Unconventional imaging in ion beam therapy: status and perspectives

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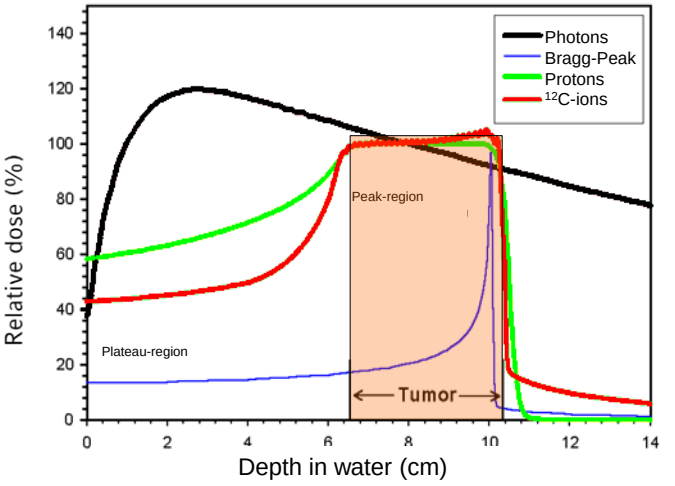
The quest for precision

The finite range with the characteristic "Bragg-peak"



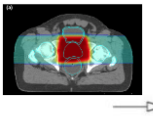
… increased sensitivity to uncertainties

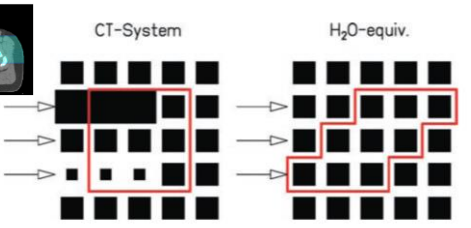
Range uncertainties

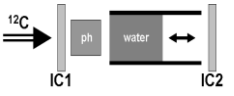
Planning uncertainties:

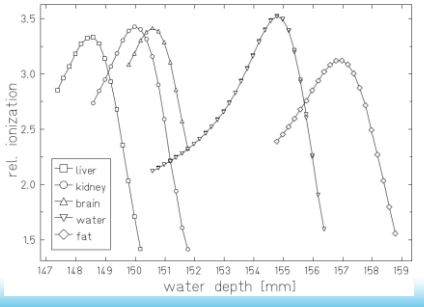
CT-range calibration curve

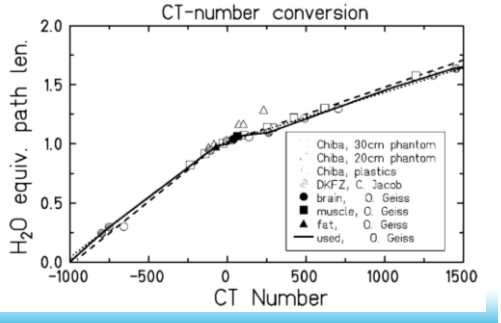
~ 1 – 3 % uncertainties









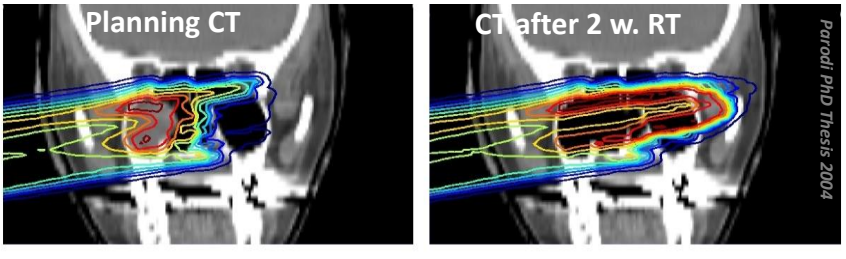


Rietzel et al, Rad Onc 2,14 2007

Krämer et al, PMB 2000

Range uncertainties

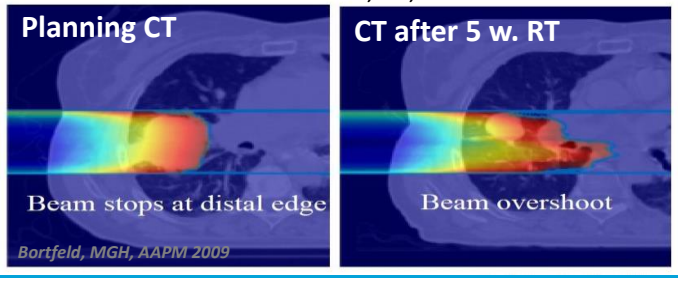
Chordoma, ^{12}C, GSI Darmstadt



Delivery uncertainties:

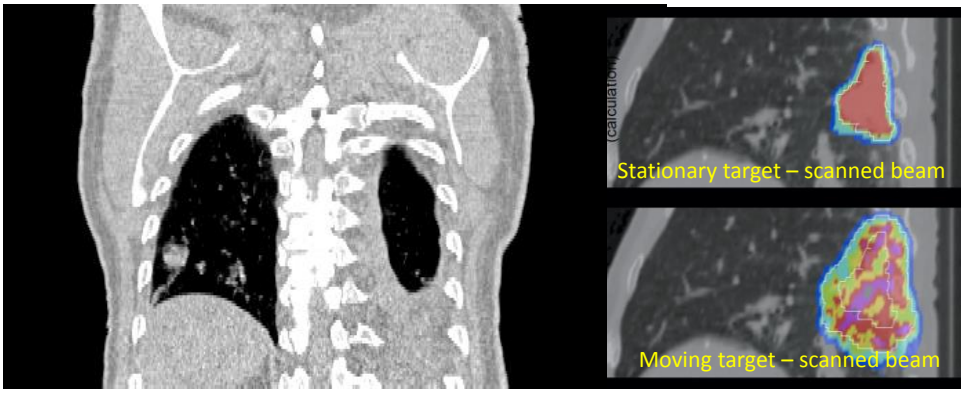
Interfractional anatomical changes

Bronchial-carcinoma, ^{1}H, MGH Boston



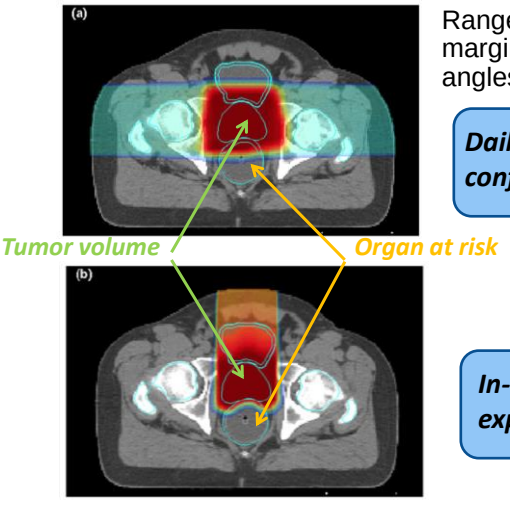
Range uncertainties

Delivery uncertainties: **intrafractional anatomical changes**



E. Rietzel et al, MGH; C. Bert et al, GSI Darmstadt

In-vivo verification



Tang et. al. Med.Phys. 2012

Range uncertainties result in conservative margin expansion and choice of beam angles avoiding Bragg peak before OARs

Daily practice of compromising dose conformality for safe delivery

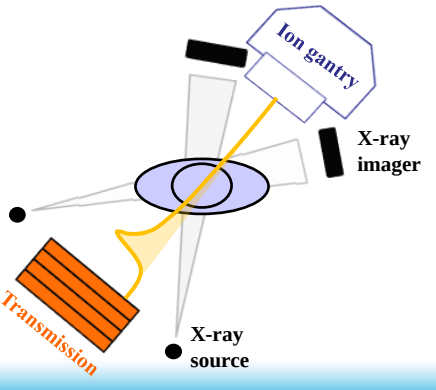
In-vivo verification could enable full exploitation of ion therapy potential

Imaging for treatment verification

Current efforts for in-room imaging in ion beam therapy

- Anatomical confirmation via X-rays or transmitted ions

Imaging for confirmation of
- Treatment geometry



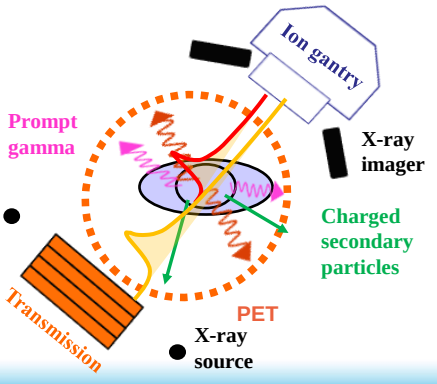
Imaging for treatment verification

Current efforts for in-room imaging in ion beam therapy

- Anatomical confirmation via X-rays or transmitted ions
- Range monitoring via emerging secondary radiation or transmitted ions

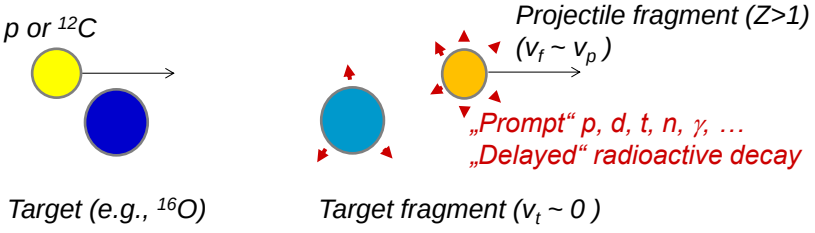
Imaging for confirmation of
- Treatment geometry
- Treatment delivery

This talk will focus on:
- Imaging of nuclear reaction secondaries
- Transmission ion imaging



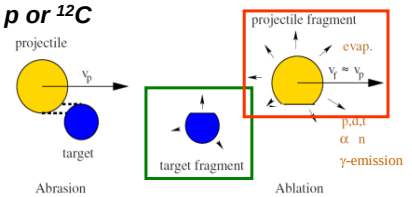
In-vivo treatment visualization

- Primary ions are stopped *somewhere* within the patient, with dose and range mainly dependent on Coulomb interaction
- Nuclear reactions induce measurable emerging radiation



Only Positron-Emission-Tomography clinically investigated so far

In-vivo PET-based verification



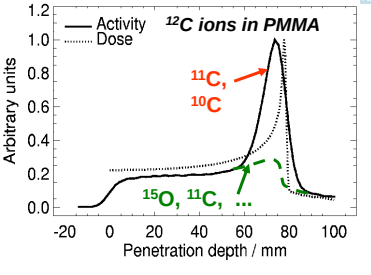
(projectile fragmentation only for Z>1)

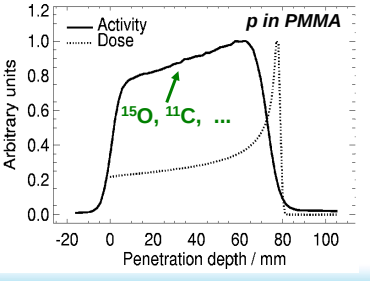
β⁺-emitter yield (^{15}O, ^{11}C,..., with $T_{1/2}$ ~ 2, 20,... min) as by-product of irradiation

A(r) ≠ D(r)

Tradeoff between **better spatial correlation** (^{12}C) and **stronger signal** (*p*)

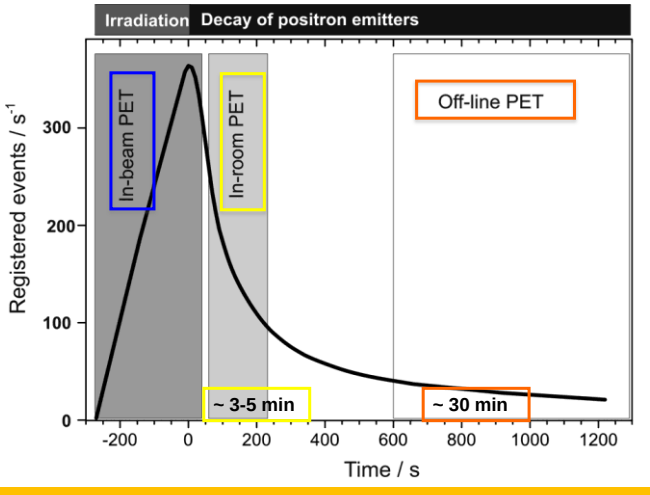
Dose-guidance from comparison of **measured** vs **expected** β⁺-activity





K. Parodi et al, IEEE TNS 2005

The possible workflows

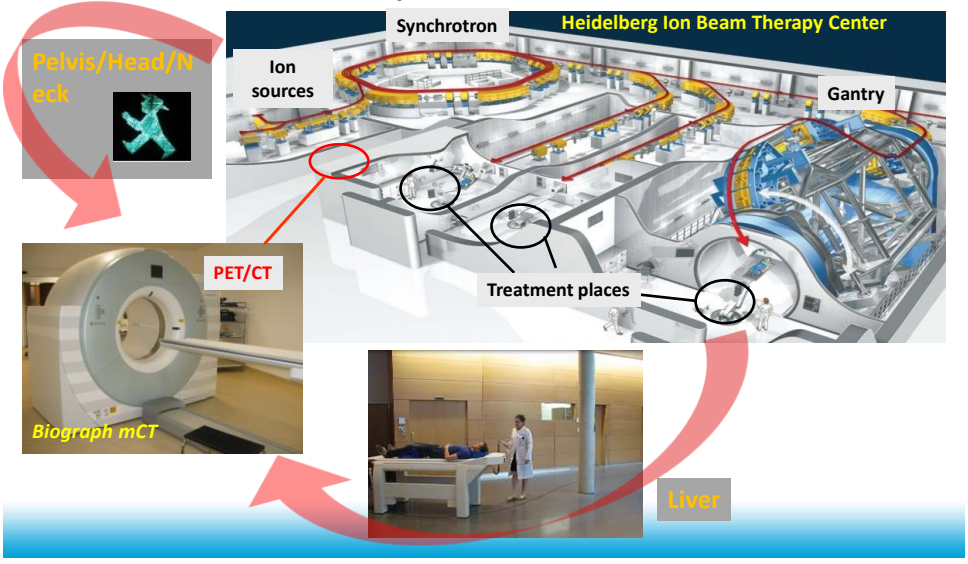


PET is a dynamic process, depending on time of irradiation and acquisition

Shakirin, ..., Parodi, ... PMB 2011

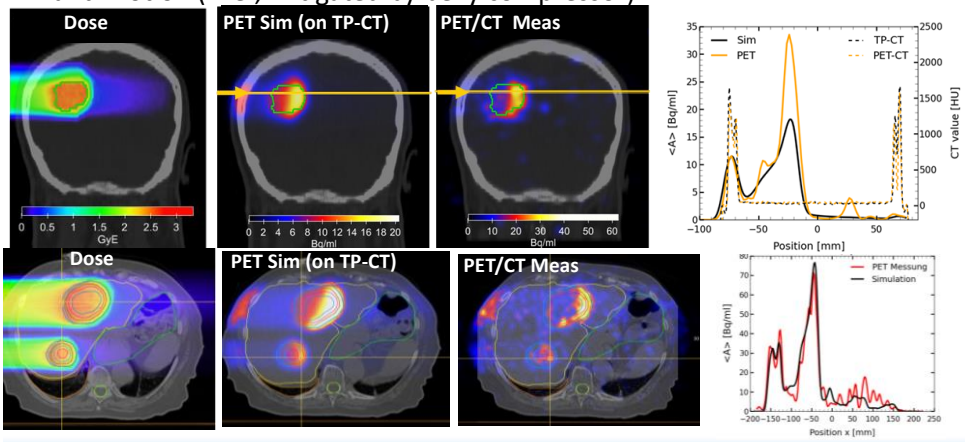
PET/CT-based verification at HIT

Commercial PET/CT next to treatment rooms



Clinical experience of offline PET/CT ^{12}C @HIT

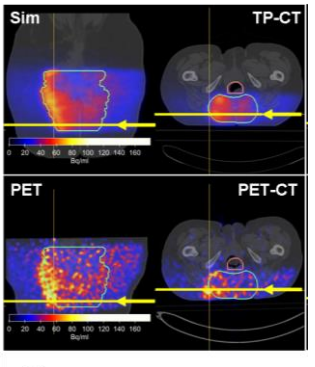
- Enhanced distal activity edge due to ^{11}C projectile fragments
- Reliable extraction of range information despite washout (brain) and motion (liver, mitigated by belly compressor)

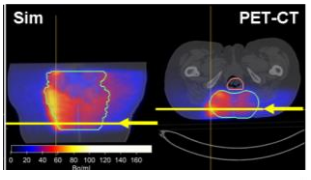


Bauer, …, Parodi, Radiother Oncol 2013

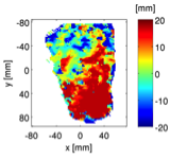
Clinical experience of offline PET/CT ^{12}C @HIT

Bauer, …, Parodi, Radiother Oncol 2013

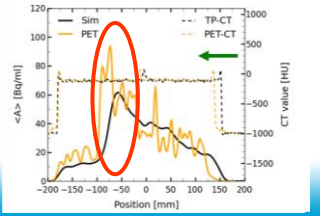


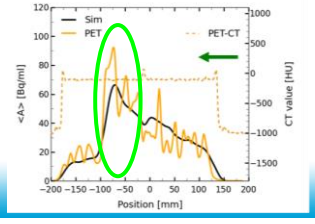


- Suspected mispositioning supported by new simulation on CT from PET/CT
- New treatment plan was performed to improve robustness against variations

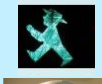


Range difference map in BEV





3GyE ^{12}C ~ 17 min

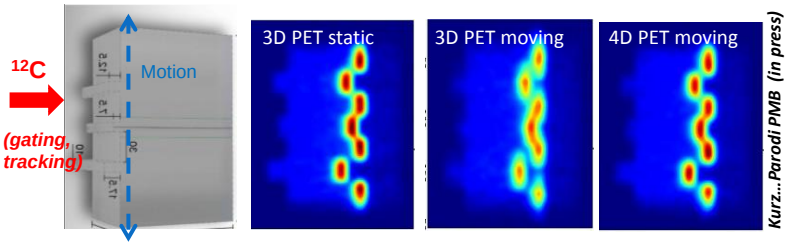


~ 13 min

30 min

4D PET/CT-based verification

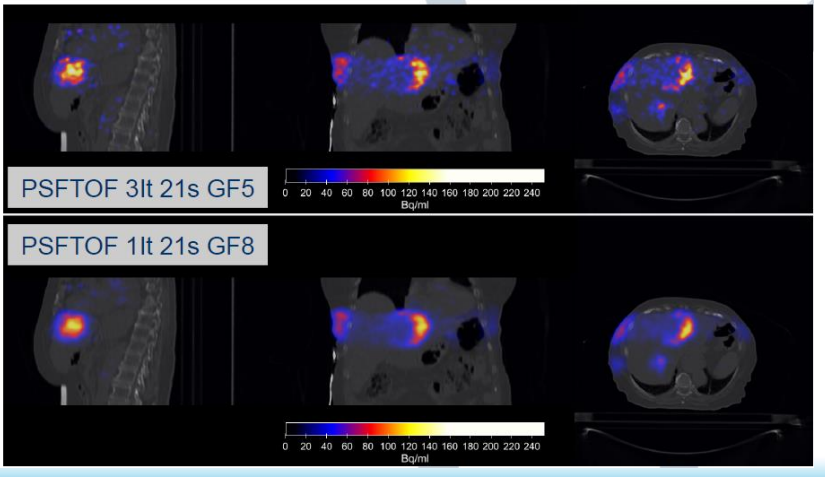
Phantom and clinical studies on detectability of range changes and interplay effects in the presence of motion



ENVISION

Outlook: image quality

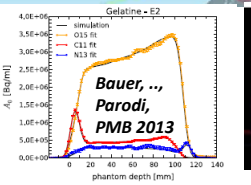
- Offline PET imaging suffers from several limitations
- Optimizing imaging parameters can yield significant improvements



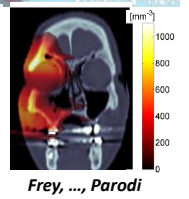
Kurz, ..., Parodi, Med. Phys. (in press)

Outlook: modeling / workflow

- Improve MC prediction via experimental based adjustement of β+ activation cross sections (especially feasible for *p*)
- Speed up calculation with analytical approaches, ideally using same pencil beam algorithms as TPS
- Overcome limitations of CT-based tissue classification by multimodal imaging
- Robust, automated range assessment from PET distributions based on profile shift analysis or % fall-off in BEV
  (meas. vs calc., meas. vs meas.)

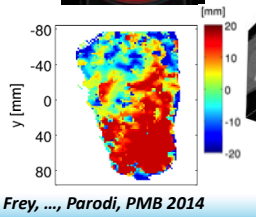


Bauer, .., Parodi, PMB 2013

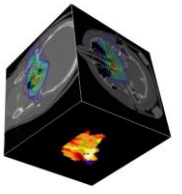


Frey, ..., Parodi PMB 2013

Bauer, ..., Parodi, to be submitted



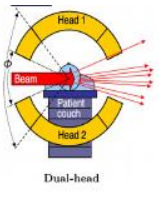
Frey, ..., Parodi, PMB 2014



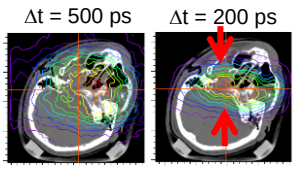
Helmbrecht et al, PMB 2012

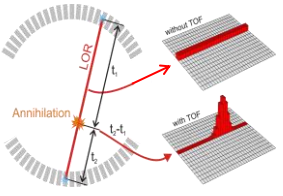
Hardware improvements: dual head solutions

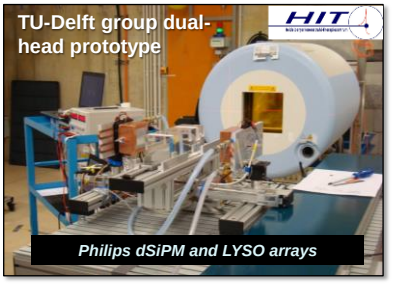
- Detector developments towards ultra-fast Time-of-Flight (TOF) in-beam PET



Crespo et al, PMB 2007





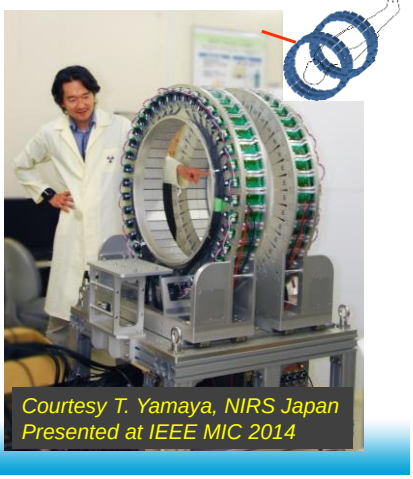


P. Cambraia Lopes et al, presented at IEEE MIC 2013

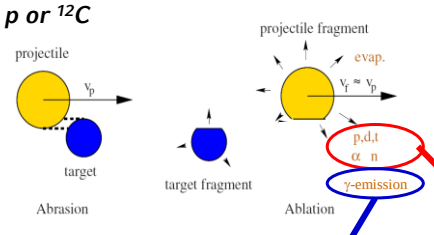
Hardware improvements: full ring solutions

- Prototype small bore PET/CT scanner just started clinical study at MGH
- Large scale in-beam full ring openPET scanner prototype being developed and tested with stable and radioactive ion beams at NIRS

Courtesy G. El Fakhri, PhD

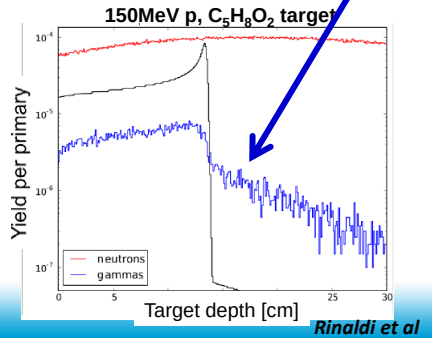


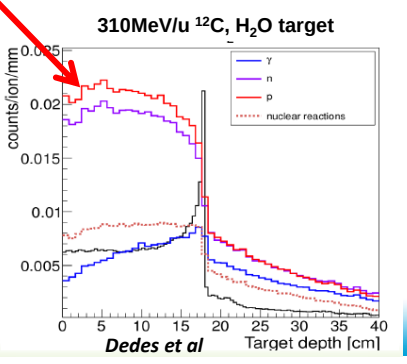
Prompt γ / protons imaging



The challenge

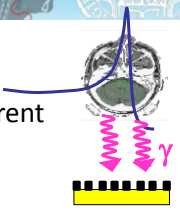
- Efficient detection of high energy γ embedded in neutron background
- Scattering of secondary protons



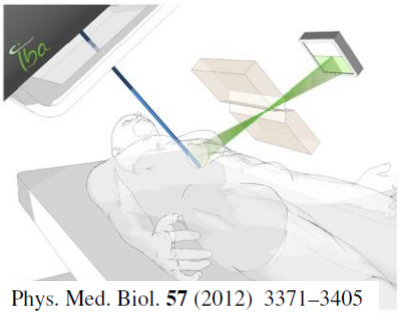


Prompt γ imaging

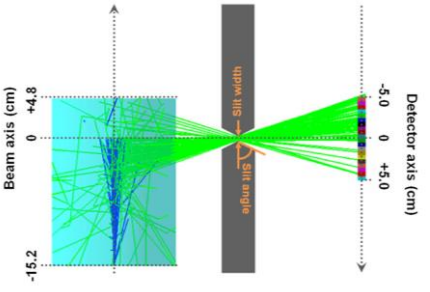
Real-time imaging of collimated prompt γ (e.g., at 90°)



- Detector developments of many groups worldwide with different concepts of mechanical or electronic collimation



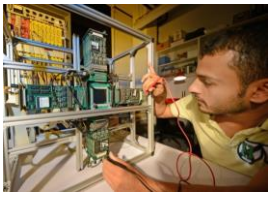
Phys. Med. Biol. **57** (2012) 3371–3405

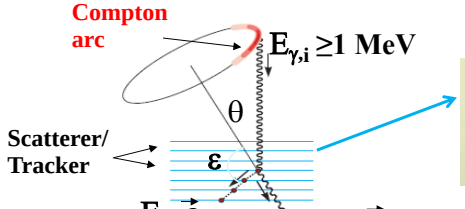


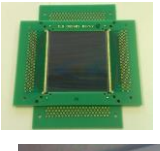
Mechanical collimation with slit camera (1D at end of range)

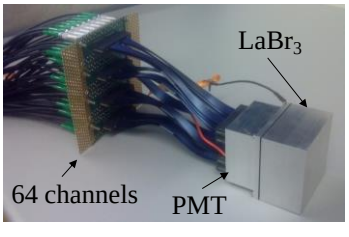
Prompt γ imaging

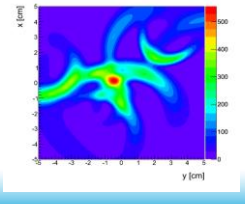
The Munich design for γ and electron tracking







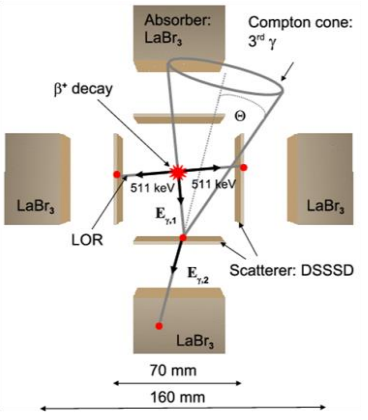




Electronic collimation (3D)

P. Thirolf, C. Lang, S. Aldawood, .., K. Parodi, LMU

Outlook: hybrid detectors



Hybrid detector concepts

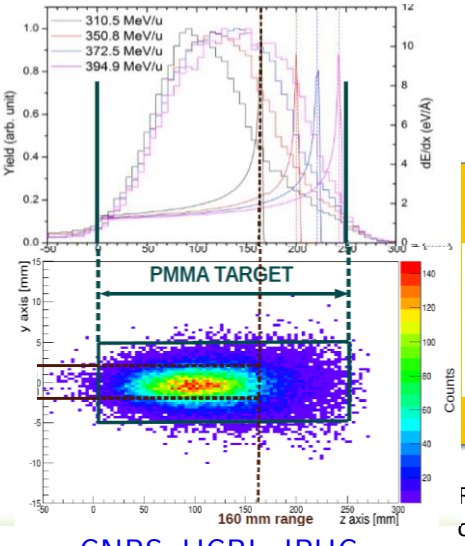
Multi-purpose detectors could exploit complementary information on different time scales

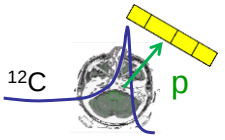
E.g., we are considering imaging of prompt gamma during beam-on and (γ)-PET during beam interrupts *(depending on delivery time structure)*

P. Thirolf, C. Lang, S. Aldawood, .., K. Parodi, LMU

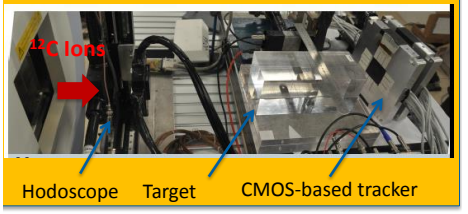
WP3: Light charged particles

Real-time imaging of emerging protons (from ^{12}C ions)





^{12}C beam [310-395 MeV/u] in PMMA at HIT, Heidelberg



Results similar to MC and findings of other groups (Gwosch et al PMB 2013)

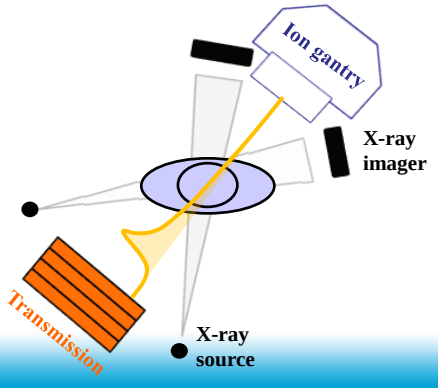
CNRS, UCBL, IPHC

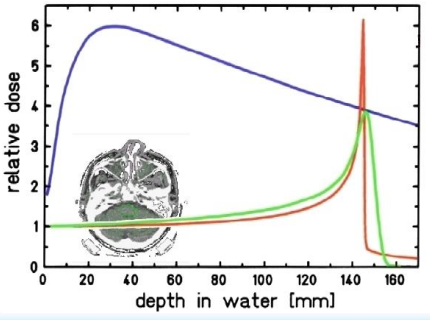
Reithinger, Dauvergne, Testa, Ray, Rinaldi, Parodi et al, IEEE 2012, PTCOG 2013; Courtesy V. Reithinger

Ion transmission imaging

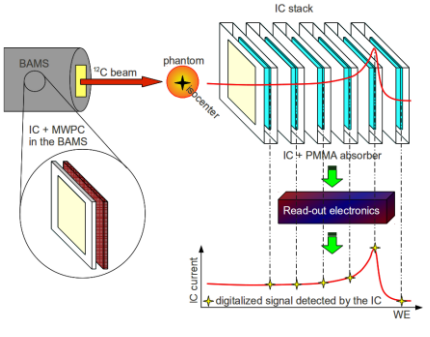
Ion-based radiography / tomography could:

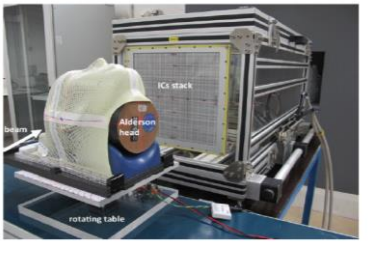
- Decrease range error via direct Relative Stopping Power determination
- Eliminate CT artifacts from metal / dental implants
- Replace X-ray imaging for daily, lower-dose image guidance





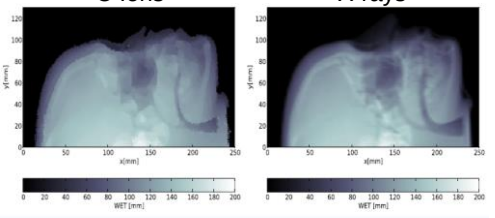
Carbon ion radiography prototype using ionization chambers @HIT





- 61 PPIC 30x30 cm^2
- 3 mm PMMA absorber slabs
- 2 read-out modules of 32 channels with real time controller
- Active scanning beam delivery syster

^{12}C Ions X-rays



Rinaldi, …, Parodi, PMB 58 2013
Rinaldi, …, Parodi, PMB 59 2014, 2014b

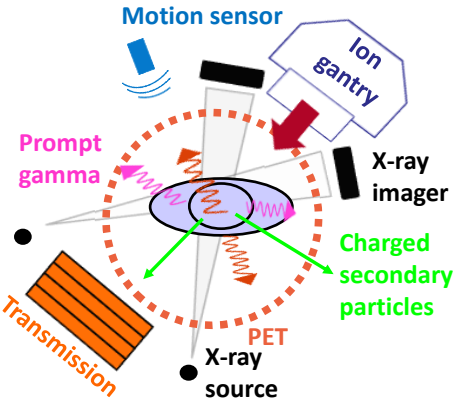
DFG project (GSI, UKL-HD, LMU)

Conclusion and perspectives

Increasing developments towards in-vivo, real time validation of beam range complemented by low-dose anatomical information at the treatment site

R&D in detector development, experimental validation, clinical integration (depending on beam production / delivery)

Synergy with multimodal diagnostic imaging for planning, follow-up …



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