Achievable image quality of helium-beam radiography (αRAD) of high-WET objects with a system based on thin silicon pixel detectors

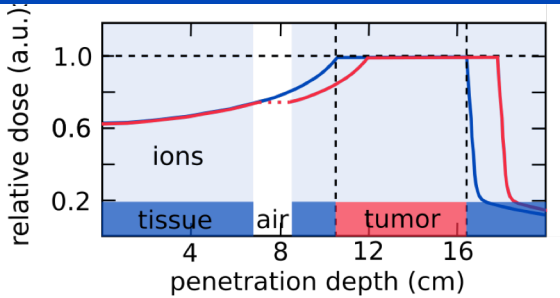
T. Gehrke[1,2,3]

M. Metzner[2,3], C. Knobloch[2,3], F. Kehrein[2,3], R. Hermann[4] C. Schömers[4], S. Scheloske[4], S. Brons[4], A. Peters[4], O. Jäkel[2,3,4], M. Martisikova[2,3]

[1] Department of Radiation Oncology, **Heidelberg University Hospital**, Im Neuenheimer Feld 400, Heidelberg, Germany
[2] Department of Medical Physics in Radiation Oncology, **German Cancer Research Center (DKFZ)**, Im Neuenheimer Feld 280, Heidelberg, Germany
[3] Heidelberg Institute for Radiation Oncology (HIRO), National Center for Radiation Research in Oncology (NCRO), Im Neuenheimer Feld 280, Heidelberg, Germany
[4] **Heidelberg Ion-Beam Therapy Centre (HIT)**, Im Neuenheimer Feld 450, Heidelberg, Germany

Helium-beam radiography (αRAD) – Application in Ion-beam therapy

- **Important** to detect **any uncertainty**
  - like **anatomical changes** or
  - uncertainties on **relative stopping power (RSP)** based on **x-ray CT**



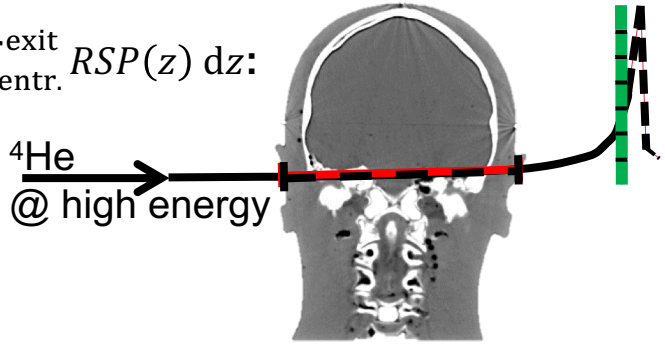
Low-dose αRad @ day of treatment

- **Direct information on WET** $= \int_{\text{entr.}}^{\text{exit}} RSP(z)\,\mathrm{d}z$**:**

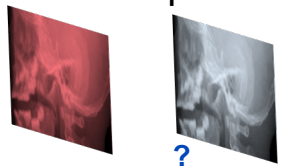
  avoiding conversion

  from photon-imaging

  to physics of ions.



Verification of WET-map from **planning CT** in treatment position!



$\mathrm{WET}_{\mathrm{meas}} \overset{?}{=} \mathrm{WET}_{\mathrm{CT}}$

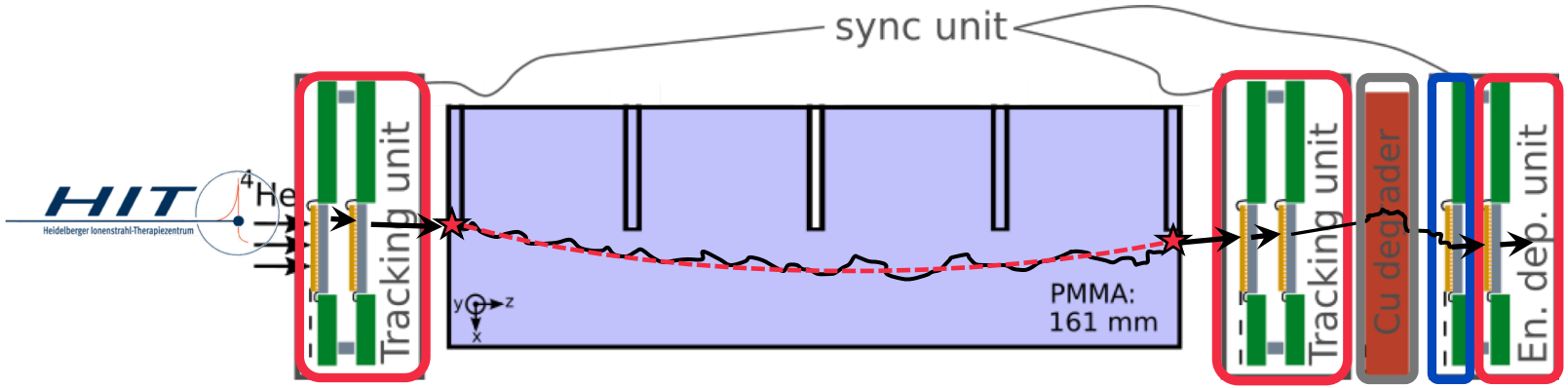
- **Patient alignment** based on two orthogonal ion radiographs.

Low-dose ion imaging:
Collins-Fekete et al., 2021; PMB **66**(105009)

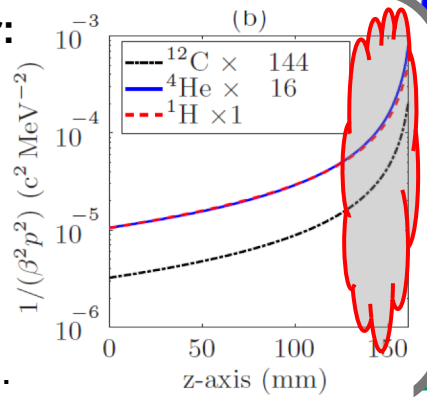
Pencil-beam range probes:
Hammi et al., 2017; PMB **63**(1)

Patient alignm. with pRAD:
ProtonVDA, Mark Pankuch, PTCOG 2020

Detection system – based on silicon pixel detectors



- **Improving spatial resolution w/ degrader:**
  - $\sigma^2_{\mathrm{MCS}} \propto \int_{z_0}^{z_1} \frac{(z_1 - z)^2}{\beta(z)^2 c^2 p(z)^2 X_0} \mathrm{d}z$
  - **Idea:** push the low-β region out of object and out of rear tracker.
  - Safety margin to avoid BP pull back in obj.



et al., 2008, Med.Phys. **35**(11)
Collins-Fekete et al., 2015, PMB **60**(13)

Timepix: Llopart et al., 2007, NIM A **581**(1-2)
Detection system: Gehrke et al., 2018, PMB **63** 035037

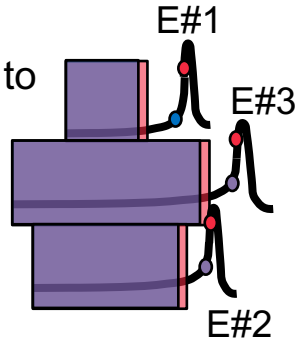
SR-improvement: Amato et al., 2020, MedPhys **47**(5)

dkfz.

Previous results & current research questions

- …for head-sized objects:
  - Spatial resolution (SR) $MTF_{10\%}$=0.6 lp/mm
  - WET resolution 0.8 % @ 350 µGy, 0.22 mm pixel pitch (detector's WET=4.90 mm)
- …for fun:

- Can we perform **quantitative αRAD,** i.e. obtain **WET maps**?
- Can we image the **pelvis/abdomen** region (WETs **up to 320 mm)** with sufficient **image quality**?
- Can we apply **energy-painted** αRAD to **anthropomorphic objects** with large WET variations to maintain high WET resolution everywhere?



Spatial & WET resolution: Gehrke et al., 2018, PMB **63** 035037; Amato et al., 2020, MP **47**(5)
Energy modulation for other systems: DeJongh et al., 2021, MP 48; Dickmann et al., 2021, EJMP 81

Quantitative αRADS @ high initial energies → WET maps

- **Newly established ^{4}He beams at HIT:**
  up to 330 MeV/u → 600 mm range

Please wait for corresponding publication (in progress)

- **Calibration function:**

$$\mathrm{WET} = R_0 - \left(p \cdot \alpha^{1/p} \cdot (\mathrm{d}E)\right)^{p/(1-p)}$$

Quality assessment of WET maps

Ⓘ Single-ion **WET precision** (σ_{WET})

Please wait for corresponding publication (in progress)

preliminary:

0.7% ≤ σ_{WET} ≤ 1.6% for WET range [250 mm, 313 mm]

Comparison to US pCT prototype II:
0.8% ≤ σ_{WET} ≤ 1.6%, WET range [180 mm, 240 mm]

dE/dx – WET:
Bortfeld, 1997, MedPhys **24**(12)

WET precision, US pCT phase II:
Bashkirov et al., 2016, MedPhys **43**(2)

dkfz.

Quality assessment of WET maps

II **Spatial resolution** (SR)

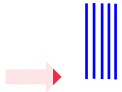
Ground truth (GT)

αRad

III **WET accuracy**

GT ∗ GaussKernel

Rel. difference map



Please wait for corresponding publication (in progress)

$MTF_{10\%}$= 0.46 lp/mm
@ WET_{obj} = **286 mm!**

Comparison to HeRad with US pCT prototype II:
$MTF_{10\%}$= 0.61 lp/mm
@ WET_{obj} = **100 mm**

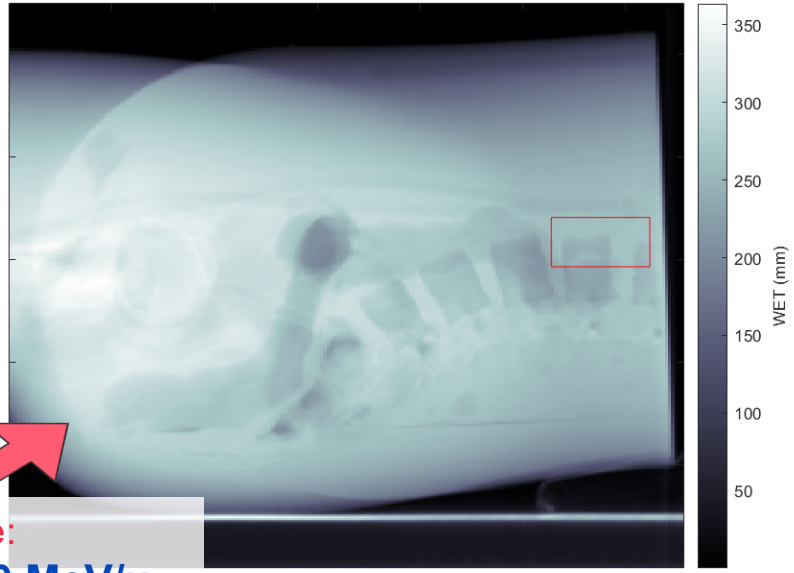
Please wait for corresponding publication (in progress)

HeRad with US pCT II - SR:
Volz et al., 2017, CDBME **3**(2)

dkfz.

Energy-painted αRad of an anthropomorphic pelvis phantom

Digitally reconstructed radiograph (DRR) based on X-ray CT



^{4}He:

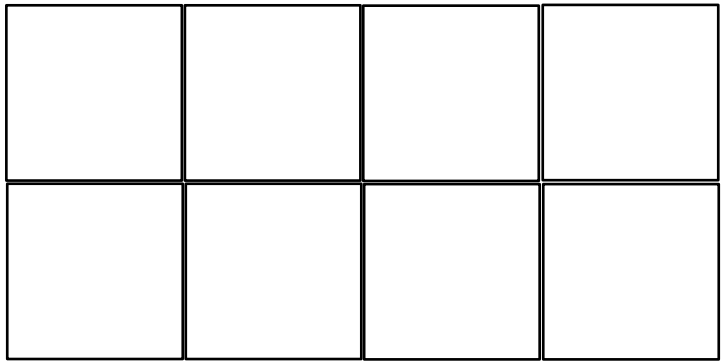
240 MeV/u

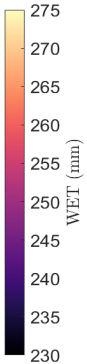
230 MeV/u

220 MeV/u

Please wait for corresponding publication (in progress)

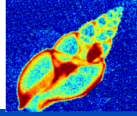
DRR (zoom)





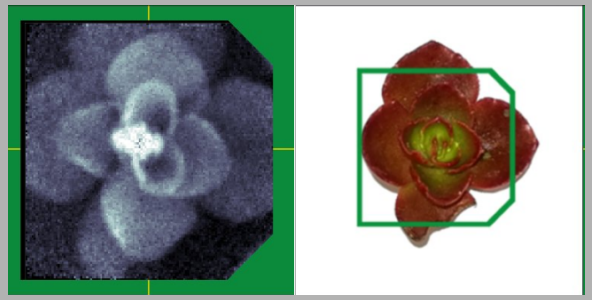
Expected dose increase: - for pelvis rad.: slightly higher than 2
- for head rad.: slightly lower than 2

Conclusion

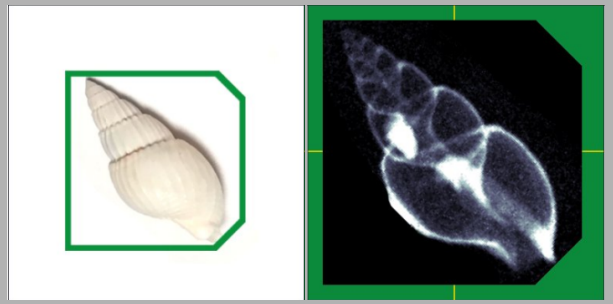


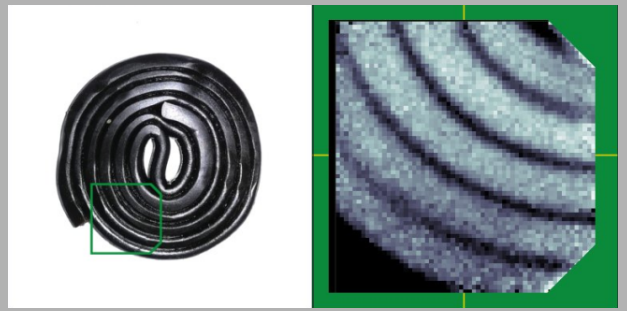
- The presented method provides **helium-beam radiographs** with **high image quality** even for **thick objects (~300 mm WET)**:
  - Single-ion WET precision**: < 1.6 %**
  - WET accuracy: MAPE=**0.22 %**
  - Spatial resolution: $MTF_{10\%}$=**0.46 lp/mm**

- **Energy painting** enables **imaging of anthropomorphic objects** with large WET variations. **Limitations** in the **dynamic range** of WET measurements with thin dE-detectors can be **overcome**.

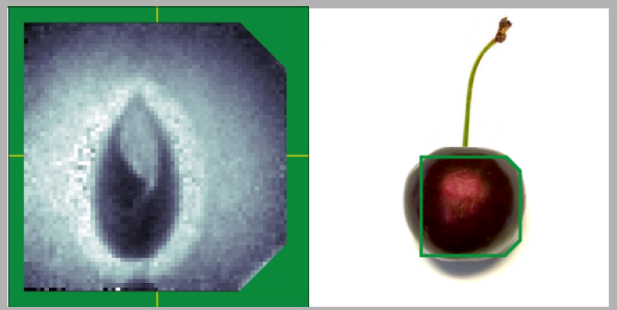


Thanks to our partners





& Thank you for your attention



funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project No.: 426970603

Images: C. Amato, L. Ghesquiere, R. Felix-Bautista, T. Gehrke, M. Martisikova

Back-up 1: Spatial resolution as a function of depth of feature