Range Verification Methods

DR. HANS-PETER WIESER, LMU MUNICH

DR. NIKLAS WAHL, PROF. DR. JOAO SECO, DKFZ, HEIDELBERG

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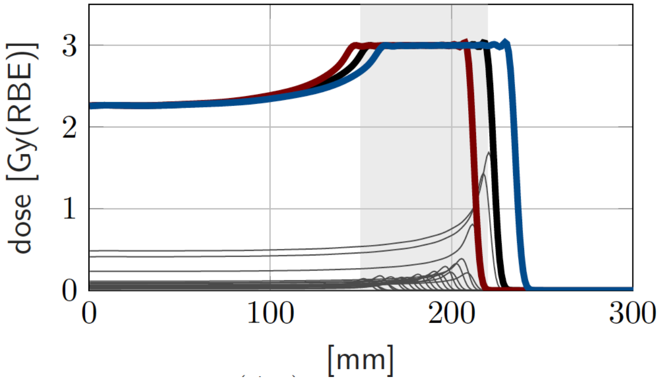
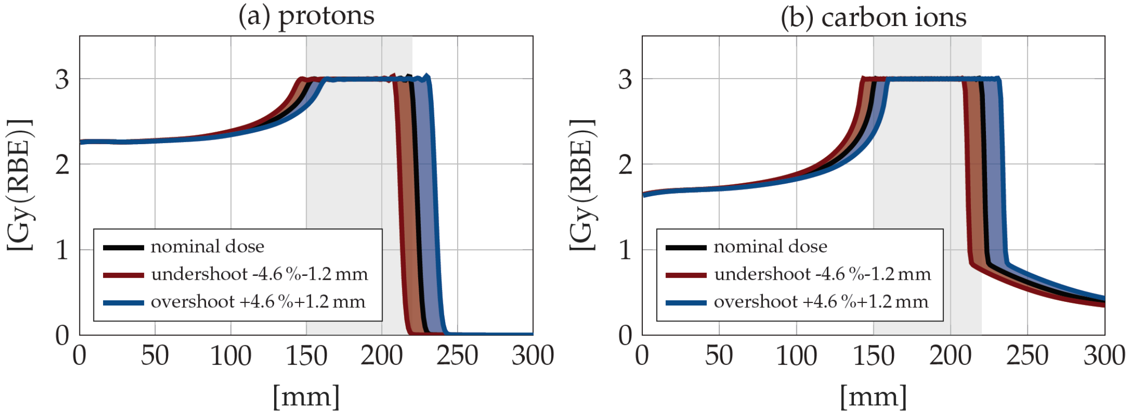
Recap: Range Uncertainties





Motivation: Accurate knowledge of the exact stopping location of ions inside the patient would allow a full exploitation of their ballistic properties.

Time matters !

In-vivo range or treatment verification in particle therapy

- Prompt Gamma imaging — 'real time', in-beam (<ms)
- PET imaging — delayed, in-beam and post-treatment (ms to min)
- Ionoacoustics — delayed, in-beam (<ms)
- Magnetic Resonance Imaging — days to weeks

Challenge and Impact

Challenge

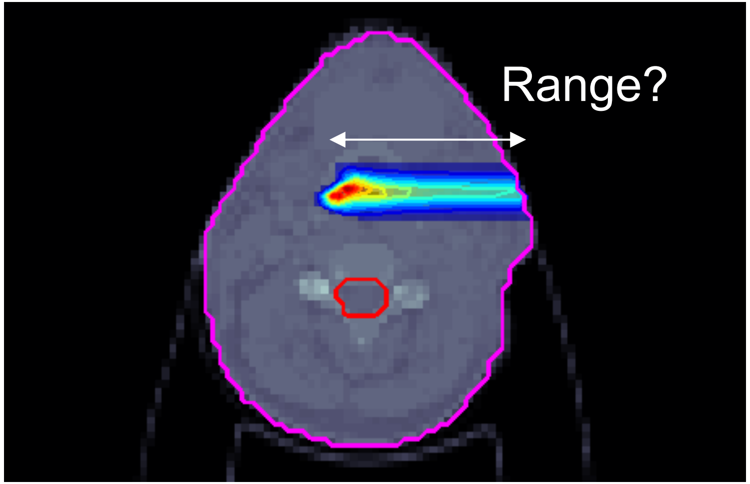
How to measure a signal from the Bragg peak during treatment

→ all primary protons stop inside the patient

→ measure secondary signatures

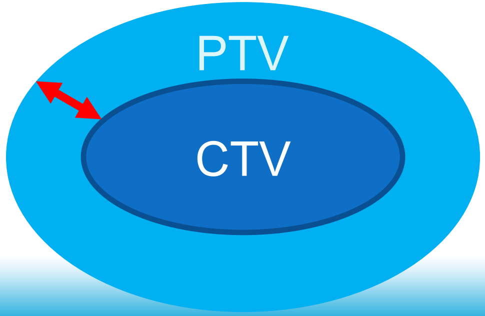
→ correlate physiological changes

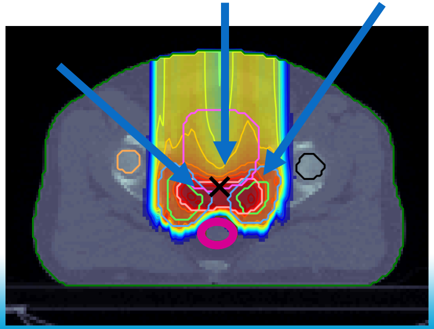
Proton pencil beam in the head



Impact

- reduced planning margins
- new beam configuration
- adaptive treatment strategies
- improved treatment outcomes





Prompt Gamma Imaging

- energetic γ emission from excited target nuclei (C,O,N)
- de-excitation <1ns of prompt γ after nuclear inelastic interaction
- spectrum over several MeV,
- exponentially decreasing with characteristic emission lines
- can escape the patient, isotropic emission

- spatial information (spatial location of emission is of interest - collimation system)

- temporal information - exploit the TOF

- exploit the photon energy → spectroscopy

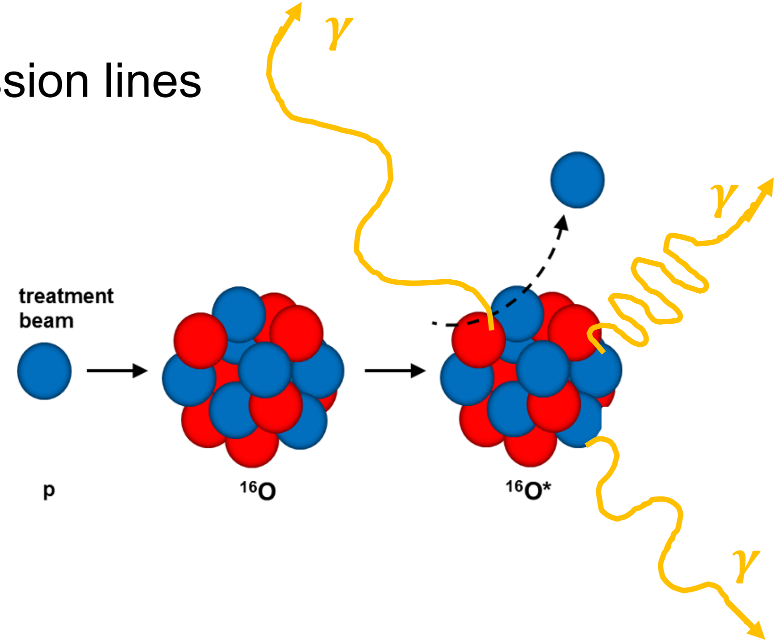


Figure adapted from https://www.med.physik.uni-muenchen.de/research/range-verification/promptgamma/index.html

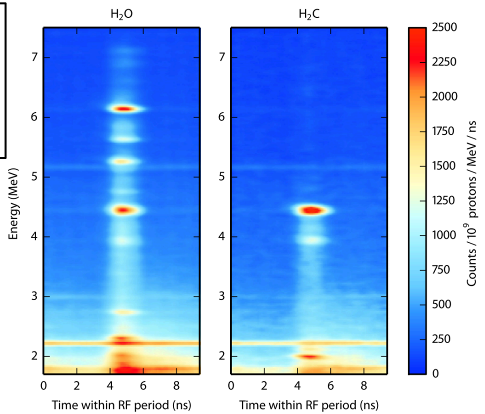
Prompt Gamma Spectroscopy

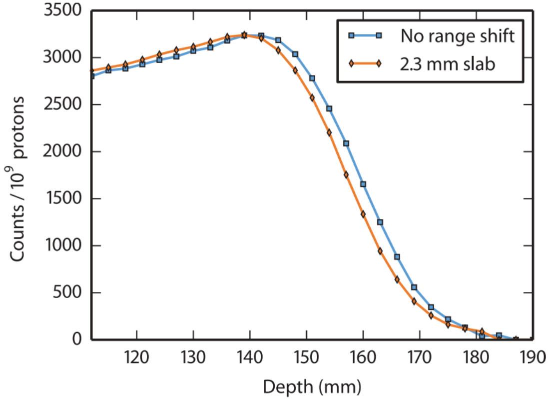
Proton range verification through prompt gamma-ray spectroscopy

Joost M Verburg[1,2] and Joao Seco[1]

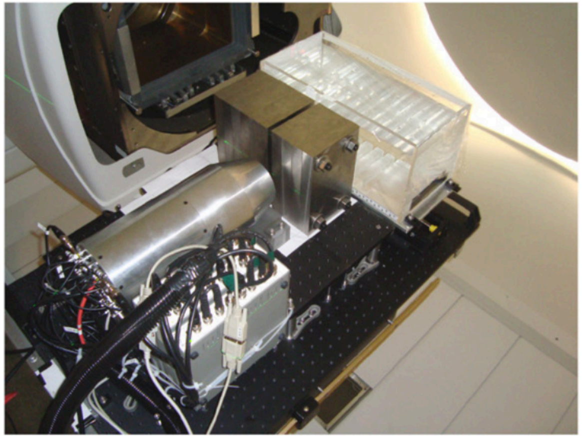
Water and polyethylene target

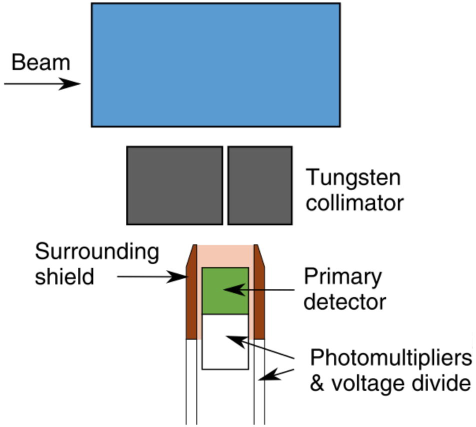
Measured discrete prompt gamma emissions

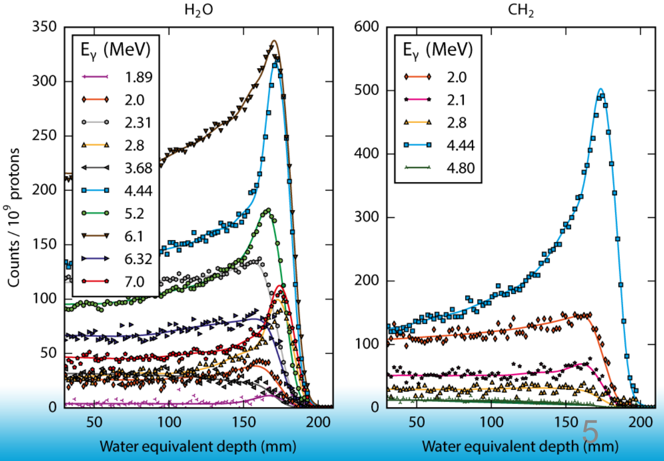




Reached clinical testing



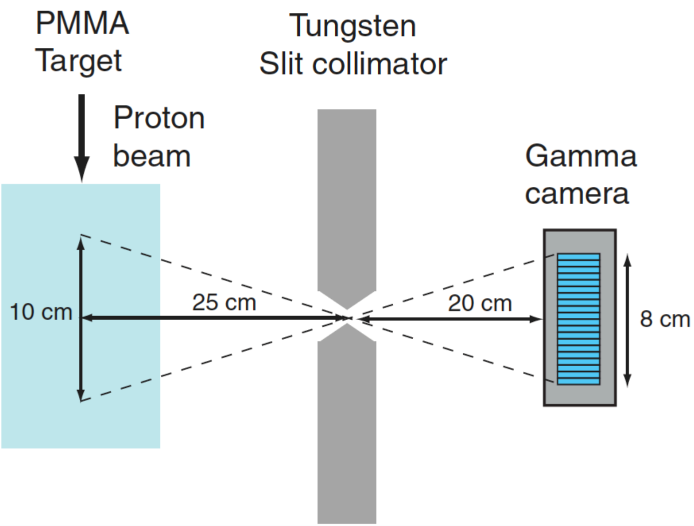




Prompt Gamma Imaging

Prompt gamma imaging of proton pencil beams at clinical dose rate

I Perali[1,2], A Celani[3], L Bombelli[3], C Fiorini[1,2], F Camera[2,4], E Clementel[5], S Henrotin[6], G Janssens[6], D Prieels[6], F Roellinghoff[6,7,8], J Smeets[6], F Stichelbaut[6] and F Vander Stappen[6]



3D imaging capabilities

requires dedicated sensor developments

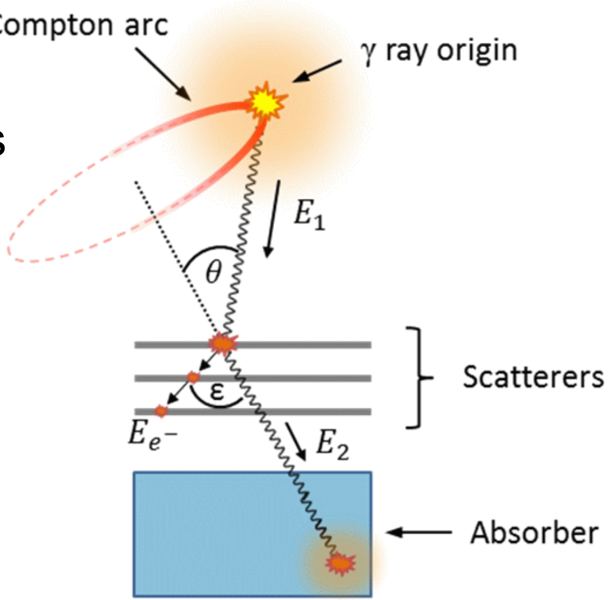


Figure adapted from https://www.med.physik.uni-muenchen.de/research/range-verification/promptgamma/index.html

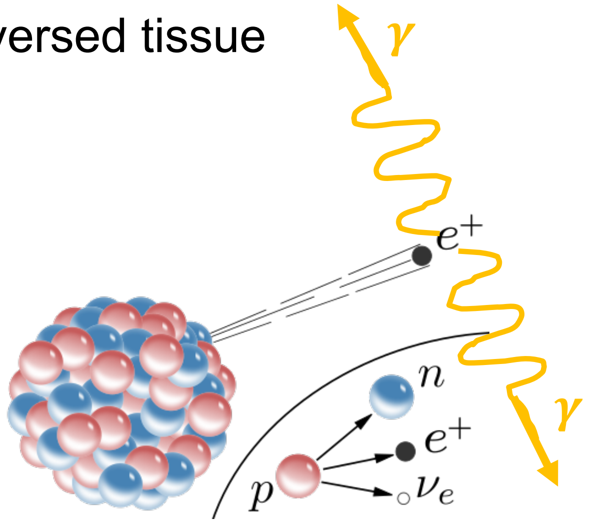
Positron Emission Tomography

- Nuclear fragmentation reactions between ions and traversed tissue
- Radioactive β^+decay is induced from ion irradiation

A(Z,N) → A(Z-1,N+1) + e^+ + ν_e

Short lived positron emitting isotopes ^{11}C ^{13}N ^{15}O

Half life times 11ms for ^{12}N up to 20min for ^{11}C.

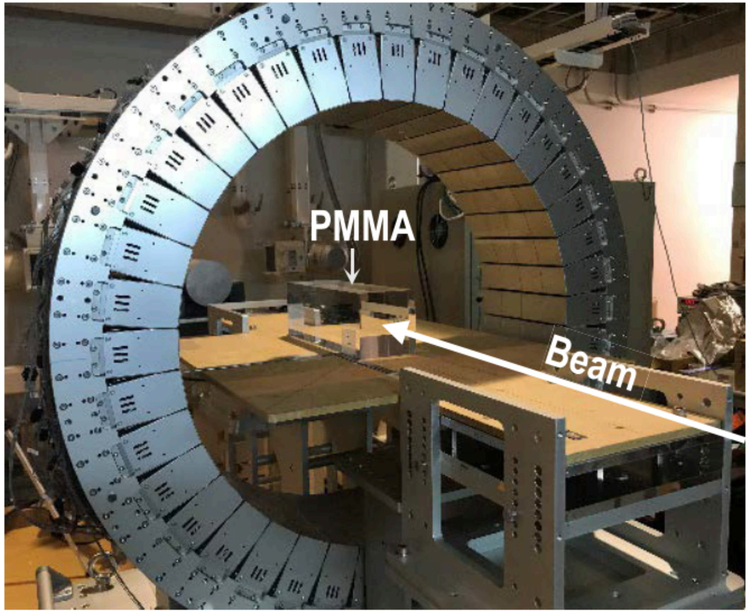


- Positron undergoes Coulomb interactions with atomic electrons until its annihilated into two photons at 511keV in opposite direction
- Detect two 511keV photons – that's the PET signal

PET Imaging

Range verification of radioactive ion beams of ^{11}C and ^{15}O using in-beam PET imaging

Akram Mohammadi[1,3], Hideaki Tashima[1], Yuma Iwao[1], Sodai Takyu[1], Go Akamatsu[1], Fumihiko Nishikido[1], Eiji Yoshida[1], Atsushi Kitagawa[1], Katia Parodi[2] and Taiga Yamaya[1]



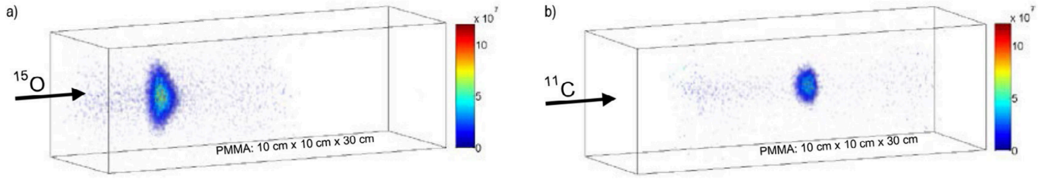


Figure 5. 3D reconstructed PET images of a PMMA phantom irradiated with the (a) ^{15}O beam and (b) ^{11}C beam.

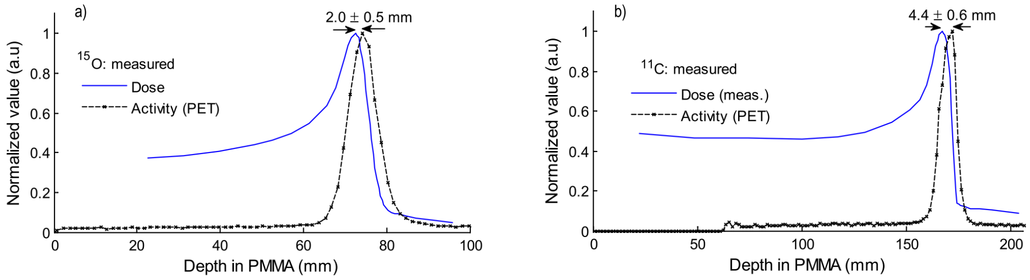
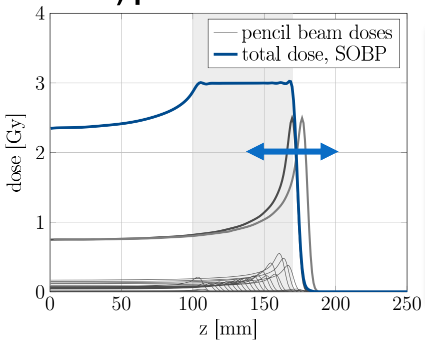


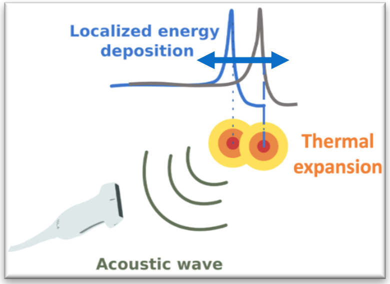
Figure 6. Comparison of the difference between the Bragg peak position and the PET peak position in mm for (a) ^{15}O and (b) ^{11}C ion beams. The results were obtained from the measurements.

Ionoacoustics

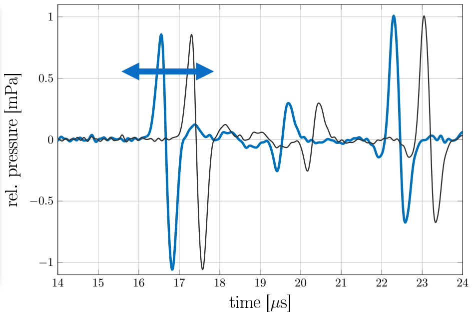
a) proton SOBP



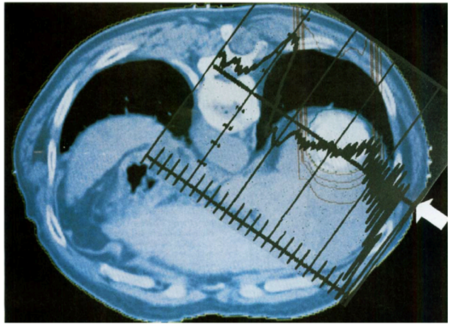
b) detection principle of ionoacoustic waves



c) ionoacoustic wave from the energy deposition of a pulsed proton beam



1995, Hayakawa et al, Acoustic Pulse Generated in a Patient During Treatment by Pulsed Proton Radiation Beam



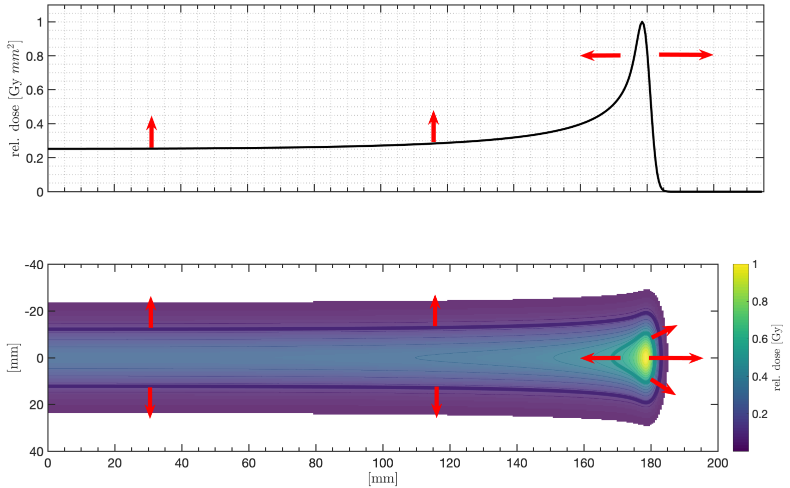
*"These results suggest the feasibility of **non-invasive monitoring of proton dose distributions** in patients by sensing acoustic pulses generated during irradiation by a pulsed proton radiation beam."*

50 ns pulse width, hepatic cancer patient, **passively scattered beam**

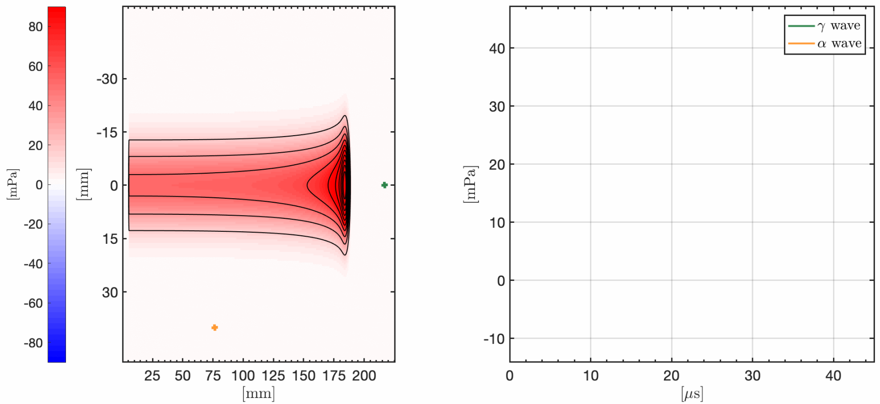
Ionoacoustics

Stopping of ions → local heating → thermal expansion → pressure wave

Cylindrical waves from the entrance
Spherical wave from the Bragg Peak



Simulation of wave propagation



Pressure wave is weak and typically below 200kHz

MR imaging

- MR offers good soft-tissue contrast
- detect physiological changes that correlate with beam range
- post-treatment verification using T1 weighted MRI scans
- In vivo proton range verification on spine could be demonstrated

Latest developments from Oncoray in Dresden:

PARTICLE THERAPY | RESEARCH UPDATE

Online MR imaging verifies proton beam range

Conclusion

- Non-invasively measuring the proton range online and in-vivo is challenging
- Secondary signals are correlated with the Bragg peak location
  - prompt γ
  - Position emission tomography (PET)
  - Ion-acoustic
- MR imaging might be an alternative solution

Thank you !

This material was prepared and presented within the HITRIplus Heavy Ion Therapy MasterClass school, and it is intended for educational purposes to facilitate students; people interested to use any of the material for any other purposes (such as other lectures, courses etc.) are requested to please contact the authors

Hans-Peter Wieser h.wieser@lmu.de

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IN DER HELMHOLTZ-GEMEINSCHAFT

Heavy Ion Therapy Research Integration

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