylindrical	5

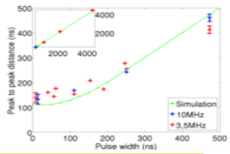
* immersion transducers Olympus

W. Assmann et al Med Phys 2015; PhD S. Lehrack; MSc A. Maaß

1D Bragg peak characterization & simulation



Simulation for **point detector approximation**, combining Monte Carlo (Geant4) dose deposition with K-Wave acoustic propoation

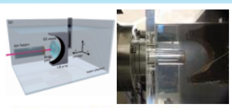


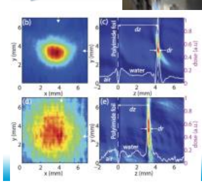
Peak to peak distance (p2p) of Bragg peak signal saturates for **short pulse durations** in ***stress confinement*** (i.e. $t_{ion} < t_{propagation}$ [$v_s \approx 1.5$ mm/µs])

Saturation value corresponds to **Bragg peak width** *(steepest gradients)*

W. Assmann et al Med Phys 2015

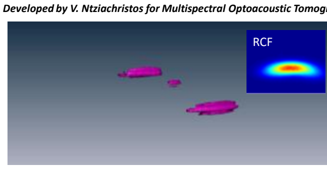
3D Bragg peak characterization: ionoacoustic tomography





First test of **64-channel Transducer-Array**

Developed by V. Ntziachristos for Multispectral Optoacoustic Tomography

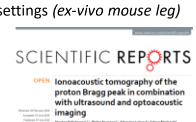


Tomography of a pencil beam wo / w Al absorber

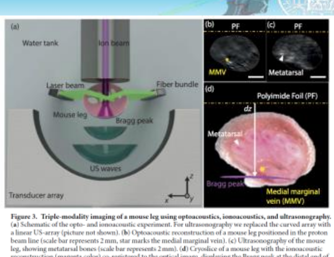
Kellnberger et al Sci Rep 2016

Triple-modality imaging

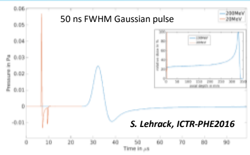
First-time combination of optoacoustics, ionoacoustics and ultrasonography in a pre-clinical settings *(ex-vivo mouse leg)*



See Patch et al, **TU-FG-BRB-9**

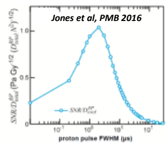


From 20MeV to clinical energies



Challenges

- Decreased signal for same proton pulse due to increased Bragg peak width
- Decreased ionoacoustic frequencies ≈ **200 kHz**
- Soft tissue attenuation *(50x water, but low US frequencies)*
- Tissue inhomogeneity and patient noise



But

Optimum expected around few μs pulse

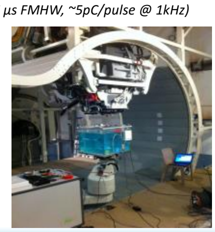
(still in stress confinement due to broader Bragg peaks)

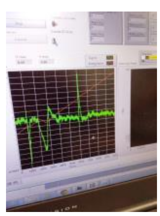
Synchro-cyclotrons offer ideal scenario for ionoacoustics

Tests at clinical energies: Synchro-cyclotron

Ionoacoustic experiment at the IBA 230 MeV synchro-cyclotron (Nice, France)

(6-7 μs FMHW, ~5pC/pulse @ 1kHz)





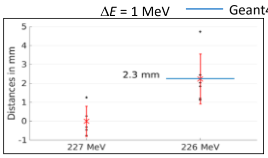
Note:
1024 averages

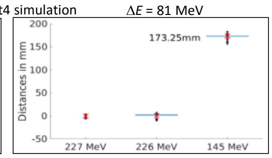
S. Lehrack et al, presented at ICTR-PHE 2016

Tests at clinical energies: Synchro-cyclotron

Energy (range) variation

ΔE = 1 MeV — Geant4 simulation — ΔE = 81 MeV





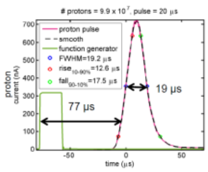
Promising mm-accuracy but reproducibility issues to due setup shortcomings

New experimental run on July 25-26 2016 *(data analysis in progress)*

S. Lehrack et al, presented at ICTR-PHE 2016

Tests at clinical energies: artificially pulsed cyclotron

Artificially pulsed cyclotron
(19 µs and 790 nA max current)

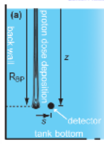


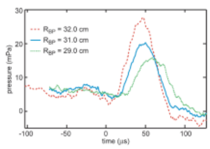
Courtesy of K. Jones, UPenn

Medical Physics

Experimental observation of acoustic emissions generated by a pulsed proton beam from a hospital-based clinical cyclotron

Kevin C. Jones, François Vander Stappen, Christopher R. Bawiec, Guillaume Janssens, Peter A. Lewin, Damien Prieels, Timothy D. Solberg, Chandra M. Sehgal, and Stephen Avery





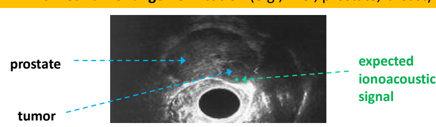
Jones et al, Med Phys 2015

See Jones et al, **SU-C-207A-4**

Conclusion & outlook

- Renewed interest in ionoacoustics, favoured by modern **pencil beam scanning**
- **Promising results** achieved at pre-clinical experimental sites as well as **clinical synchro-cyclotrons** and **artificially pulsed isochronous cyclotrons**
- Main remaining challenges are **detector sensitivity** and **tissue heterogeneities**

Envisioned clinical application will **combine ionoacoustics with ultrasonography** for **real-time range verification** (e.g., liver, prostate, breast)



Transrectal ultrasonography of prostate tumor tissue

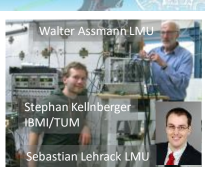
Thanks to …

LMU Munich, Department of Experimental Medical Physics
W. Assmann, **S. Lehrack**, A. Edlich, A. Maaß, S. Reinhardt, J. Schreiber, P. Thirolf

IBMI, Helmholtz-Zentrum München, Germany
S. Kellnberger, M. Omar, **V. Ntziachristos**

Universität der Bundeswehr München, Germany
M. Moser, C. Greubel, **G. Dollinger**

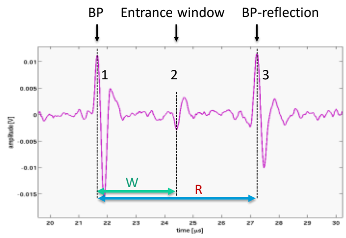
IBA, Ion Beam Applications SA, Belgium
F. Vander Stappen, D. Bertrand, D. Prieels

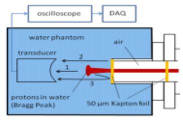


Funding from the Maier Leibnitz Laboratory & DFG Munich Center for Advanced Photonics

…and thank you all for your attention!

Ionoacoustic signal





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

Speed of sound:
1520 m/s (H_2O, 35 °C)
or **1.52 mm/µs**

New approach but old idea …

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

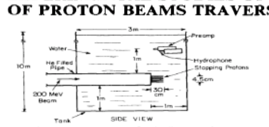
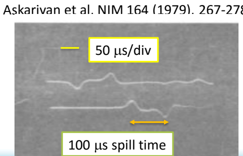


Fig. 3. Detector arrangement for the linac experiment.

6. Conclusions

We have demonstrated that an observable acoustic signal is produced in a single transducer by charged particle depositions $\geq 10^{14}$ 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. Askaryan et al. NIM 164 (1979), 267-278



Ideas for medical physics

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

J. Tada et al, Med. Phys., 18, (1991), 1100-1104

A review of the processes by which ultrasound is generated through the interaction of ionizing radiation and irradiated materials: Some possible applications

N. Baily, Med. Phys., 19, (1992), 525-532

- US amplitude proportional to energy deposition
  - ➢ ***Dose verification***
- Determination of ***beam position***

Range verification with sub-mm spatial resolution?