dosimetry in 4D

(or time-resolved dosimetry)

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overview

4D or time-resolved dosimetry (TRD)

time information and range

detectors for 0-3D TRD

in vivo TRD

motion and LET

analysis of comparisons

general definition of 4D dosimetry

3D dosimetry where detectors are moving

- dosimeters can be integrating or time-resolved
- usually to verify or QA beam delivery with presence of intrafraction or interfraction motion or anatomic changes
- one of the most studied sites is thorax, mostly with longitudinal linear motion, sometimes rotational and translational, either with solid or deformable tissue substitutes
- in phantom or in vivo

wider interpretations possible and useful

any time-resolved dosimetry (TRD)

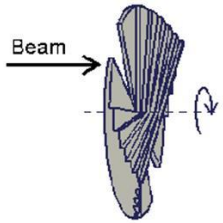
- 0-1-2-3D + time
- regardless of resolution

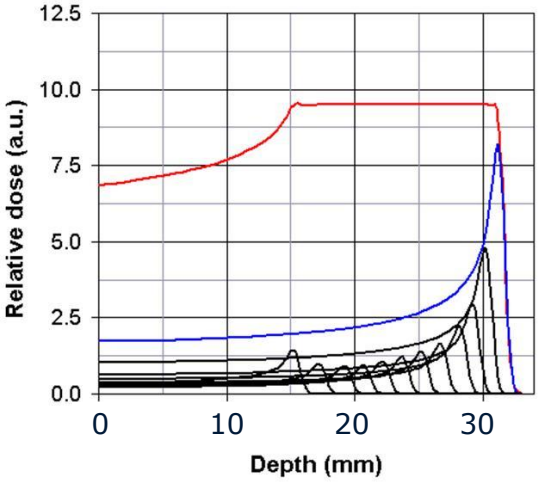
three scenarios:

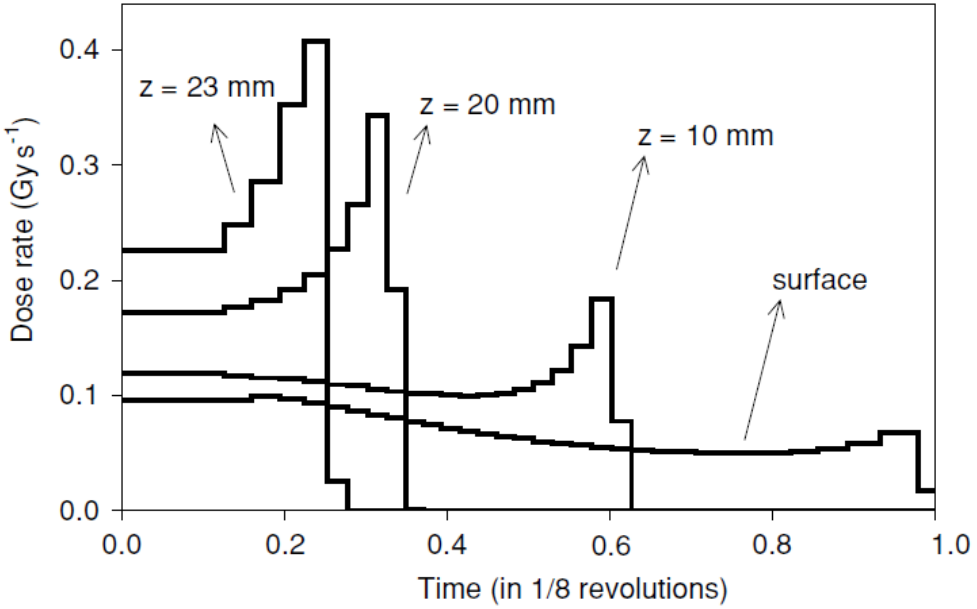
1. detectors moving
2. dynamic source (in fixed or moving frame)
3. both detectors and source moving

1&3 most commonly addressed in 4D dosimetry, but 2 with static phantom/patient also useful in particle therapy

time dependent IC current in SOBP

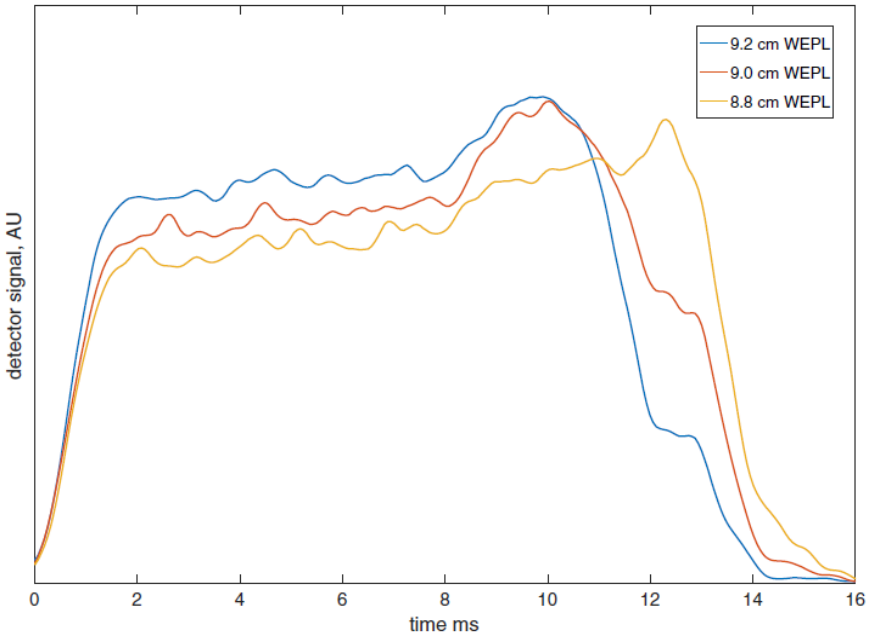


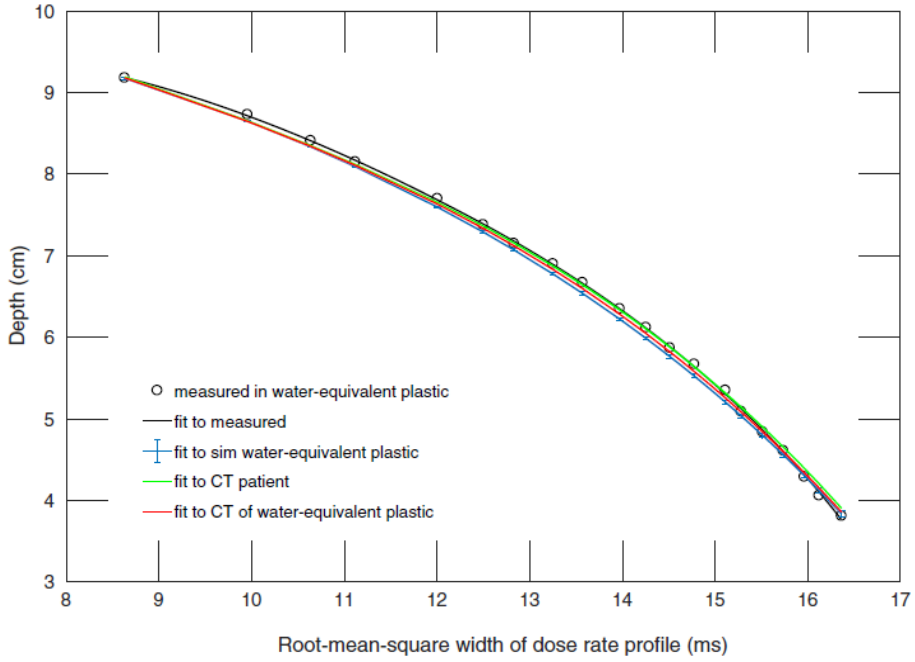




Palmans et al 2006 Phys Med Biol 51:903

e.g., diode for residual range measurement/verification



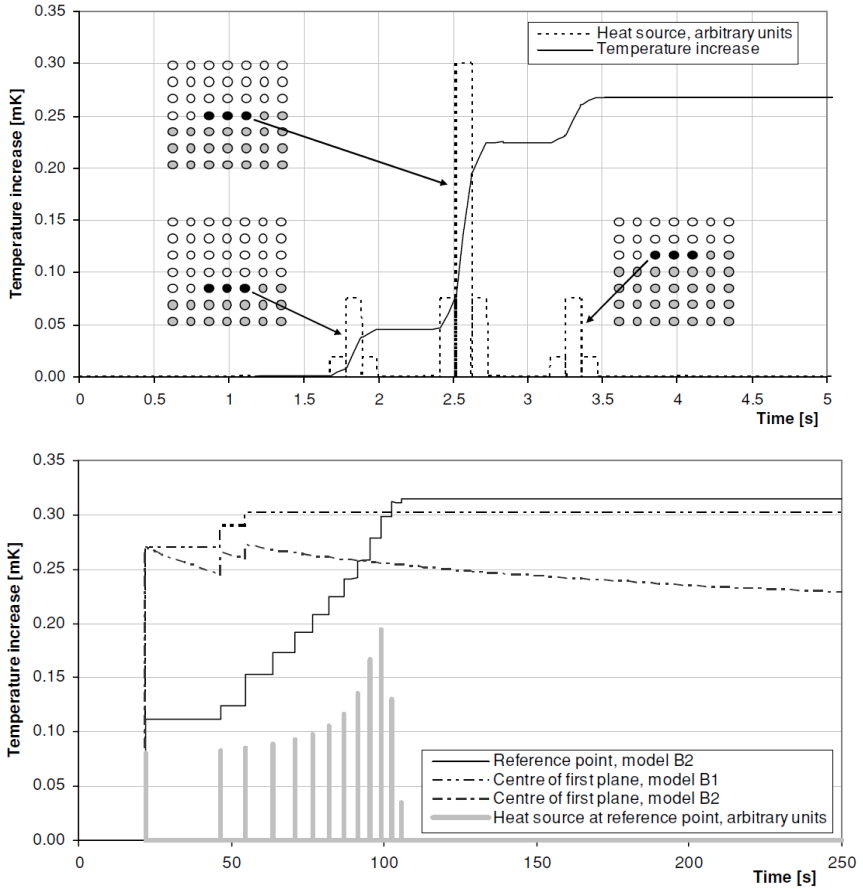


Toltz et al 2017 J Appl Clin Med Phys 18:200

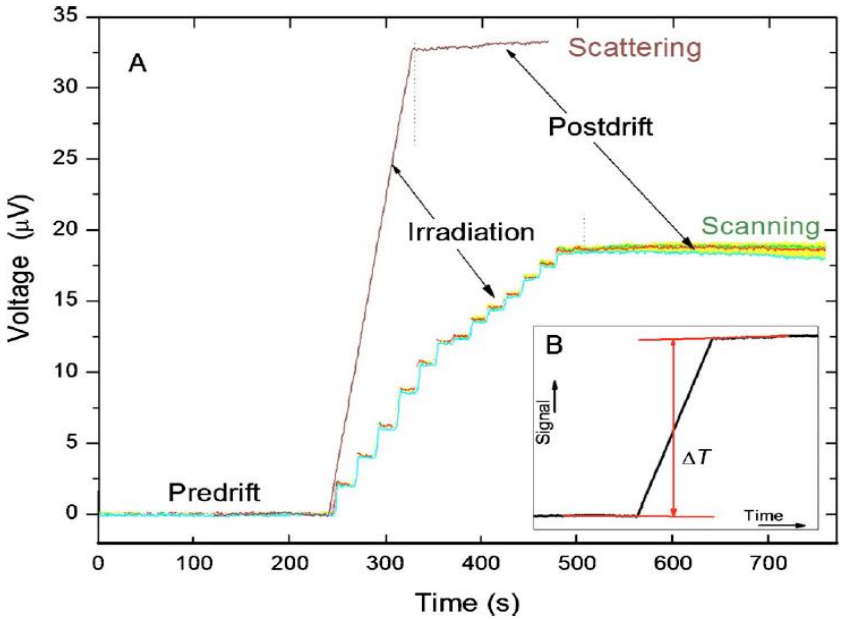
method also used for proton radiography and pCT

(Testa et al 2013 Phys Med Biol 58:8215)

works a bit differently for PBS fields

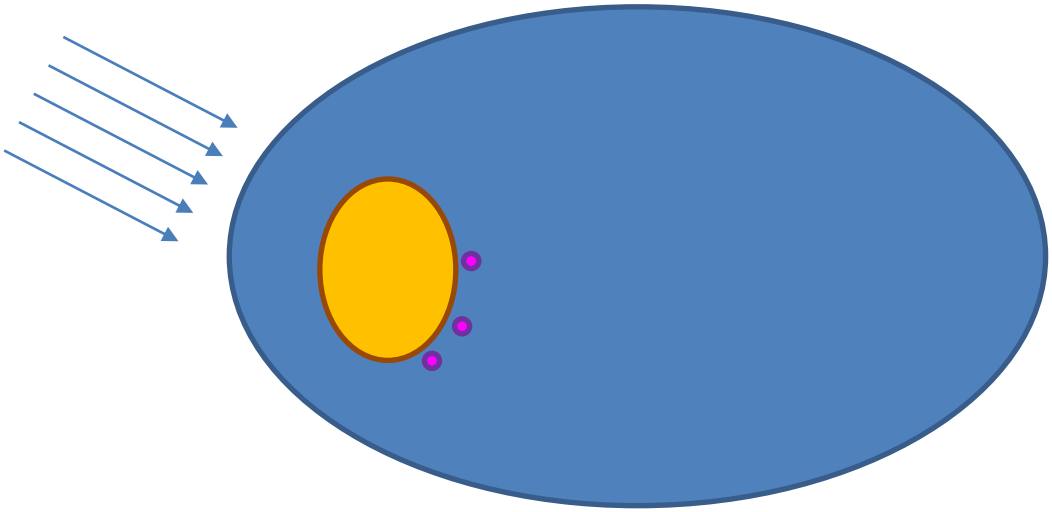


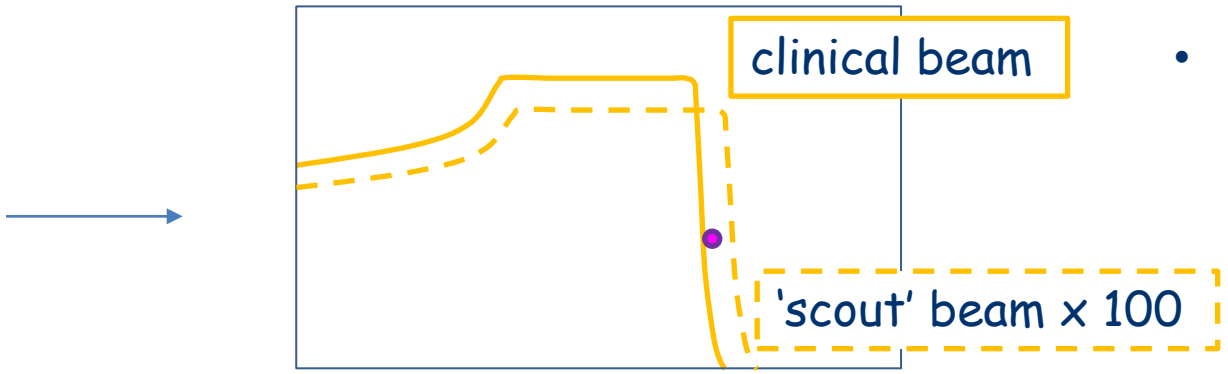
Sassowsky et al 2005 Phys Med Biol 50:5381



Sarfehnia et al 2010 Med Phys 37:3541

would this work in vivo?





possible detectors

- fiducials:
  - PIXE (La Rosa et al 2015 PMB59:2623)
  - X-B (gel, Fricke – e.g., De Deene et al 2020 PMB65:225031)
  - prompt-γ (Martins et al 2021 Sci Rep 15331)
- implantable mosfet
- diode, FOS, MOSFET via needle or catheter (e.g., Cherpak et al 2009 Med Phys 36:1672)

identifying sources of hot/cold spots

0-1-2D detectors often mentioned

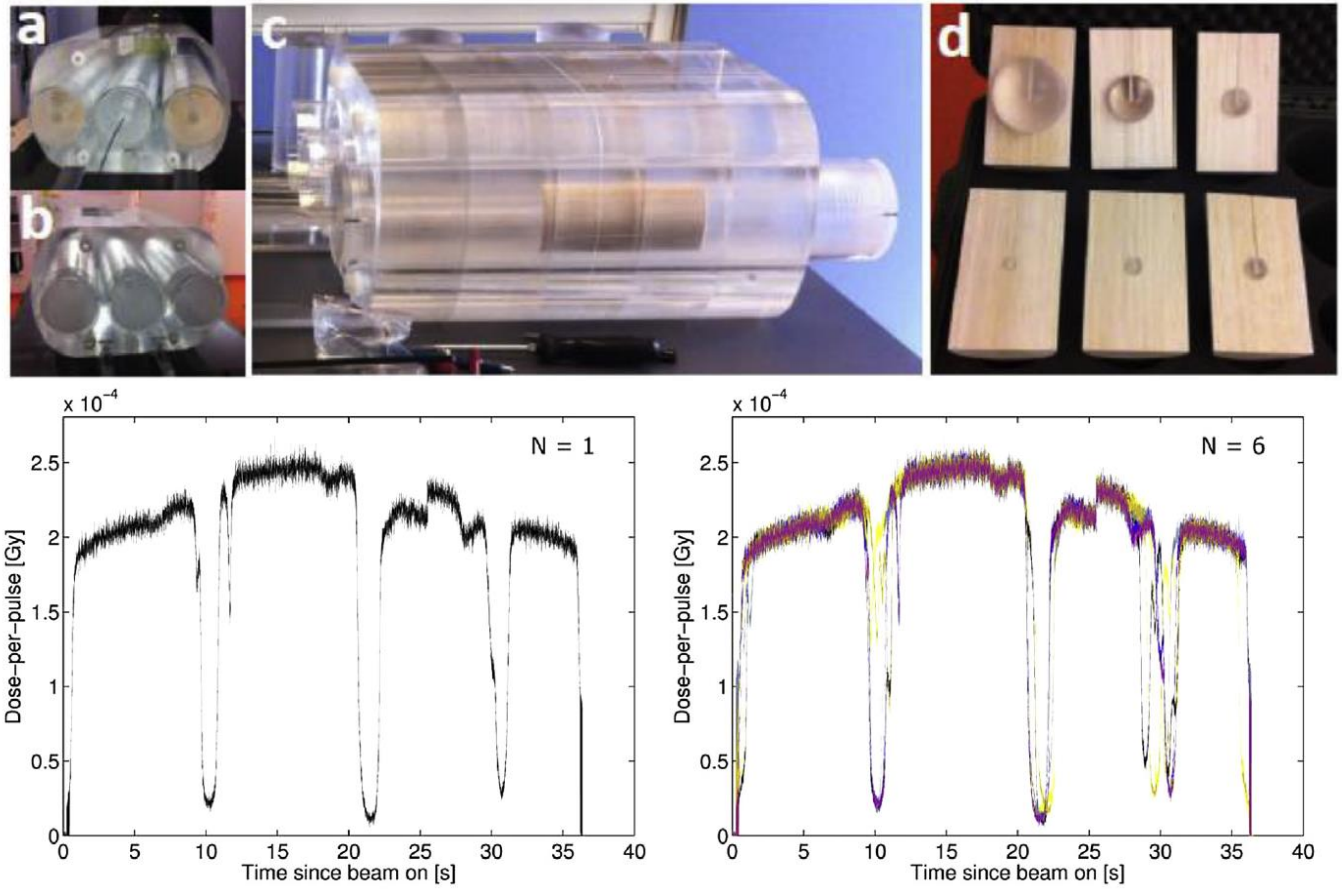
e.g., Trnkova et al 2018 Phys Med 54:121

TLD: only integrating, considerable energy dependence, limited resolution

film: high resolution, but only integrating

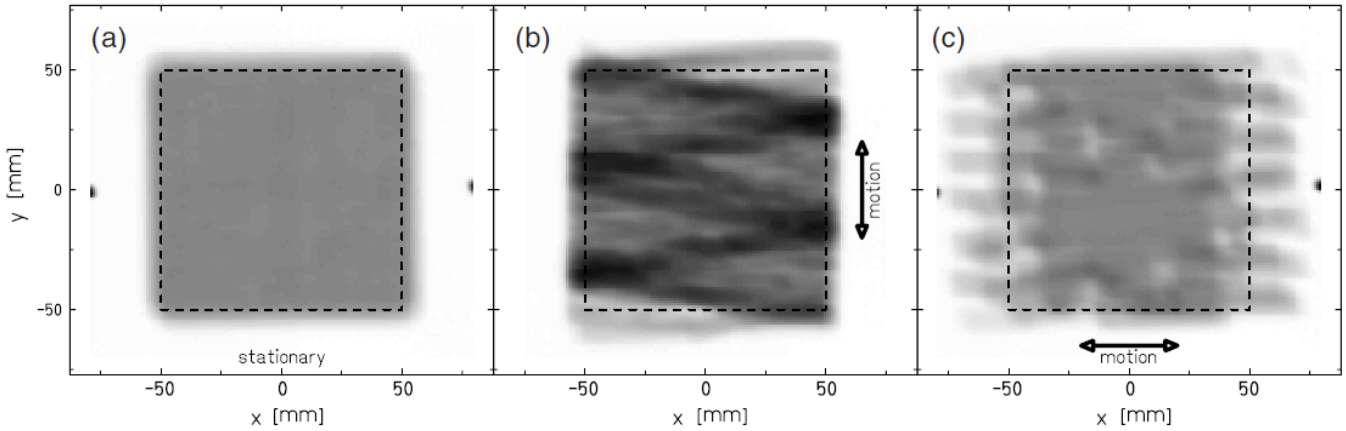
ionization chamber (arrays): reliable dosimeter but limited resolution, large uncertainty in the presence of dose gradients

OD detectors: FOS target in moving lung phantom / IMRT



Sibolt et al 2017 Rad Meas 107:373

2D detectors: film for TRD PBS protons



Bert et al 2008 Phys Med Biol 53:2253

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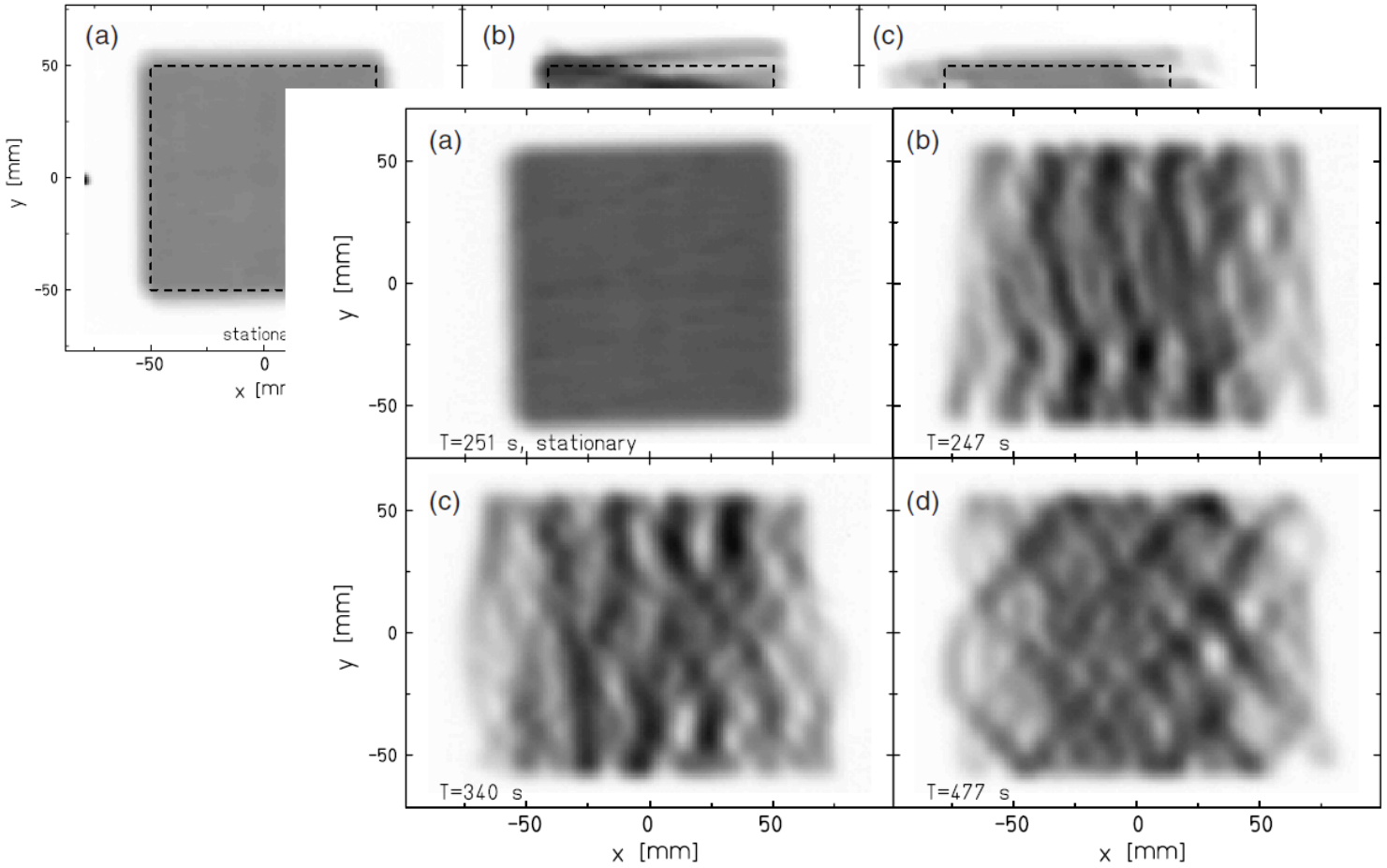

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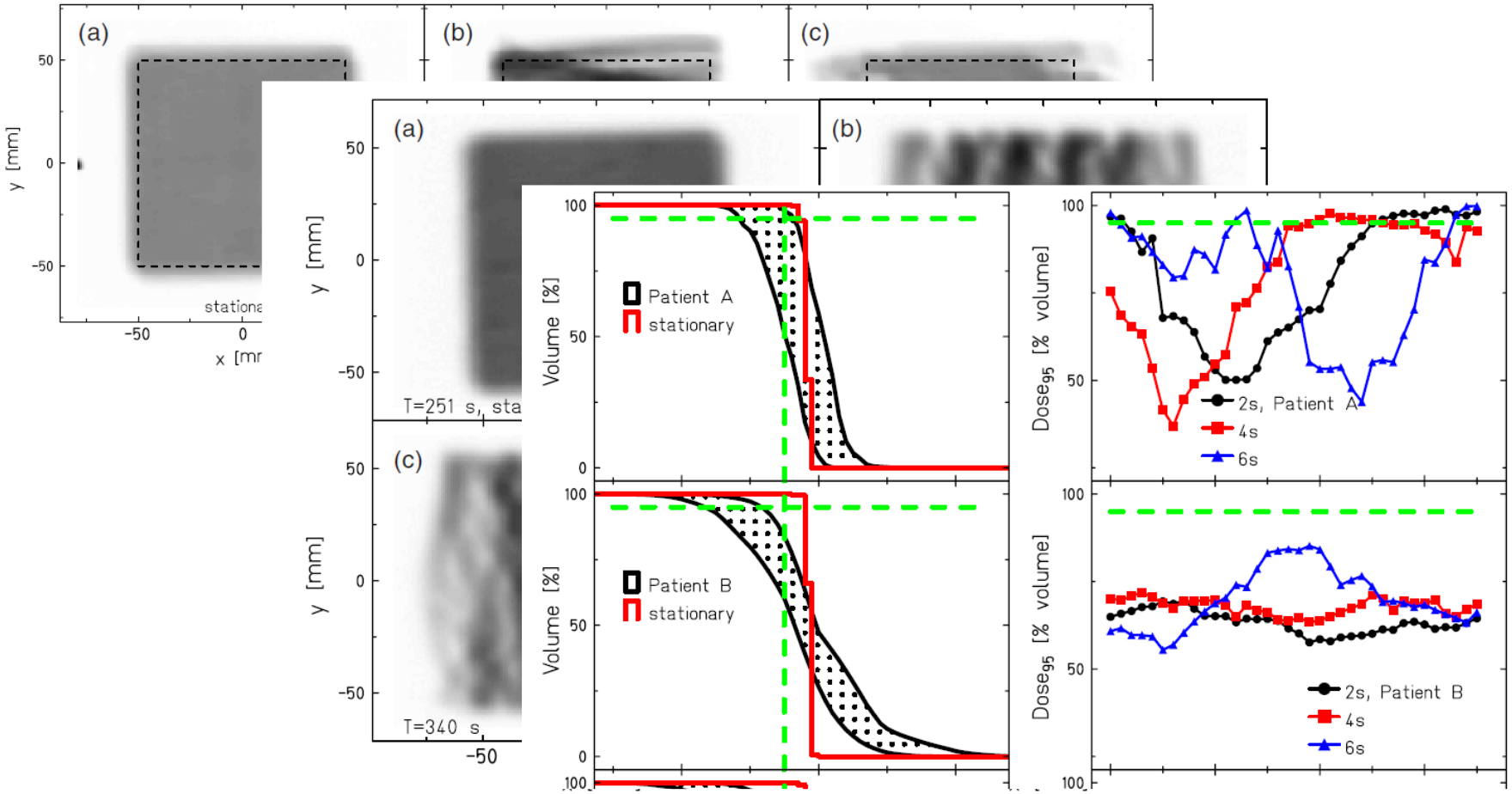
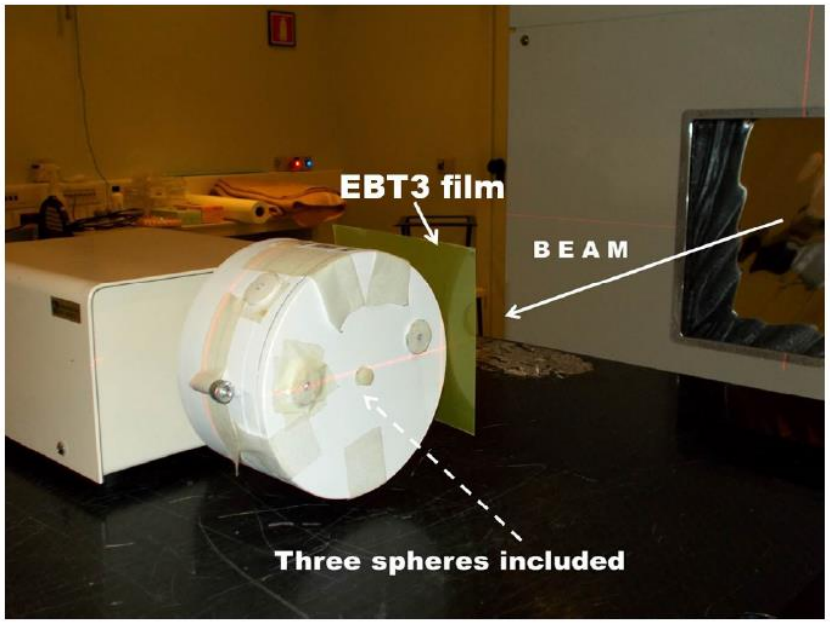
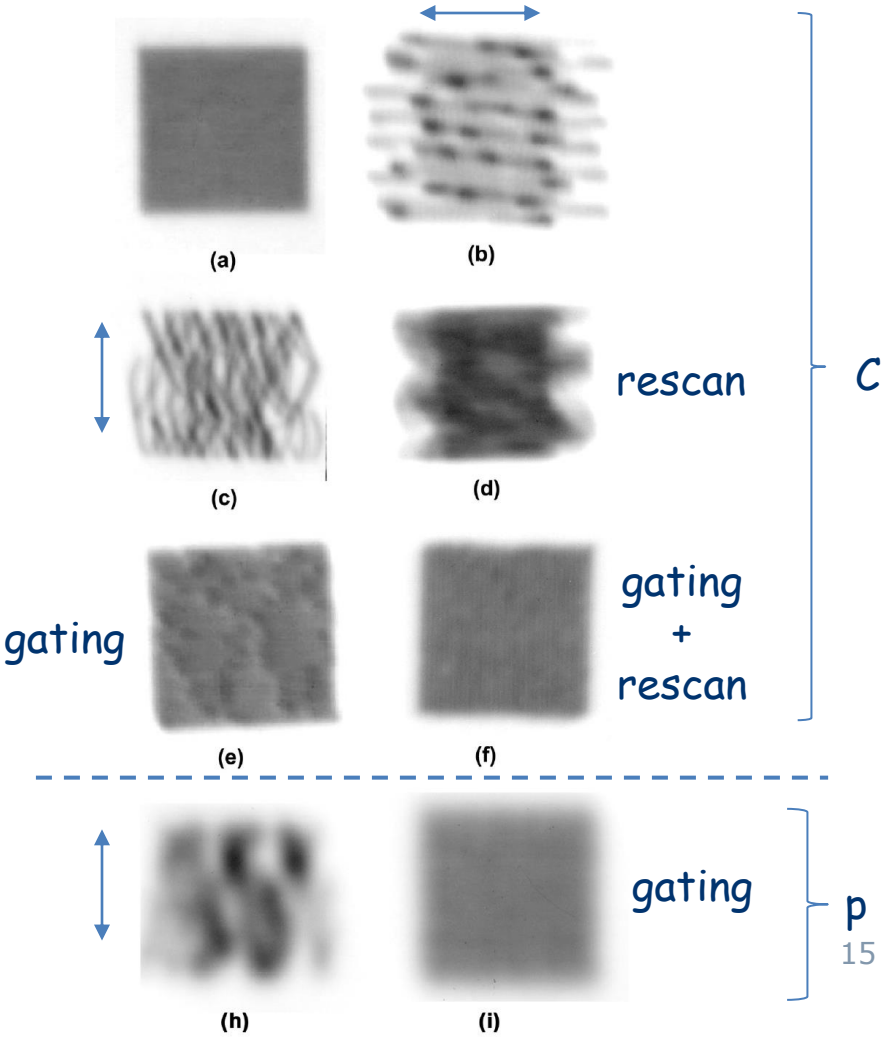


Bert et al 2008 Phys Med Biol 53:2253

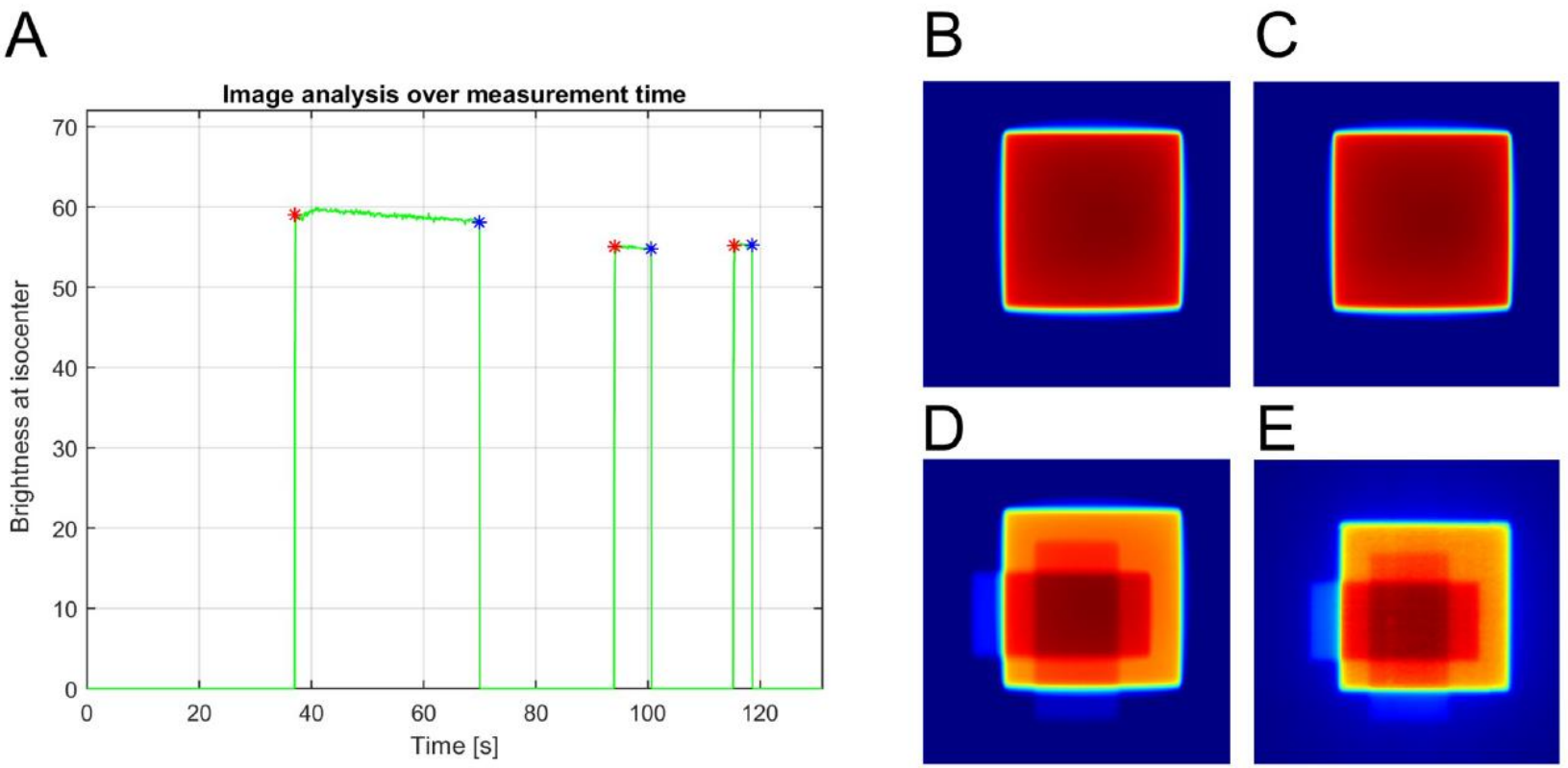
2D detectors: film for TRD PBS carbon ions





Ciocca et al 2016 Phys Med 32:1667

2D detectors: scintillating screen for TRD in IMRT



Cheon et al 2021 PlosOne 16:e0246742

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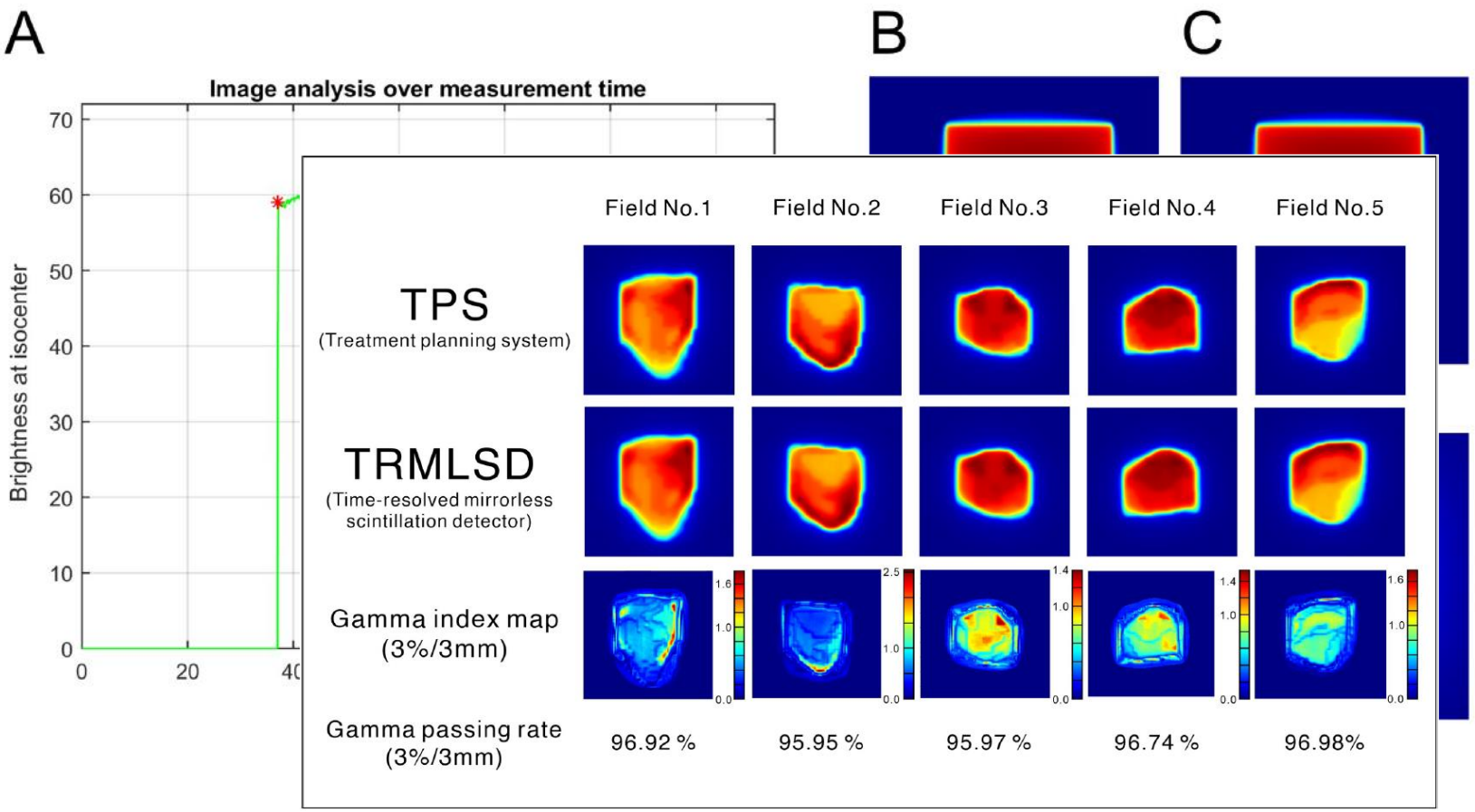

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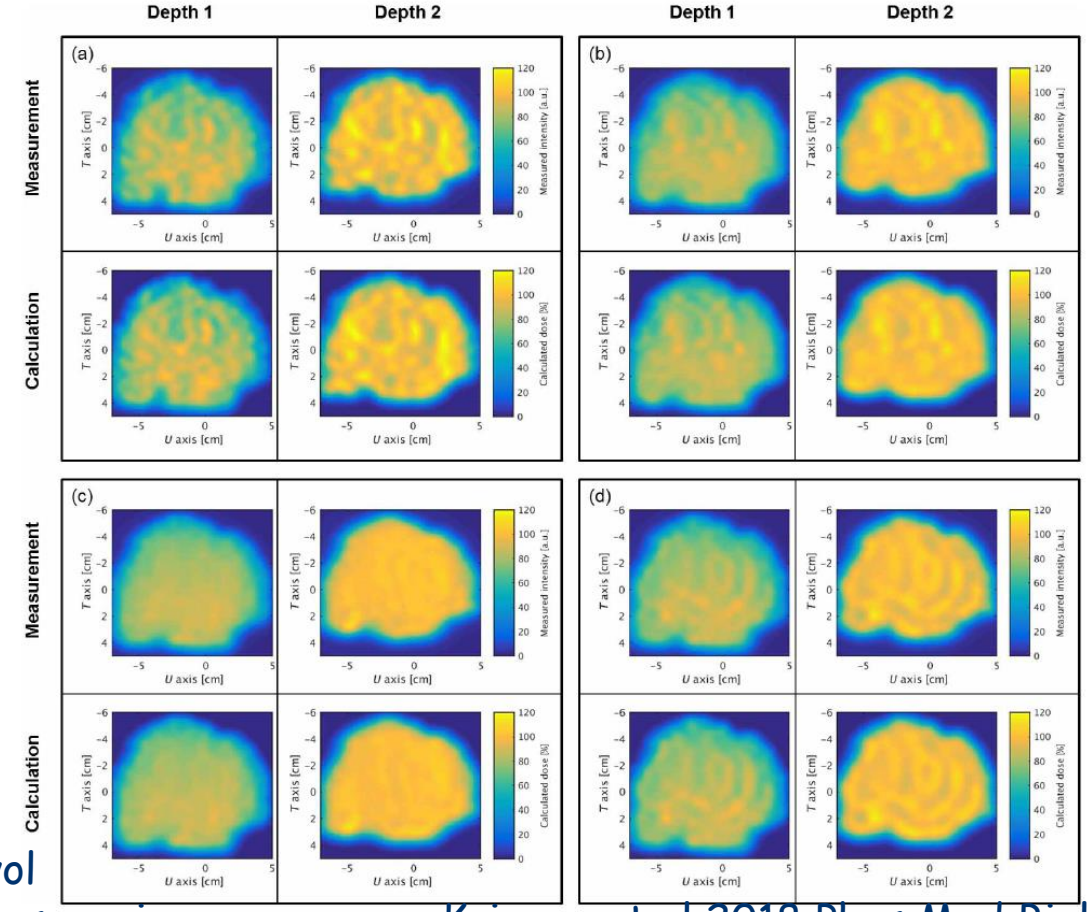
2D detectors: scintillating screen for TRD verification PBS proton delivery



layered rescanning

vol rescanning

Krieger et al 2018 Phys Med Biol 63:055005

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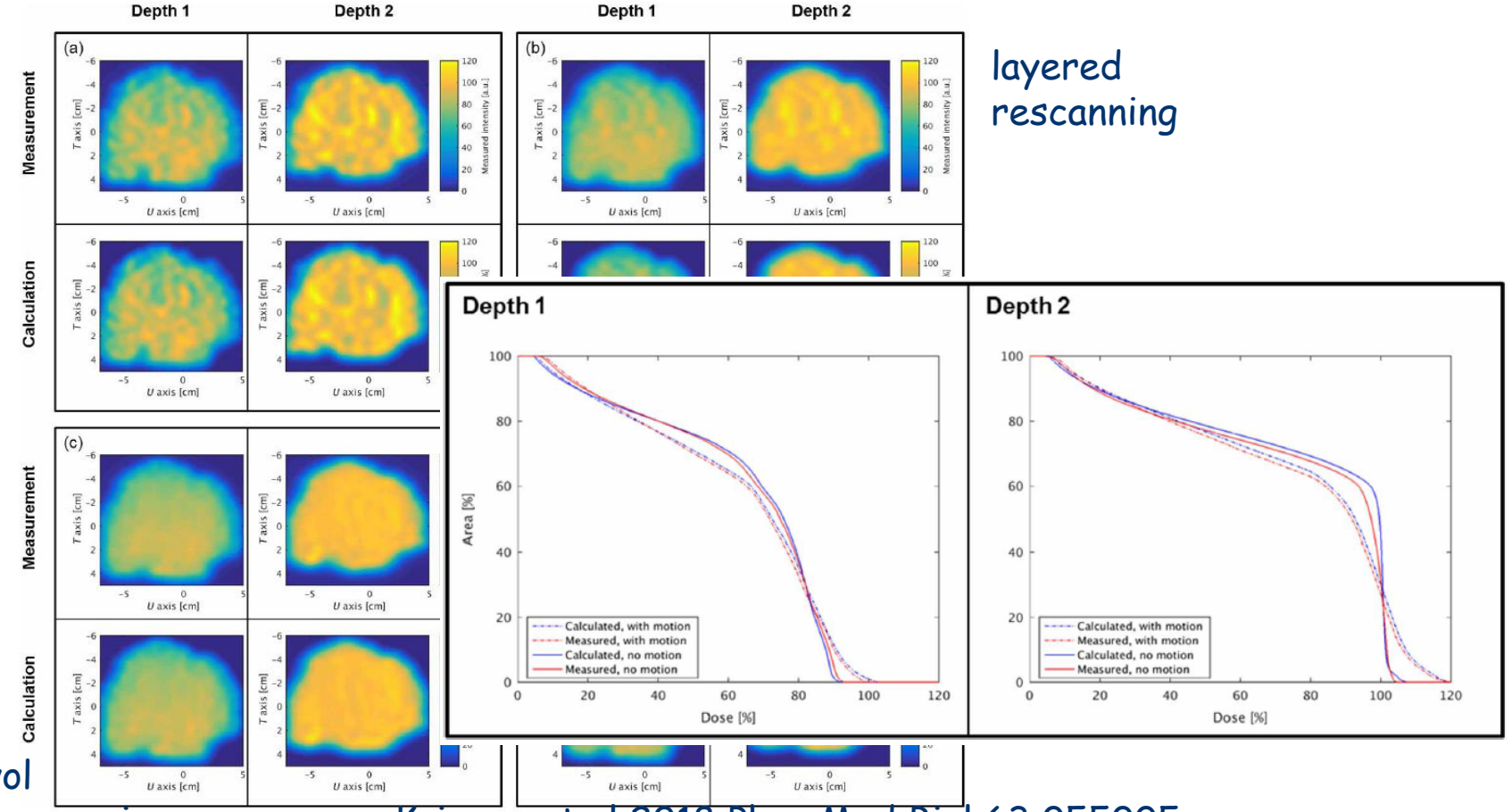

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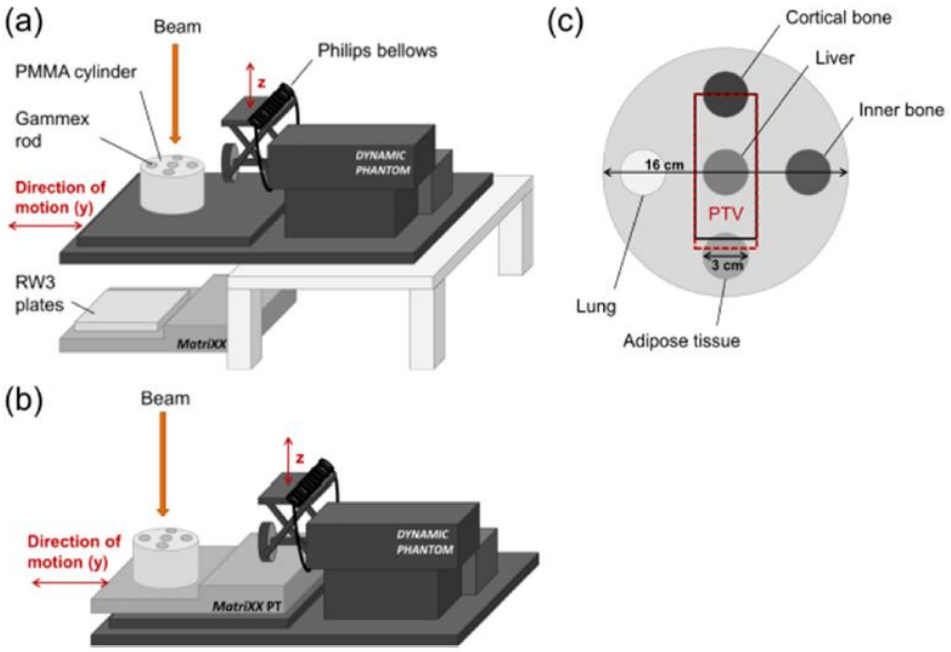
2D detectors: ion chamber array for TRD verification PBS proton delivery



Pfeiler et al 2018 Z Med Phys 28:121

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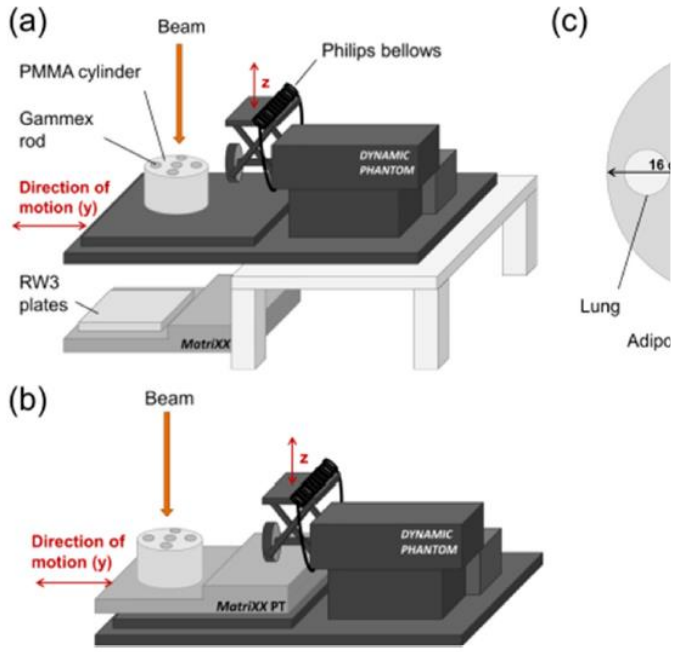
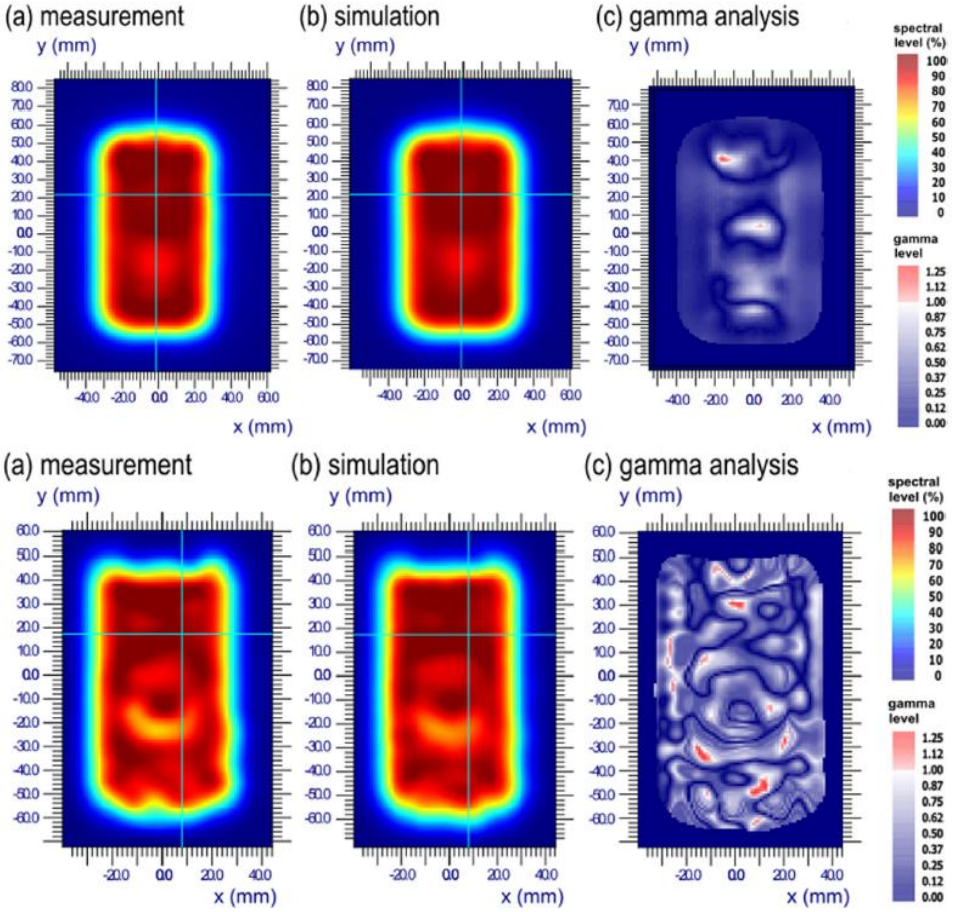
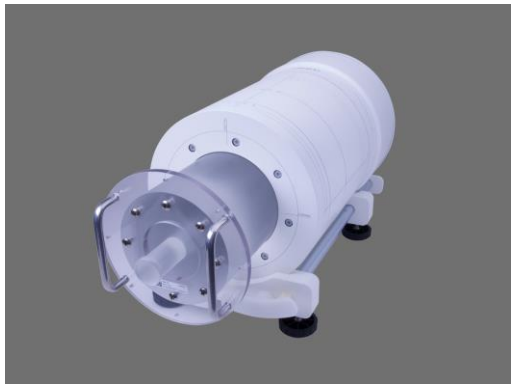


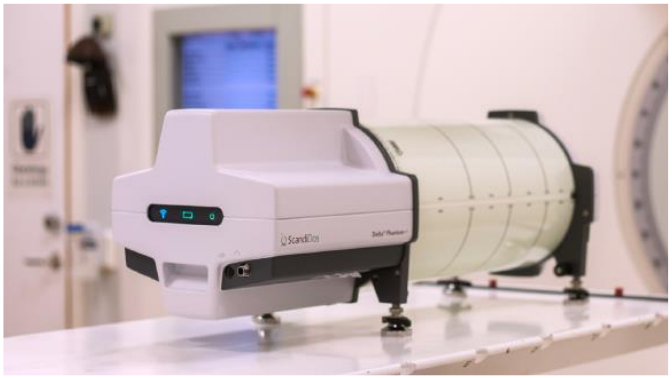


Pfeiler et al 2018 Z Med Phys 28:121

3D detectors: commercial solutions for IMRT, ARCT, VMAT, …



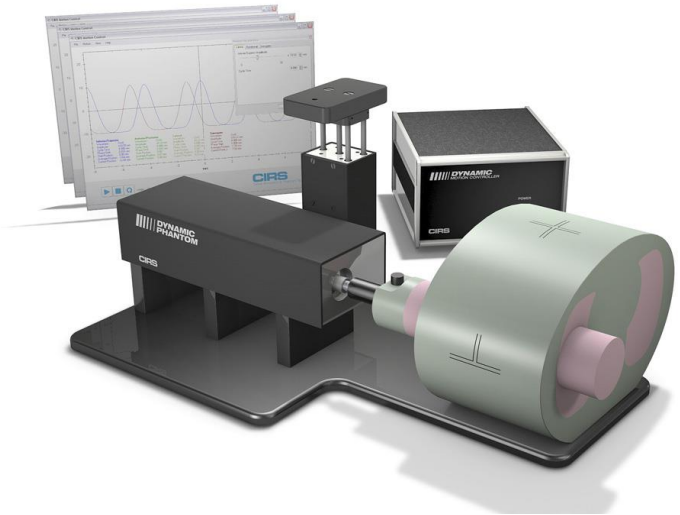
ArcCHECK – Sun Nuclear

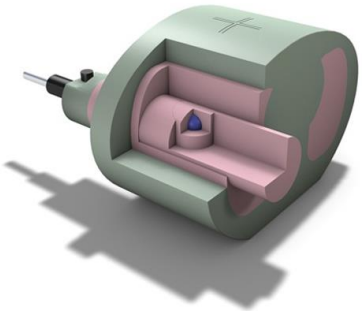


Delta^4 - ScandiDos

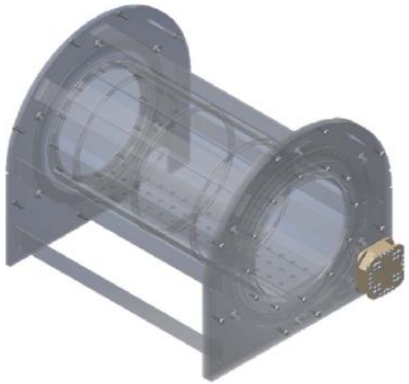
OCTAVIUS 4D

dynamic phantoms





3D detectors: MRI-linac + gel for TRD / IMRT



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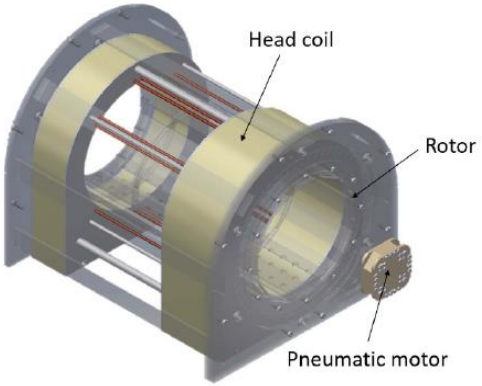
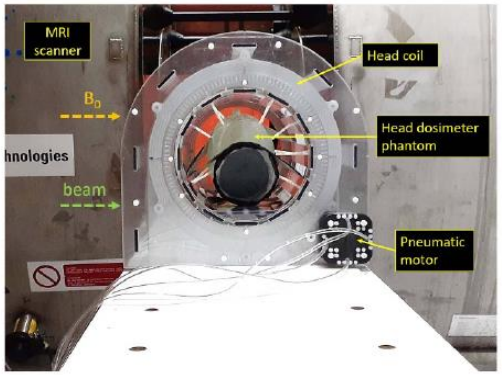
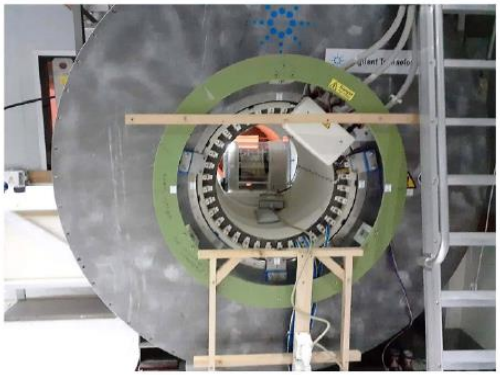


(b)



(c)



(d)

De Deene et al 2020 Med Phys 65:225031

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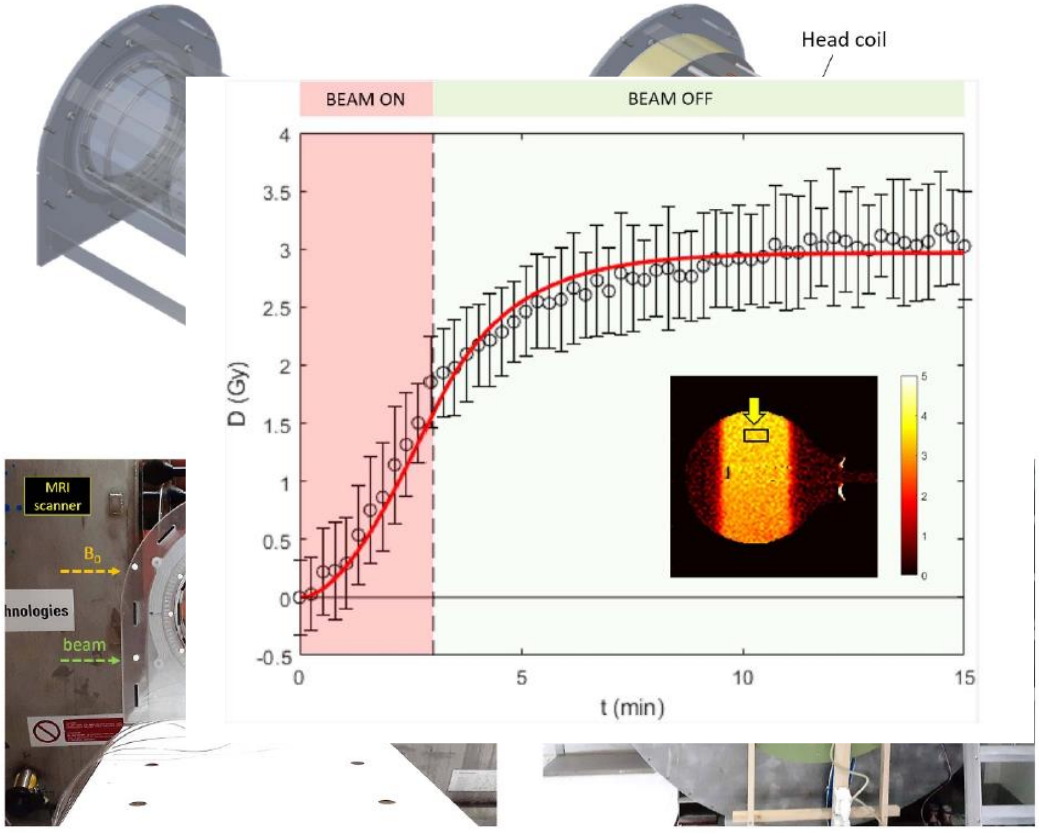

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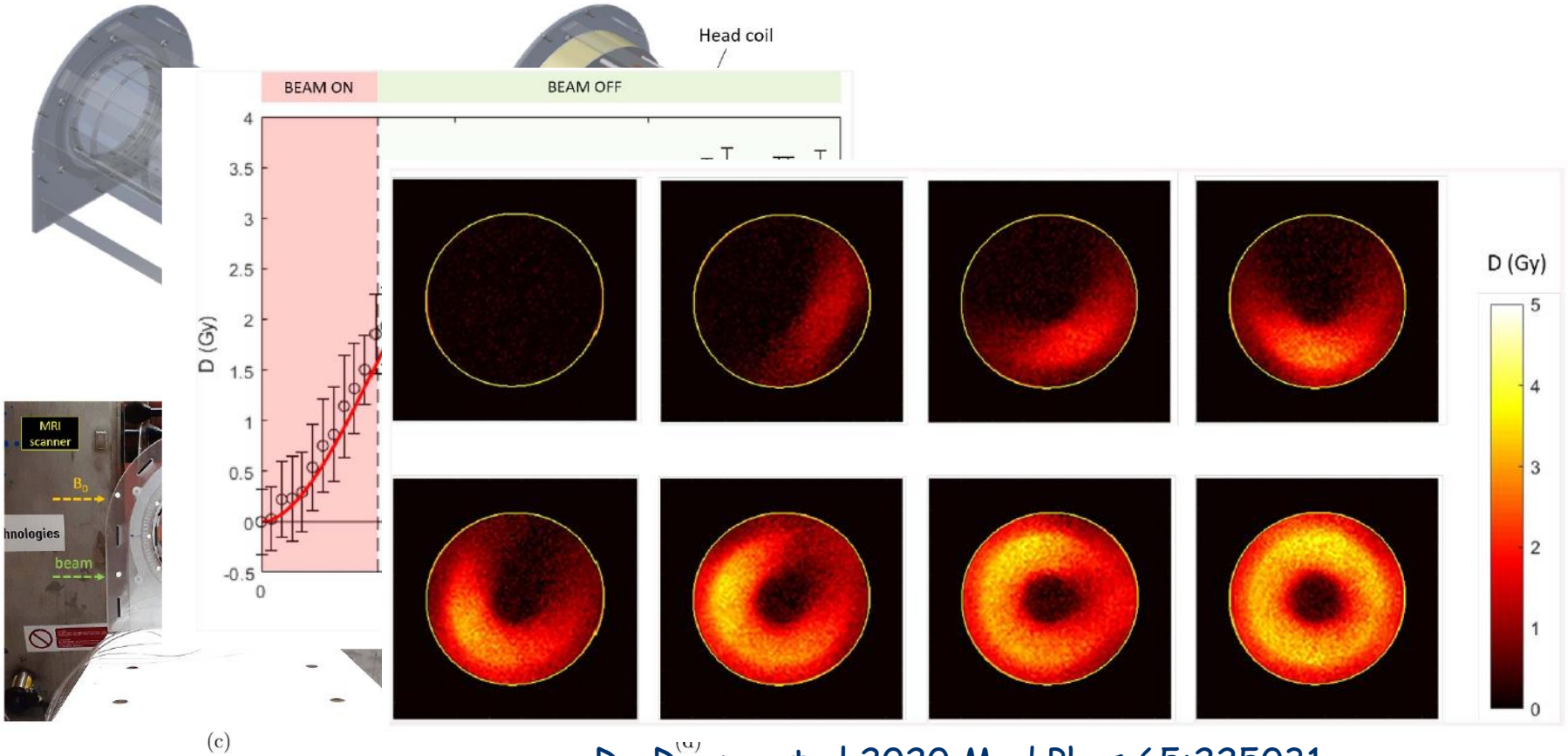

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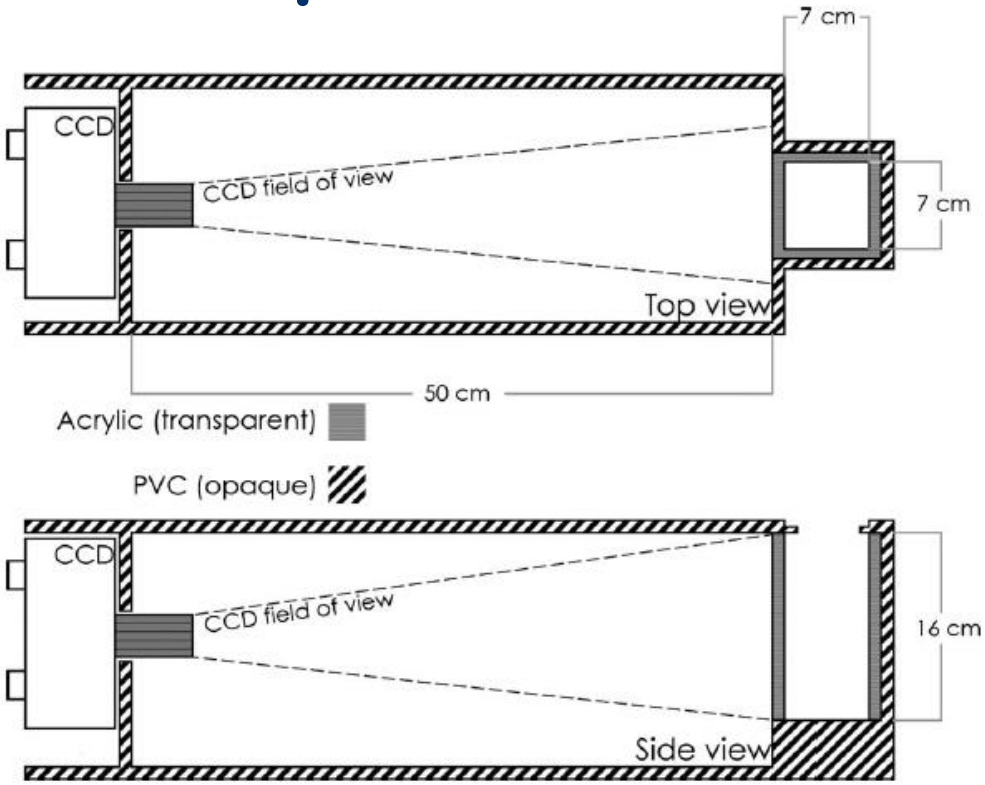
3D detectors: liquid scintillator for TRD scanned proton beams



Beddar et al 2009 Med Phys 36:1736

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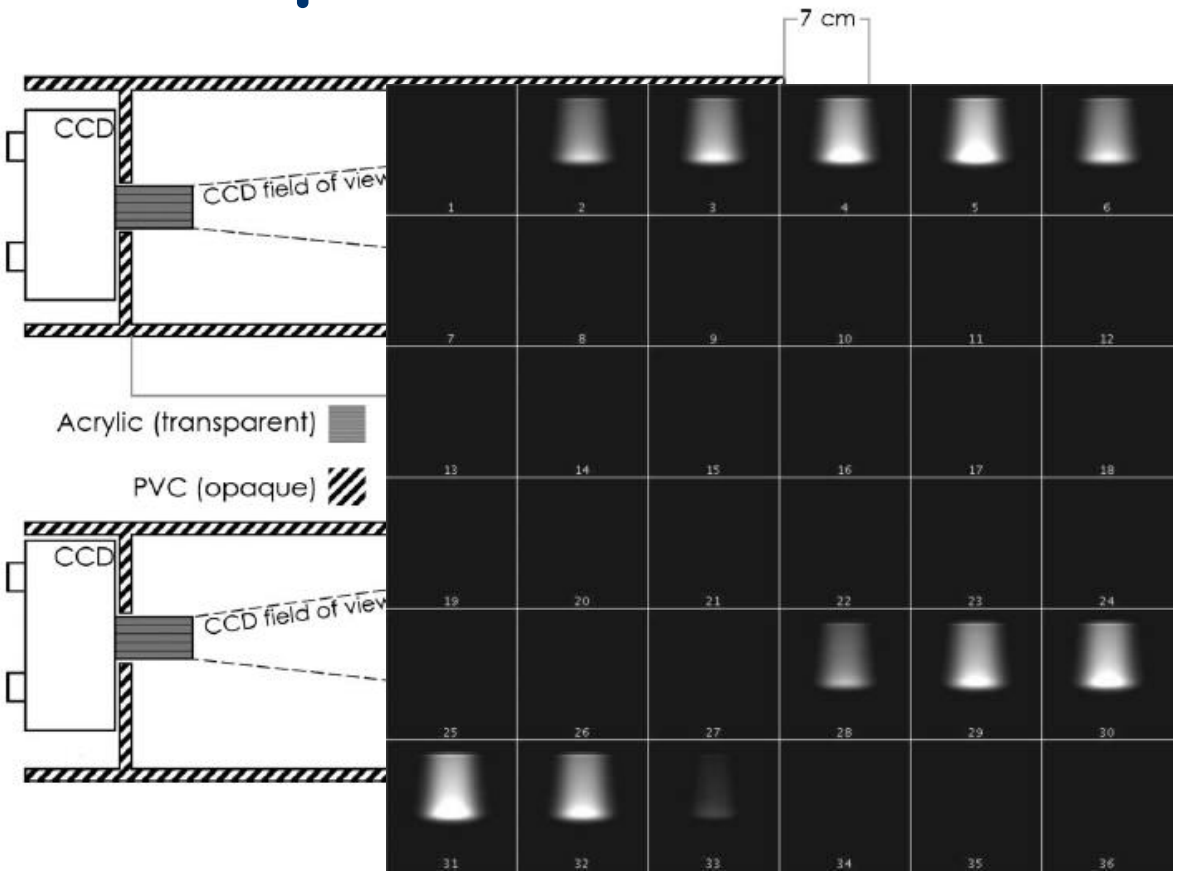
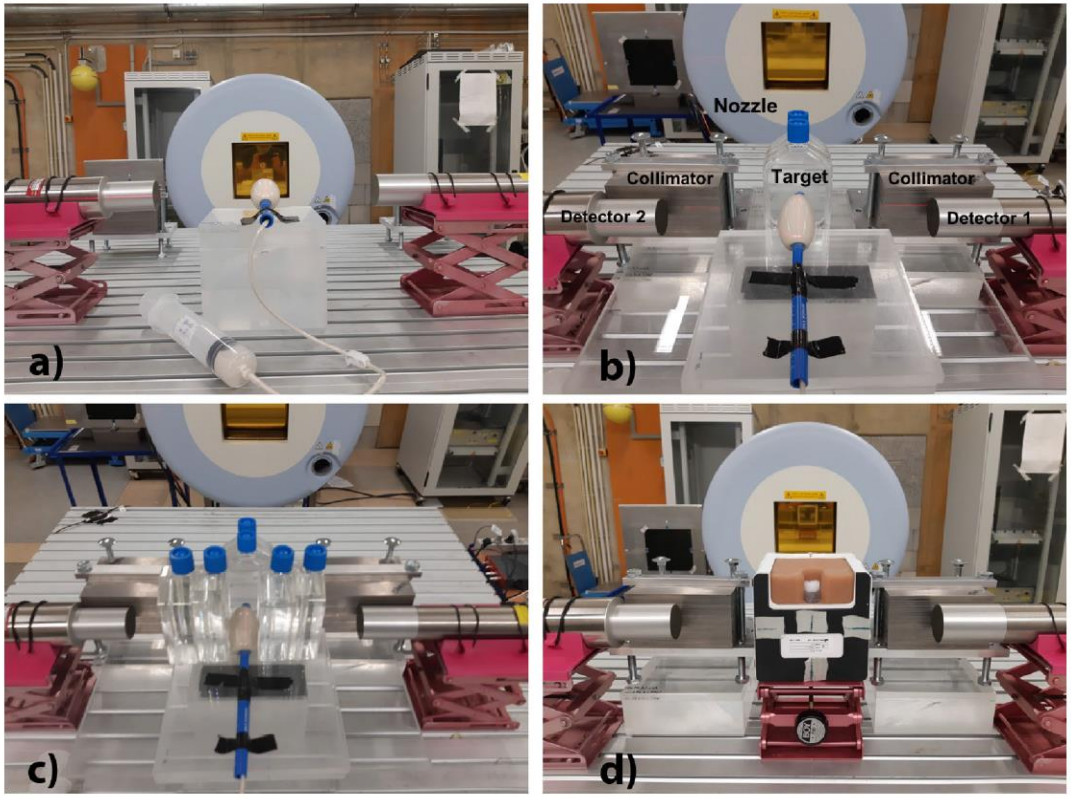


100 ms intervals

Beddar et al 2009 Med Phys 36:1736

3D detectors: prompt gamma



Martins et al 2021 Sci Rep 11:15331

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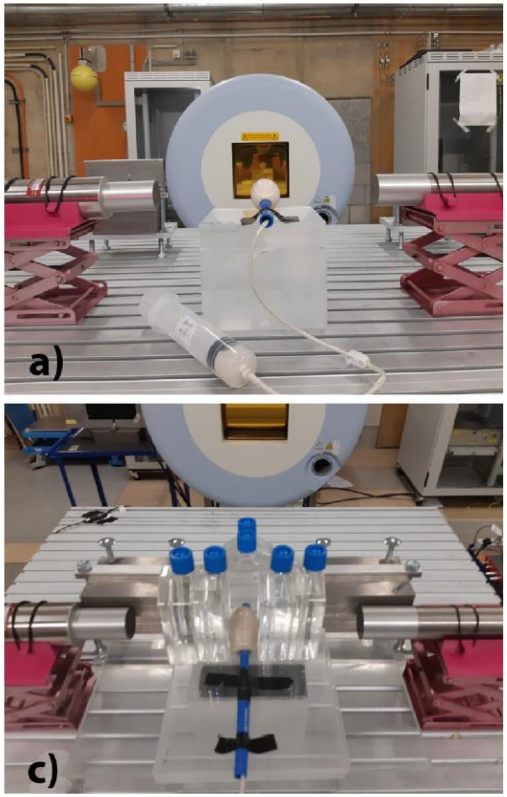

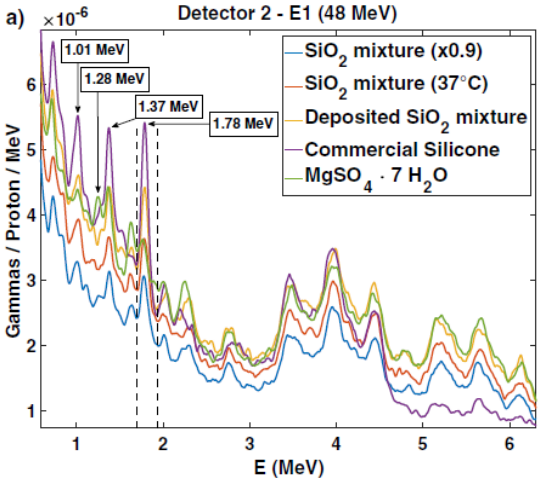

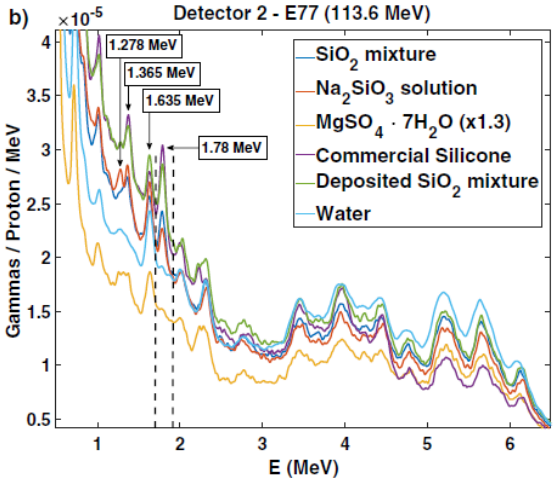

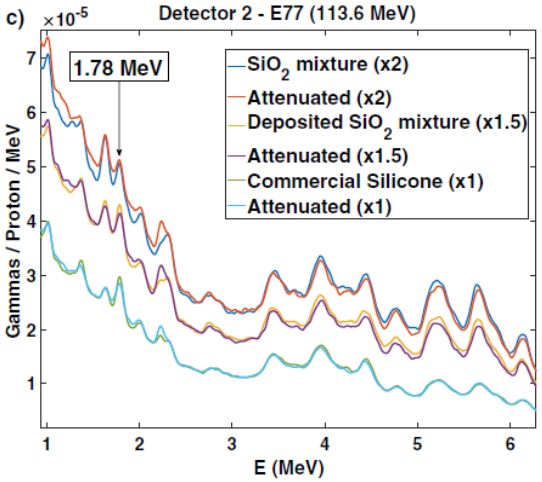

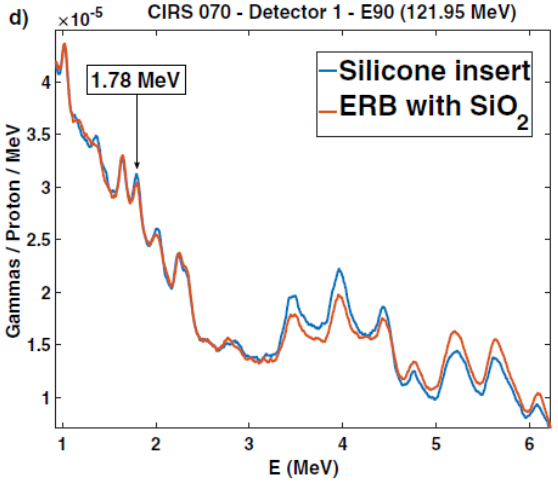

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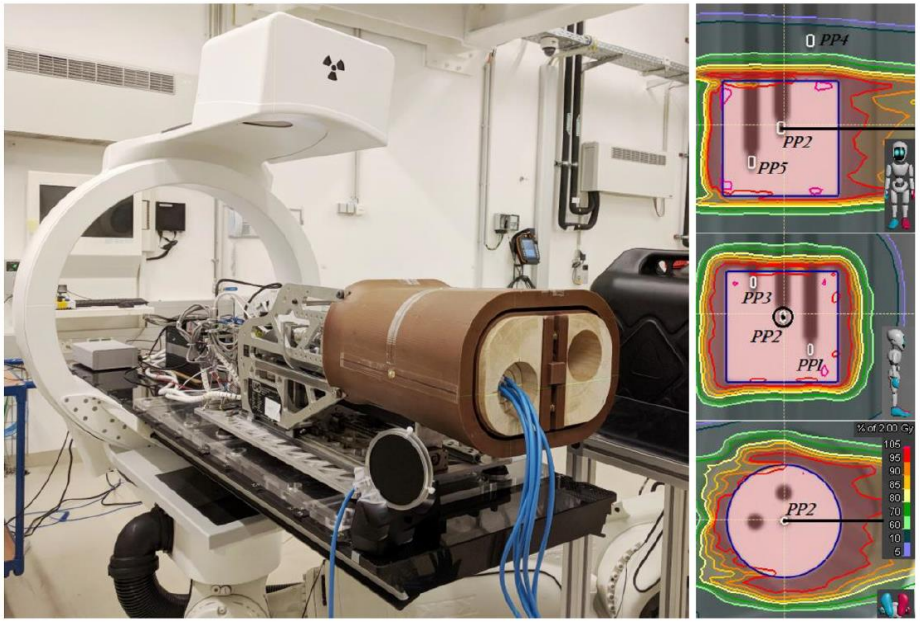
3D detectors: ionization chambers for TRD scanned proton beams



Kostiukhina et al 2020 Phys Med Biol 65:125015

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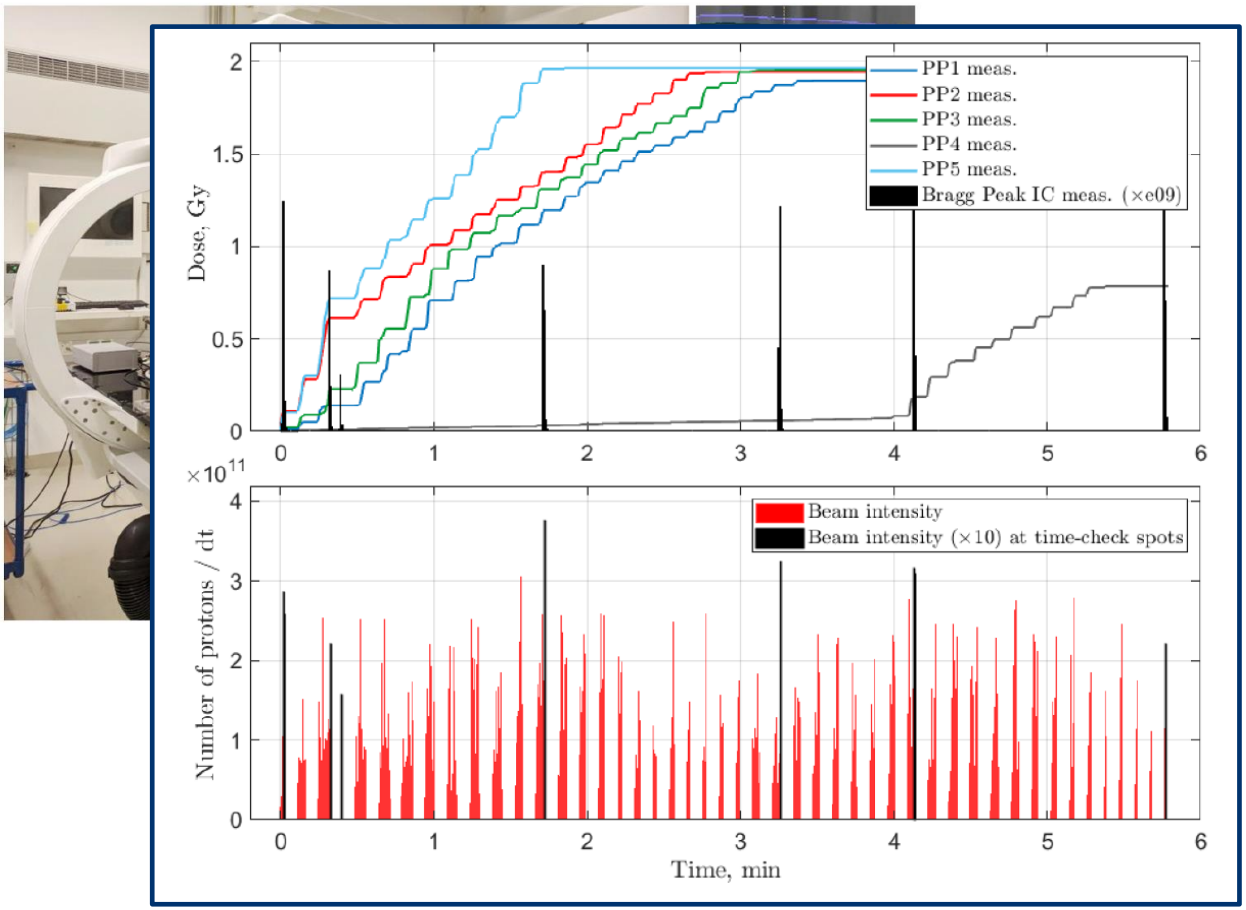

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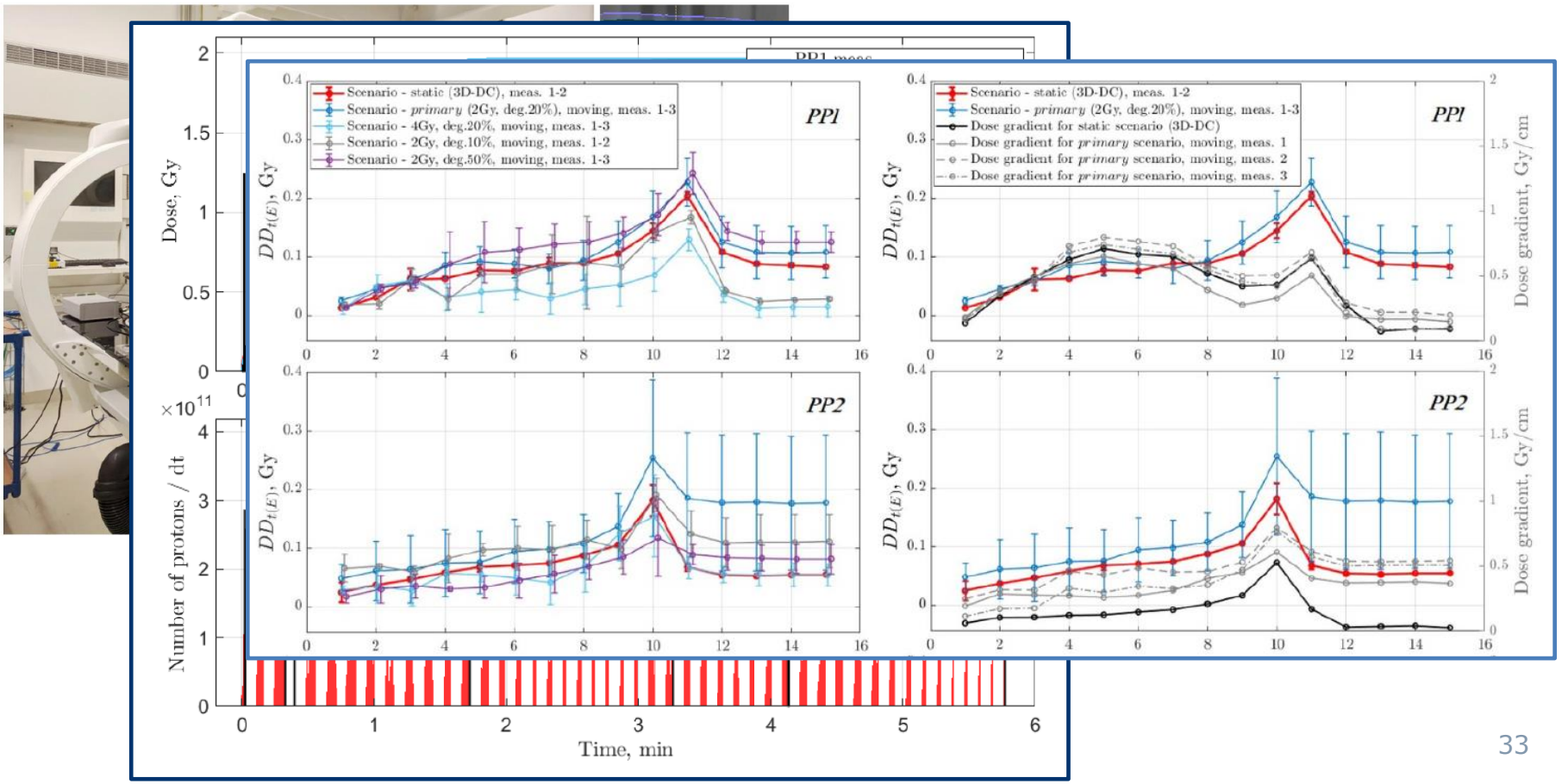


Kostiukhina et al 2020 Phys Med Biol 65:125015

in vivo TRD: portal dosimetry?

in principle yes

requires proton beam with sufficient energy as 'scout' beam

for carbon ions mixing with helium ions

in vivo TRD: MRI-PT?

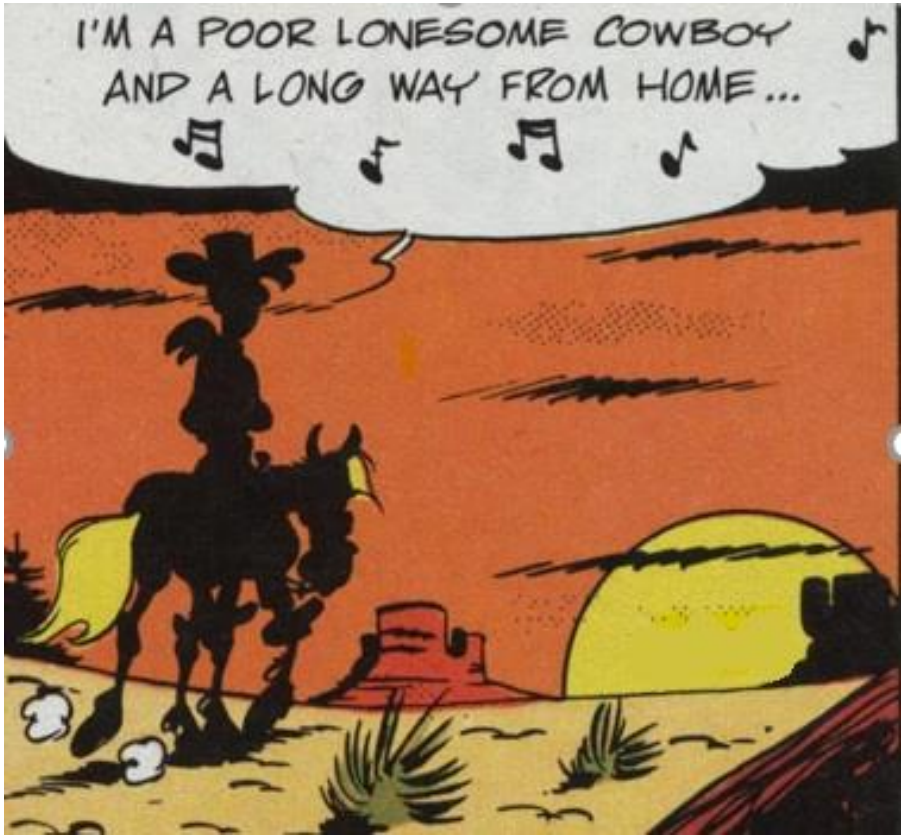
in principle yes

but requires contrast agent that changes magnetic susceptibility

in vivo TRD: prompt gamma?

in principle yes

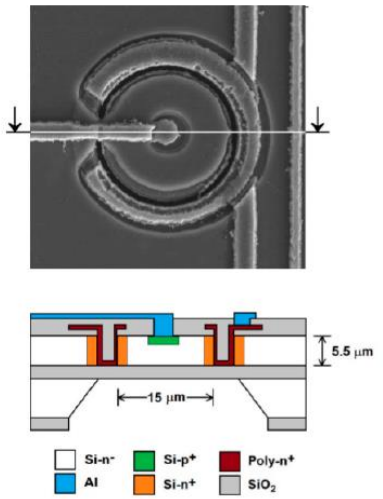
but a long way to go…



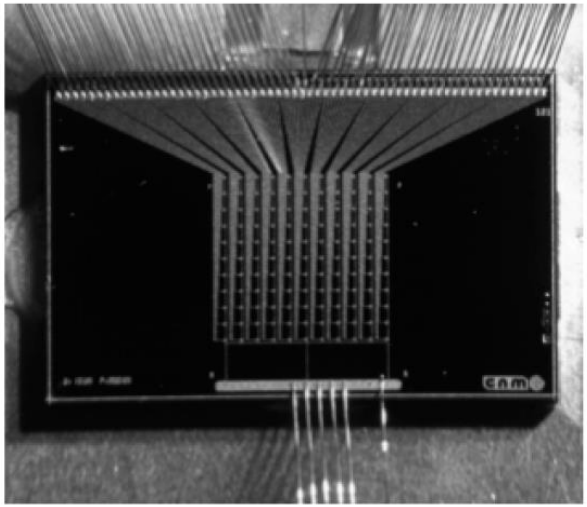
effect of motion on LET

LET cannot be measured

…but could be derived from lineal energy spectra by deconvolving energy loss straggling



(a)



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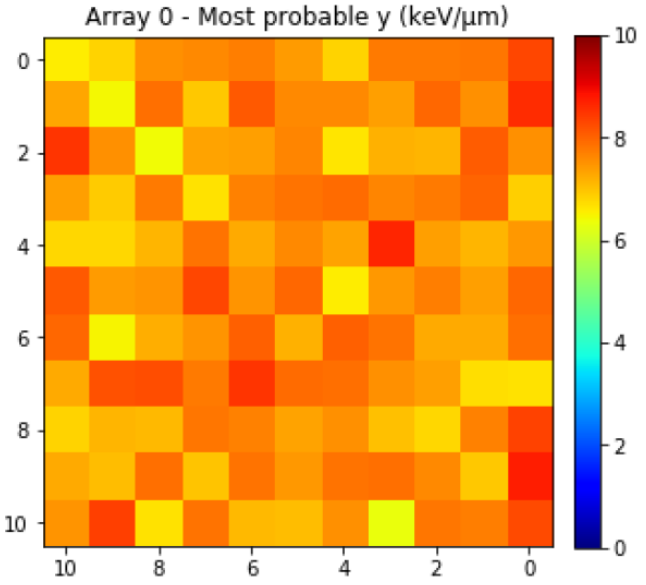

Guardiola et al 2021 Radiother Oncol 161:S126

ways to analyse deviations from plan

qualitative visual inspection

DVH

cumulative dose / intensity log files

alternative gamma evaluation (hyper-gamma)

$$\gamma_H\left(\vec{r}_m,t_m\right)=\min\left\{\Gamma_H\left(\vec{r}_m,t_m,\vec{r}_c,t_c\right)\right\}\forall\left(\vec{r}_c,t_c\right)$$

where

$$\Gamma_H\left(\vec{r}_m,t_m,\vec{r}_c,t_c\right)=\sqrt{\frac{\tau^2\left(t_m,t_c\right)}{\Delta t^2}+\frac{r^2\left(\vec{r}_m,\vec{r}_c\right)}{\Delta d^2}+\frac{\delta^2\left(\vec{r}_m,t_m,\vec{r}_c,t_c\right)}{\Delta D^2}}$$

As in the original gamma evaluation method, the evaluated point passes the test if $\gamma \le 1$

Norström et al 2013 J Phys Conf Ser 444:012021

summary

TRD can be used for improved range measurement

time structure of dose

detectors for TRD in 0-1-2-3D and in vivo

importance of time stamps for detailed comparison with plans, log-files

LET and motion