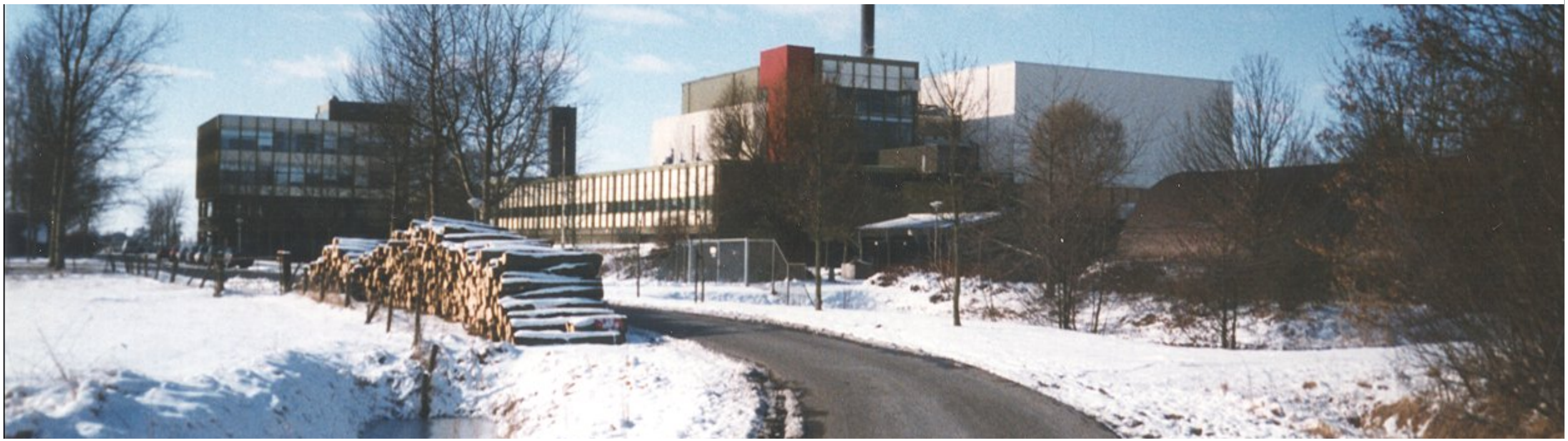
university of groningen

kvi - center for advanced radiation technology

Imaging patient and beam: developments at KVI-CART

Peter Dendooven

MediNet Midterm Meeting
Belgrade, March 12-14, 2018



Contents

- Proton therapy in Groningen
- Imaging the patient
  - dual-energy CT
  - proton radiography
- Imaging the beam
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  - dSiPM radiation hardness
- Financing for experiments at the AGOR cyclotron facility
  - ENSAR2
  - INSPIRE
  - ESA

UMC Groningen Proton Therapy Center

- **IBA *ProteusPLUS***
- **2 treatment rooms**
- **capacity ~ 600 patients per year**

www.umcgroningenptc.nl/en/

start of operations: 22 January 2018
first proton therapy treatment in the Netherlands

Imaging the patient

from anatomy to proton stopping power

3-4% uncertainty in proton range

imposes a safety margin around tumour

better

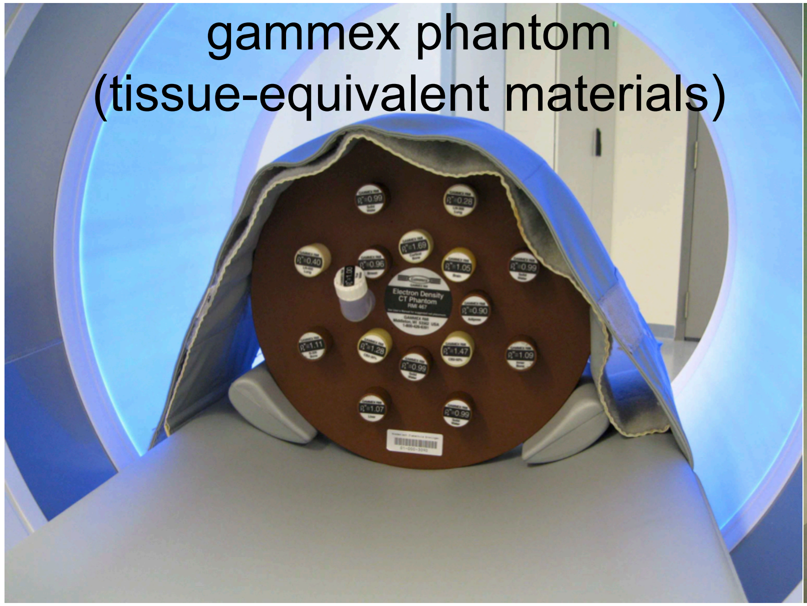
- information at multiple X-ray energies, e.g. dual-energy CT (DECT)
- information from protons: proton radiography/CT

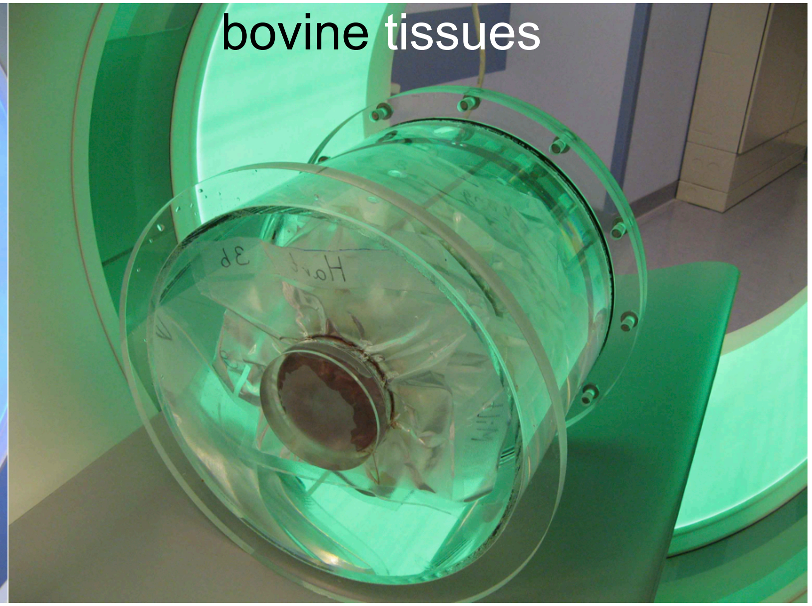
Multiple X-ray energies: DECT

dual-energy CT

Experimental investigation

(DE)CT
at UMCG


gammex phantom
(tissue-equivalent materials)

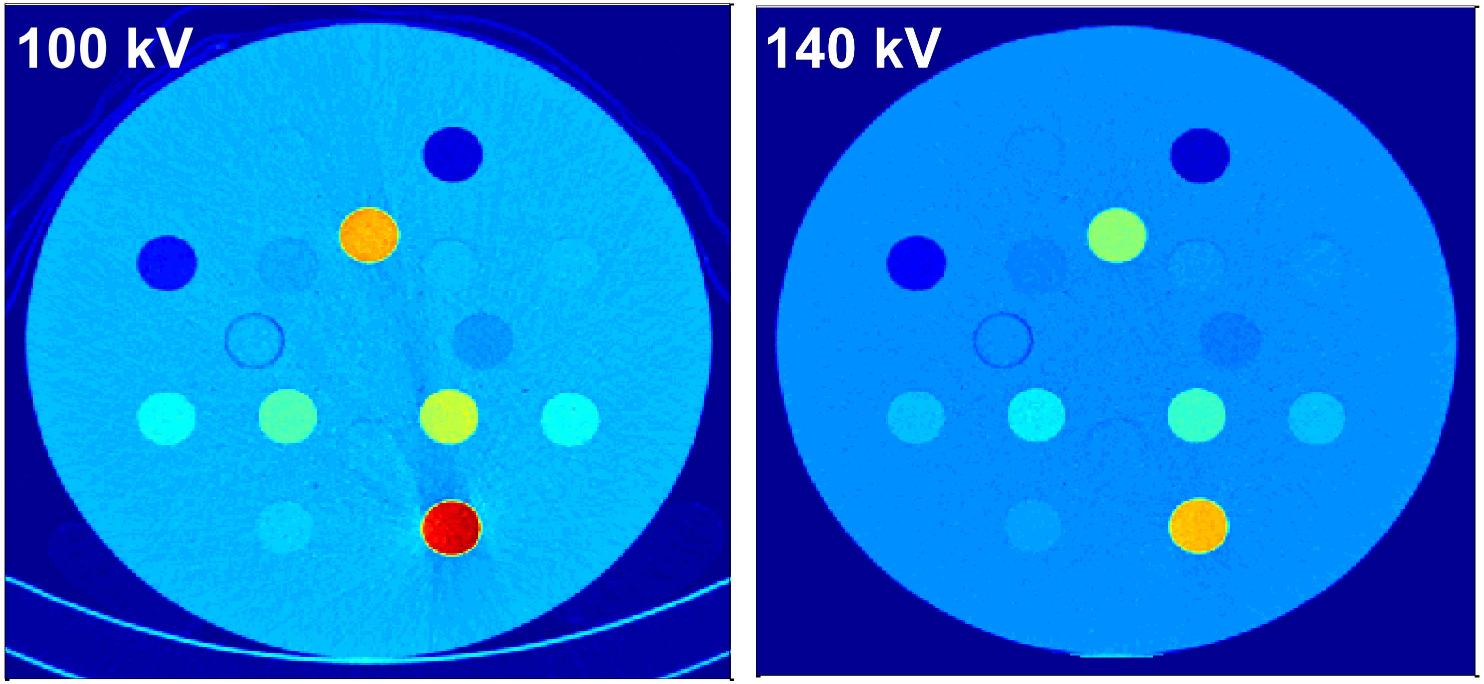

bovine tissues

proton stopping power
at KVI-CART

high-accuracy (≤ 0.05 mm)
range measurements

Multiple X-ray energies: DECT

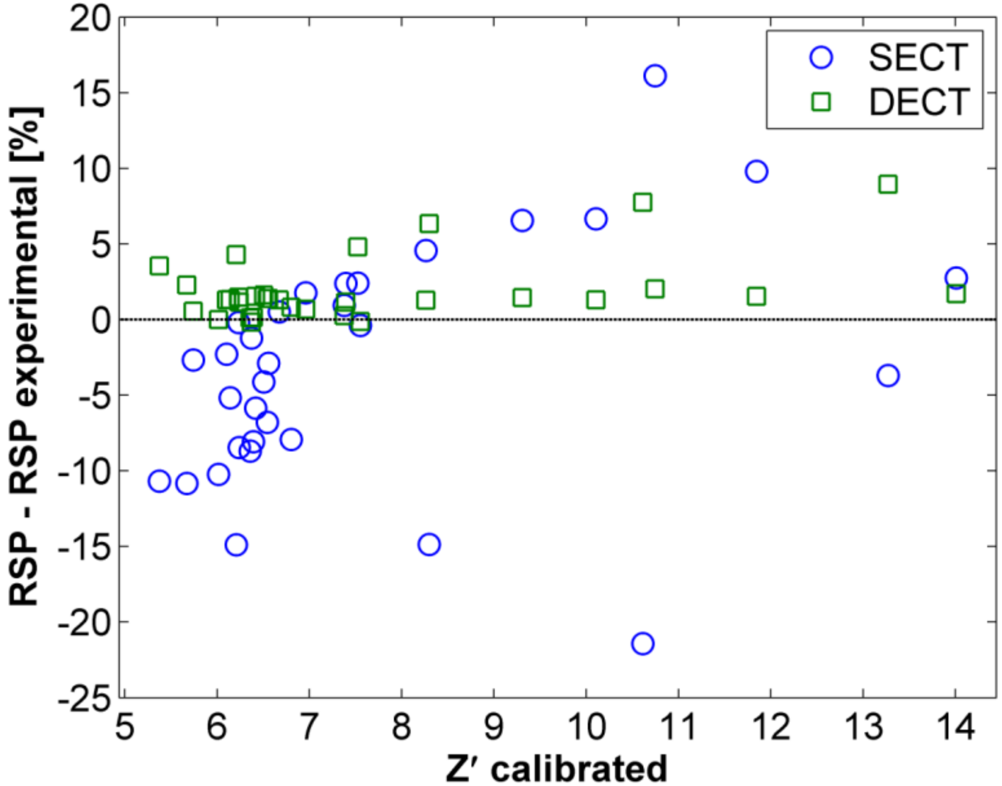
dual-energy CT



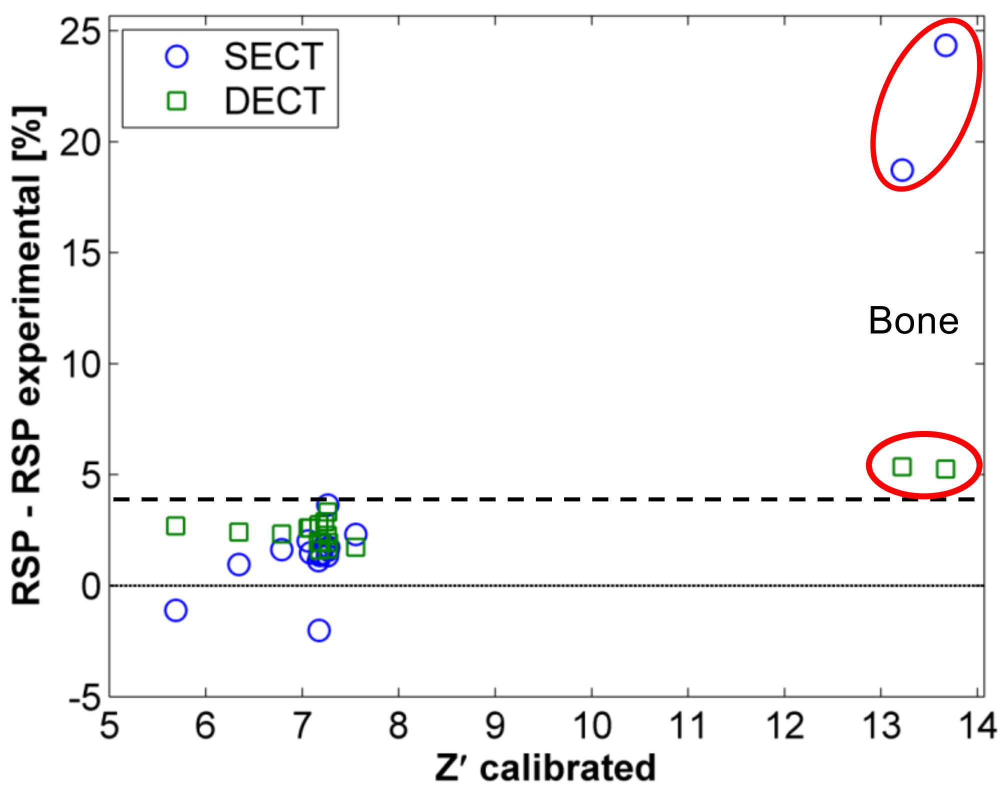
Single energy vs. dual energy CT

accuracy of relative stopping power

tissue-equivalent materials



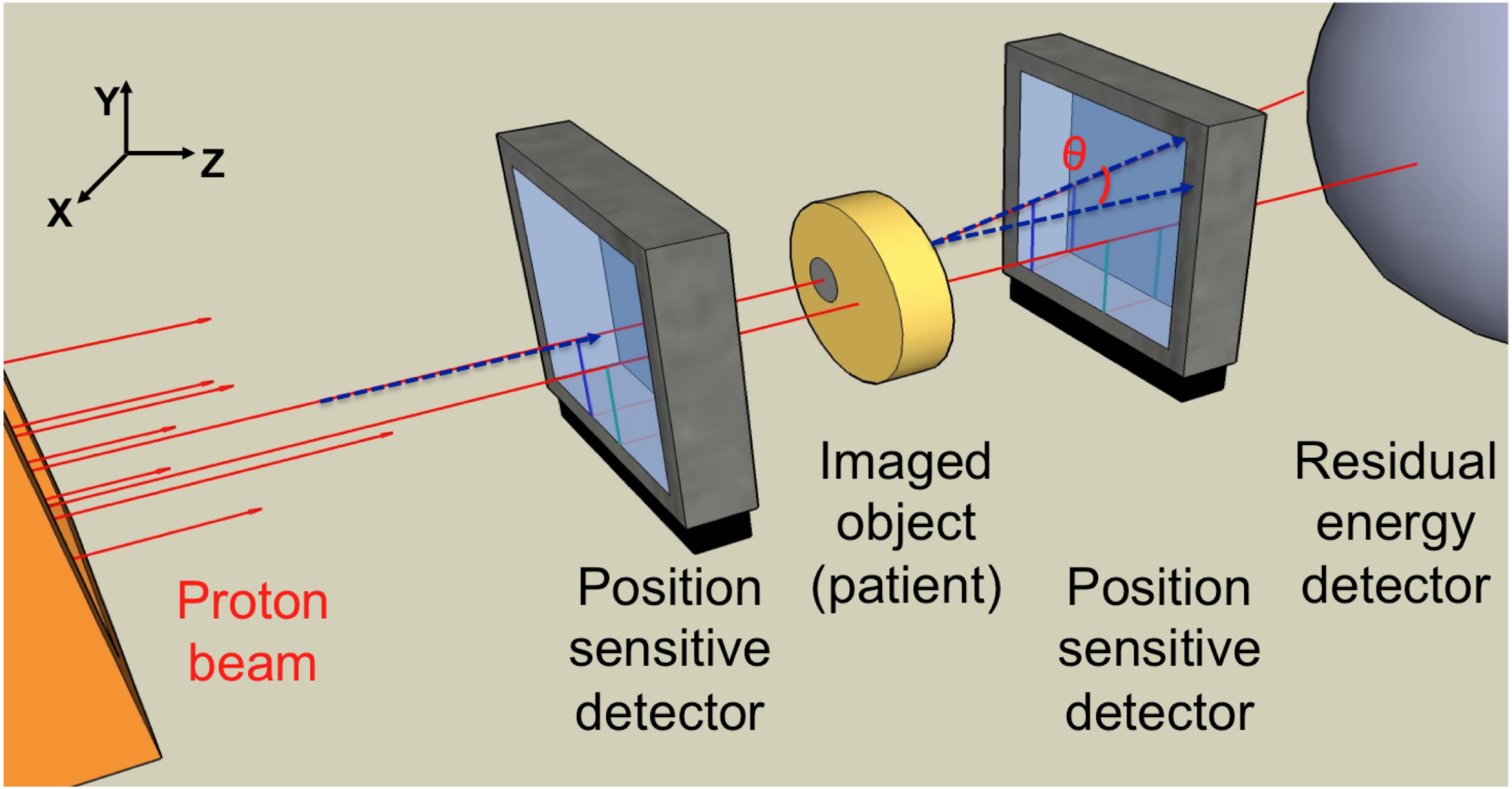
animal tissues



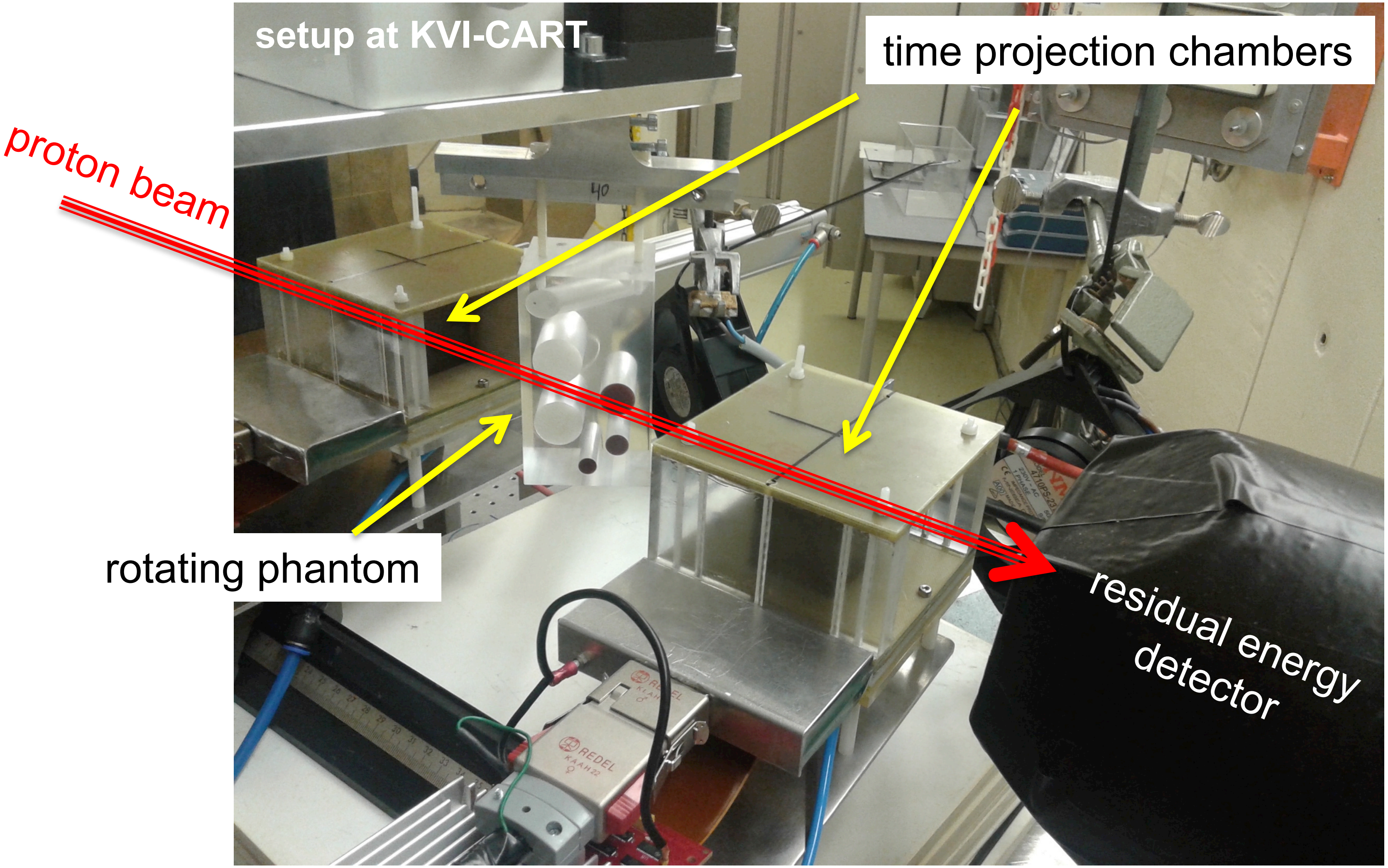
more accurate patient specific tissue proton stopping powers

J.K. van Abbema et al., Phys. Med. Biol. 60(2015)3825
J.K. van Abbema, PhD Thesis, University of Groningen (2017)
www.rug.nl/research/portal/files/49770163/Complete_Thesis.pdf

Proton radiography



TPC + Timepix/Timepix3



in collaboration with NIKHEF

Results proton radiography

The optimal balance between quality and efficiency in proton radiography imaging technique at various proton beam energies: A Monte Carlo study
Biegun AK, van Goethem M-J, van der Graaf ER, van Beuzekom M, Koffeman EN, Nakaji T, Takatsu J, Visser J and Brandenburg S
Physica Medica **41** (2017) 141-146

Proton radiography with Timepix based time projection chambers
Biegun AK, Visser J, Klaver T, Ghazanfari N, van Goethem MJ, Koffeman E, van Beuzekom M, and Brandenburg S
IEEE Transactions on Medical Imaging **35** (2016) 1099-1105

Proton energy and scattering angle radiographs to improve proton treatment planning: a Monte Carlo study
Biegun AK, Takatsu J, Nakaji T, van Goethem MJ, van der Graaf ER, Koffeman EN, Visser J, and Brandenburg S
Journal of Instrumentation **11** (2016) C12015

Proton radiography to improve proton therapy treatment
Takatsu J, van der Graaf ER, Goethem MV, van Beuzekom M, Klaver T, Visser J, Brandenburg S, and Biegun AK
Journal of Instrumentation **11** (2016) C01004

Timepix3-based detectors

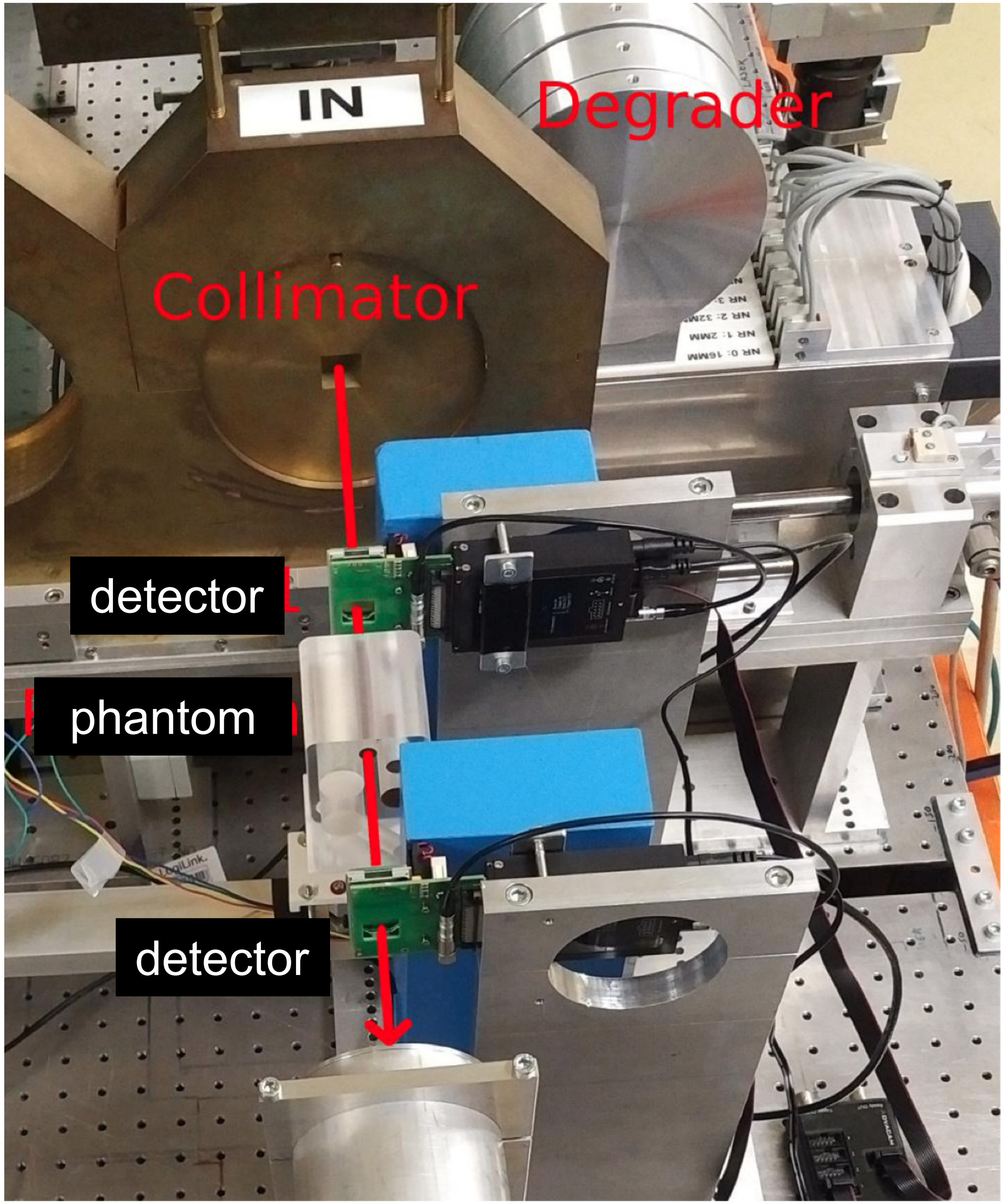
4 detectors:
- 2 x 100 μm thick silicon
- 2 x 300 μm thick silicon

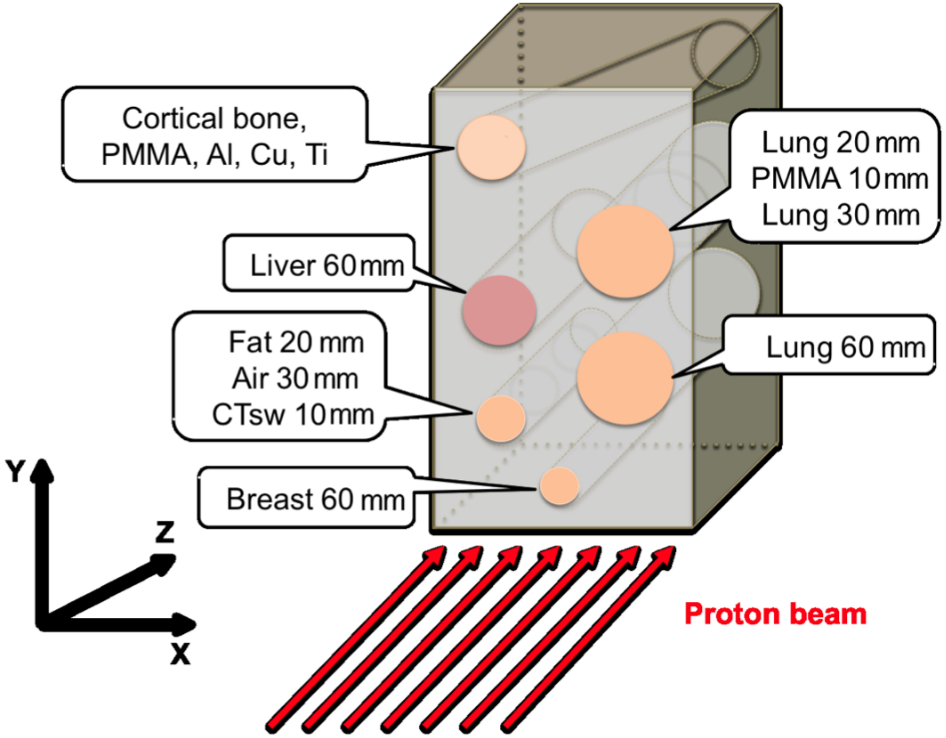
14 x 14 mm^2
55 x 55 μm^2 pixels

readout speed: 100 frames/s

modes of operation:
- counting
- energy
- time

FitPix radiography setup at KVI-CART



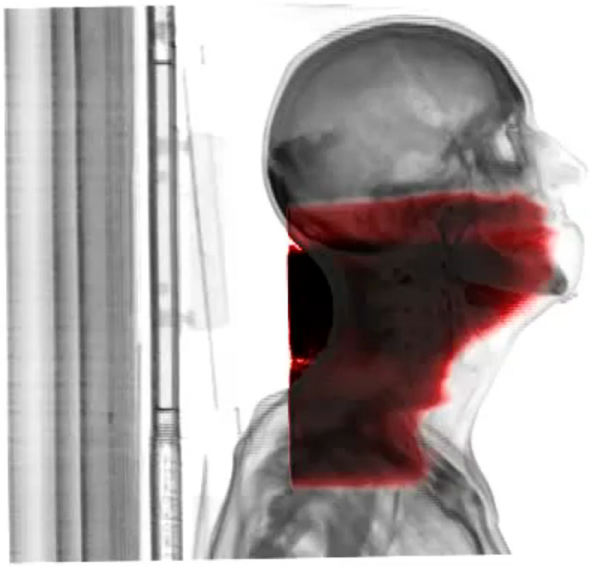


data under analysis

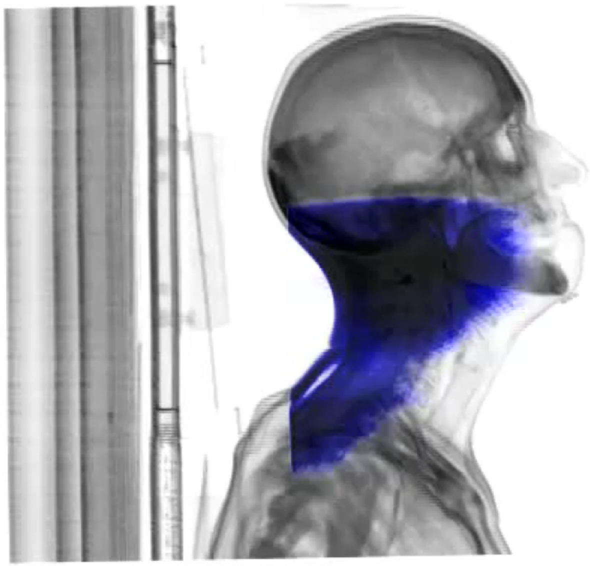
Imaging the beam

principle: production of secondary gamma radiation correlates with radiation dose

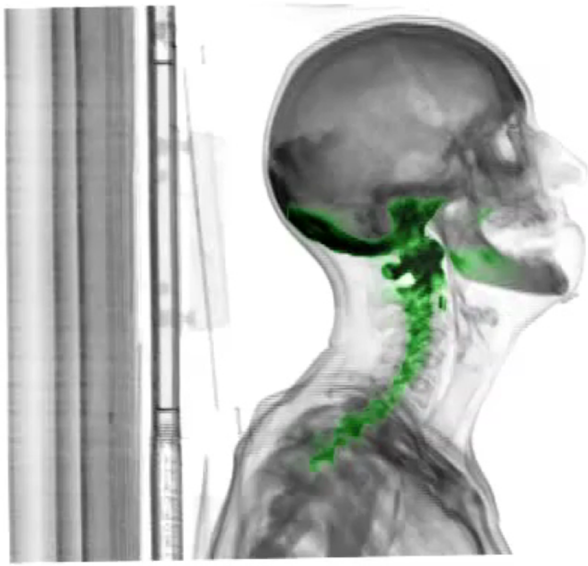
treatment planning CT
simulated dose



treatment planning CT
oxygen-15 production



treatment planning CT
potassium-38 production



Dendooven P et al

(Very) short-lived positron emitters

IOP Publishing | Institute of Physics and Engineering in Medicine

Phys. Med. Biol. **60** (2015) 8923–8947

Short-lived positron emitters in beam-on PET imaging during proton therapy

P Dendooven[1], H J T Buitenhuis[1], F Diblen[1,3], P N Heeres[1], A K Biegun[1], F Fiedler[4], M-J van Goethem[2], E R van der Graaf[1] and S Brandenburg[1]

Phys. Med. Biol. **62** (2017) 4654–4672

Beam-on imaging of short-lived positron emitters during proton therapy

H J T Buitenhuis[1], F Diblen[1,2], K W Brzezinski[1], S Brandenburg[1] and P Dendooven[1]

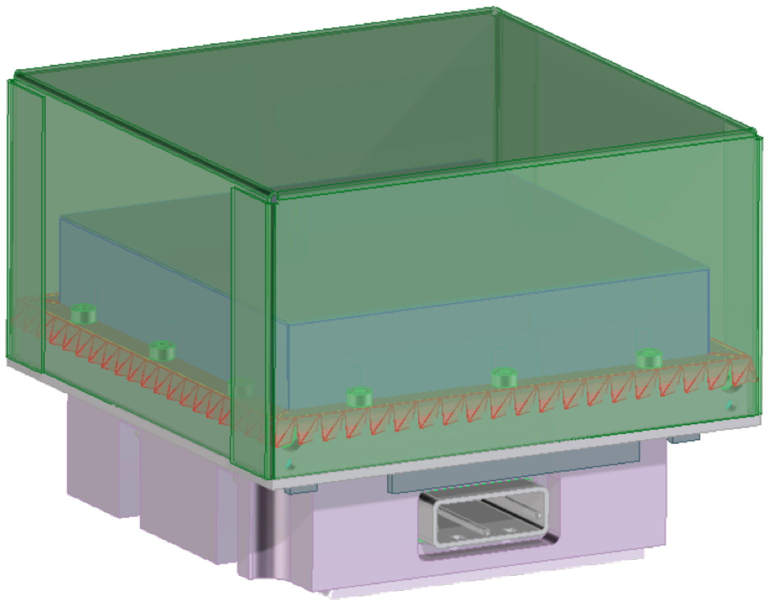
^{12}N, $T_{1/2}$ = 11 ms

Beam-on, in-beam, on-line PET

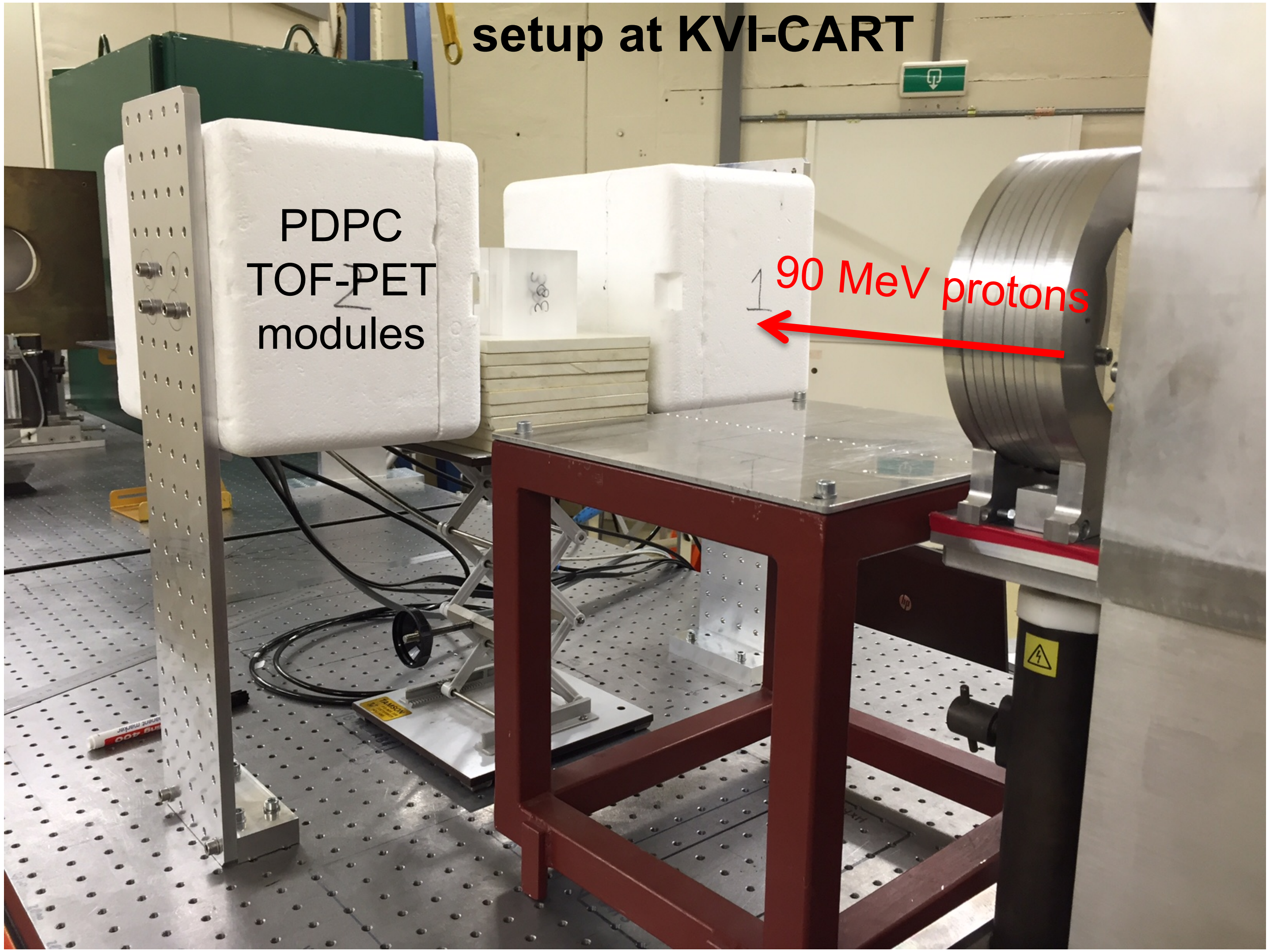
detector characteristics (for true beam-on PET):

- need time-of-flight (TOF-) PET
- high singles count rate (~25 kcps per cm^2 detector surface area)
  singles rate capability of modern TOF-PET detectors is fine,
  but electronics and data acquisition needs to be dedicated
- need anticoincidence with accelerator RF to reject prompt signals
- radiation hardness (SiPM !)

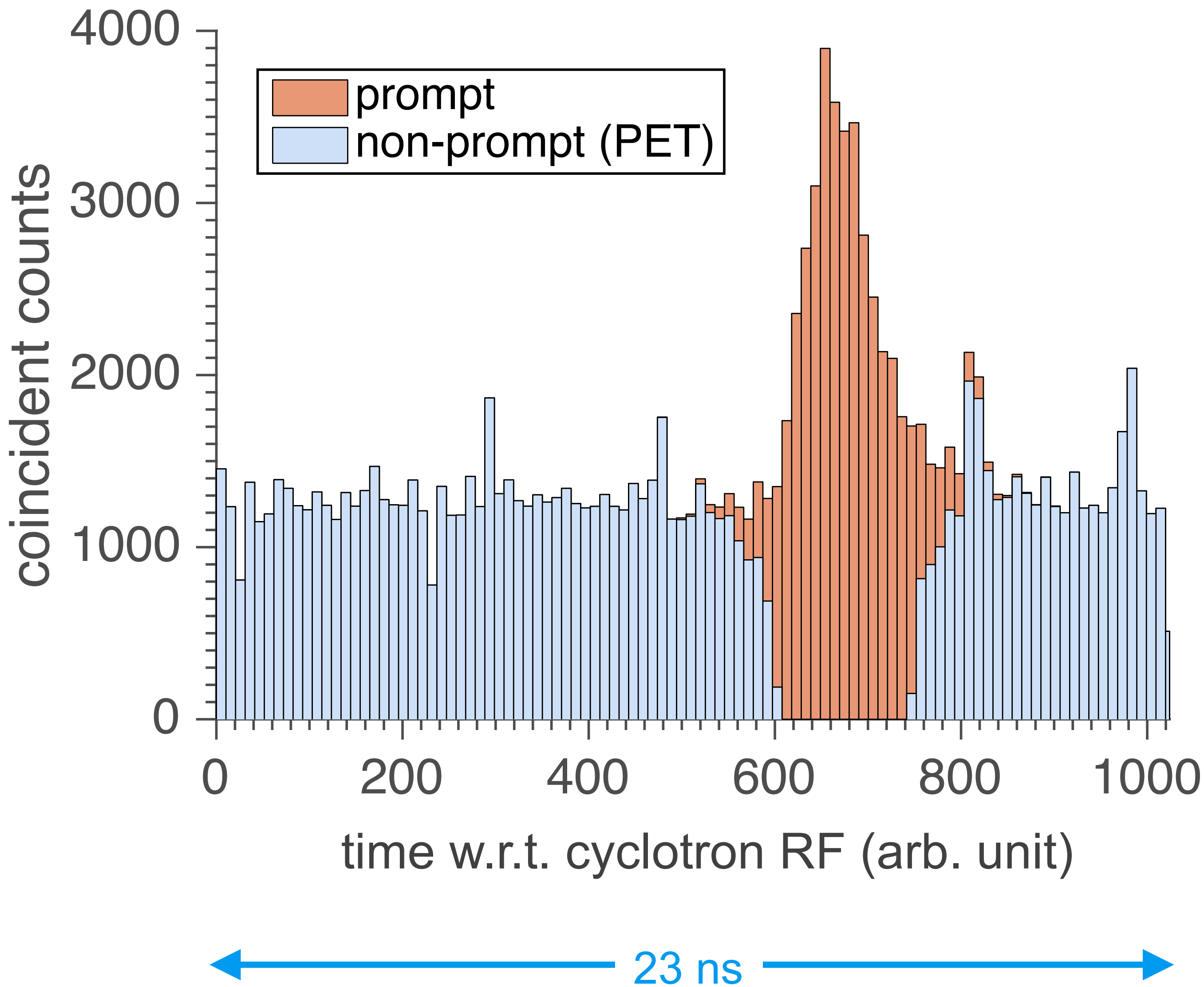
experiments using the PDPC Module-TEK



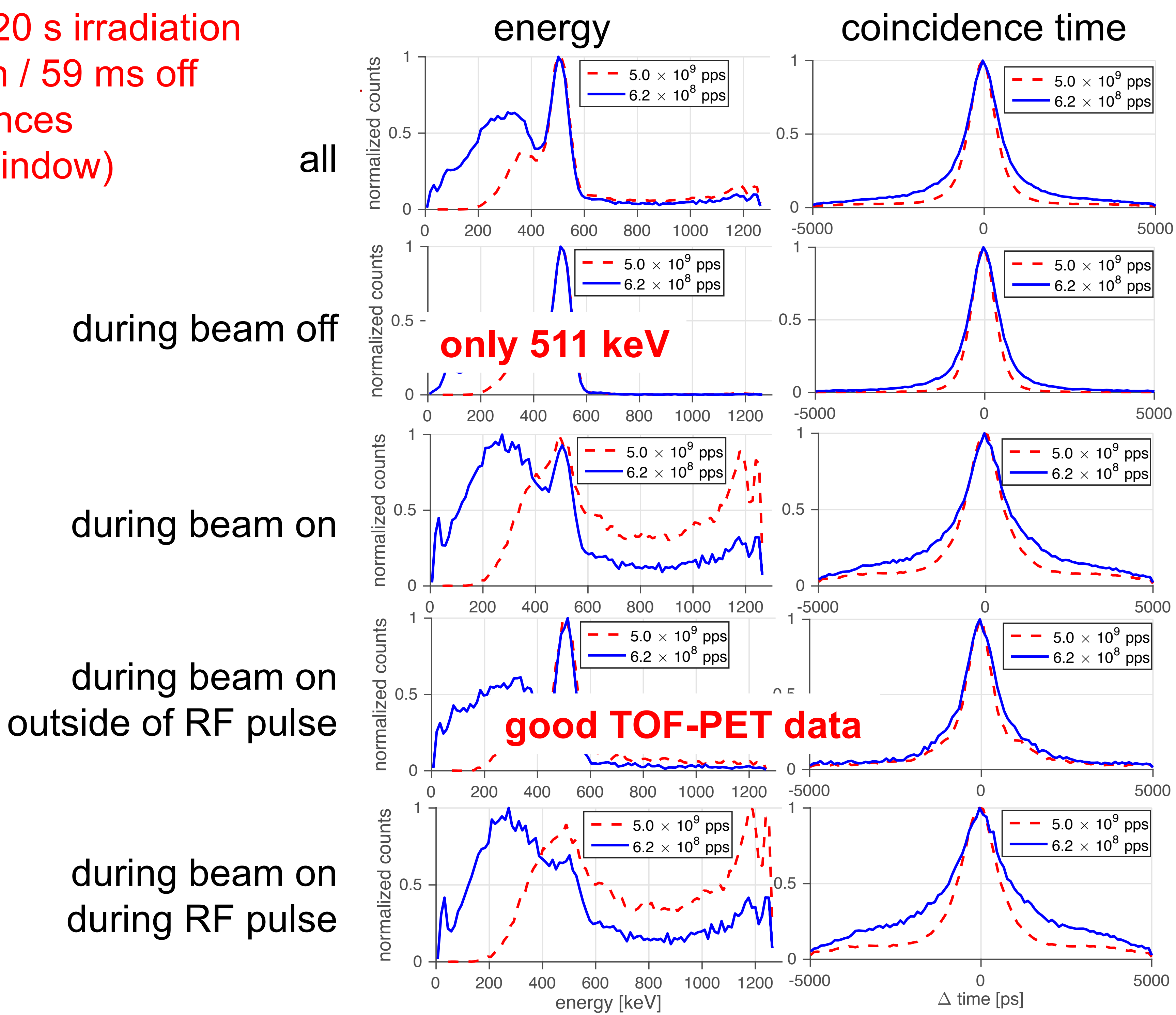
Beam-on PET experiment



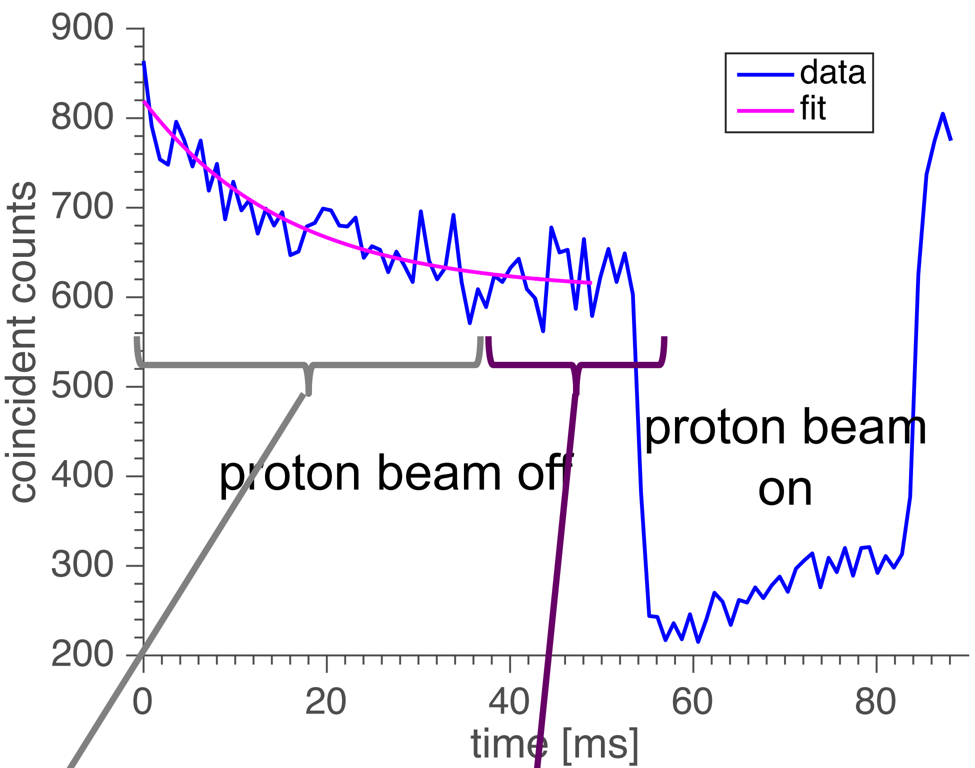
Rejection of prompt signals



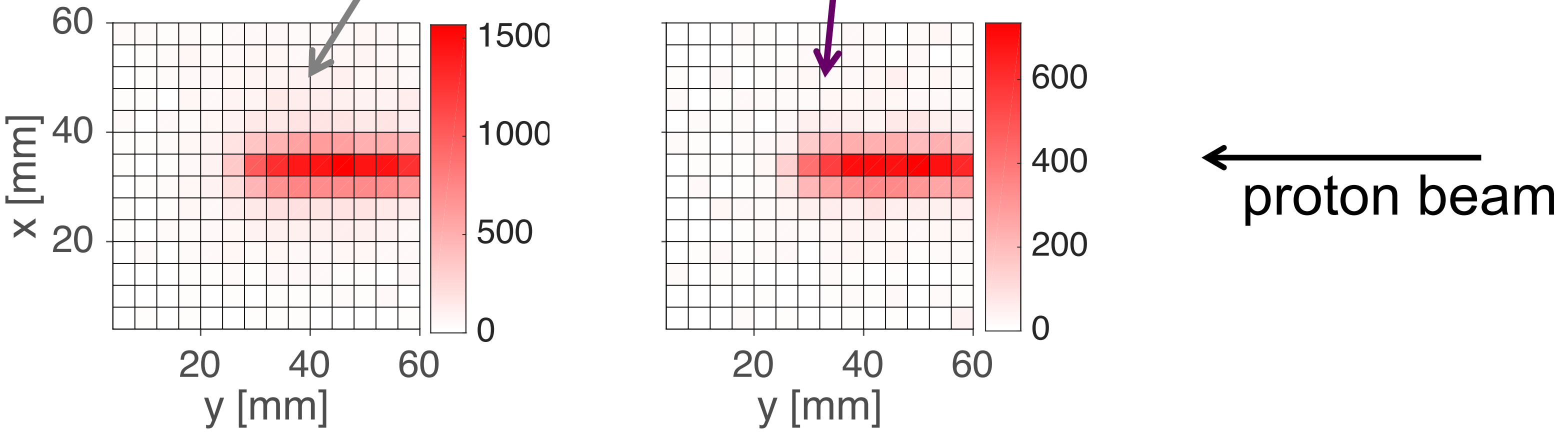
- during 120 s irradiation
- 30 ms on / 59 ms off
- coincidences
  (10 ns window)



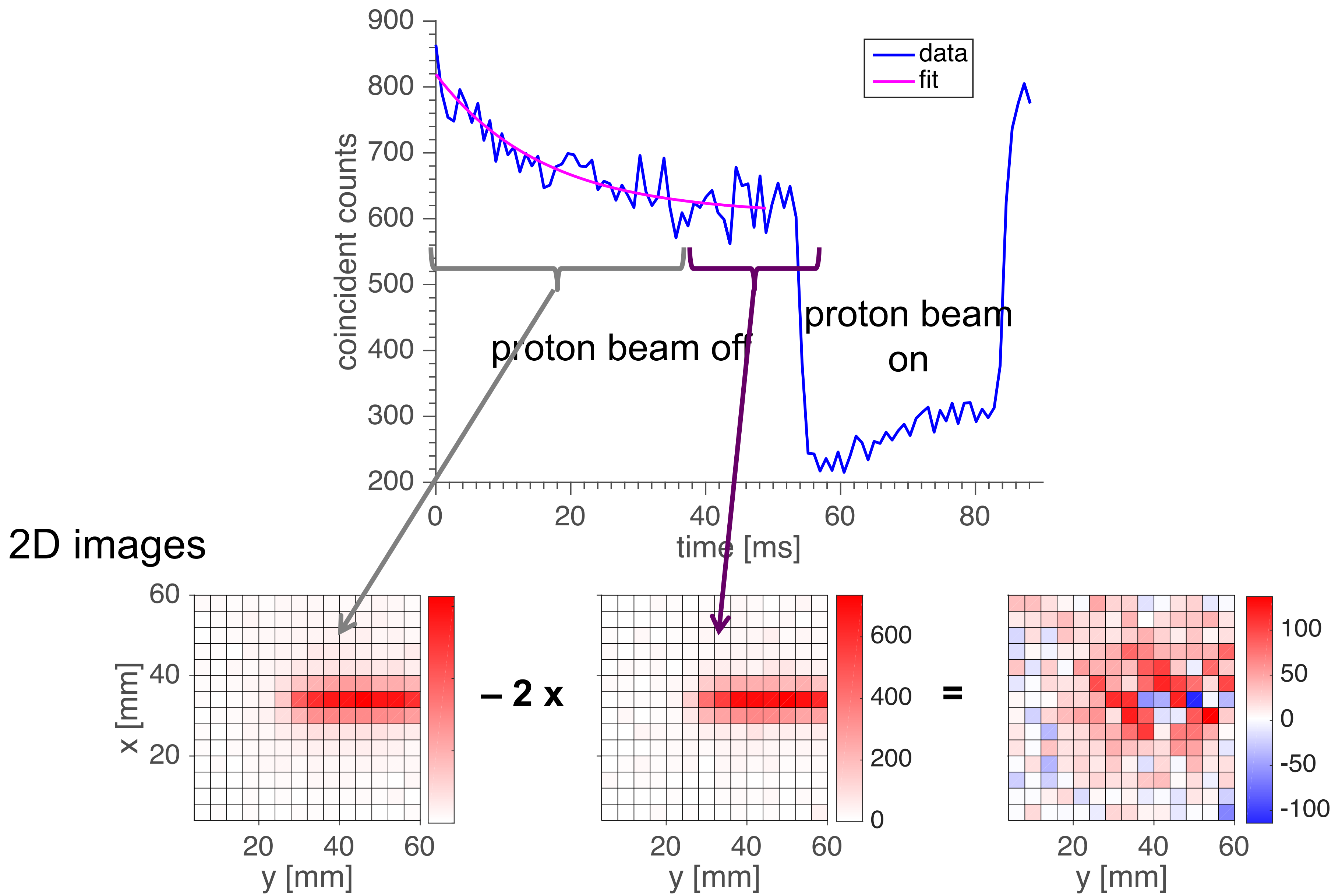
N-12-only imaging



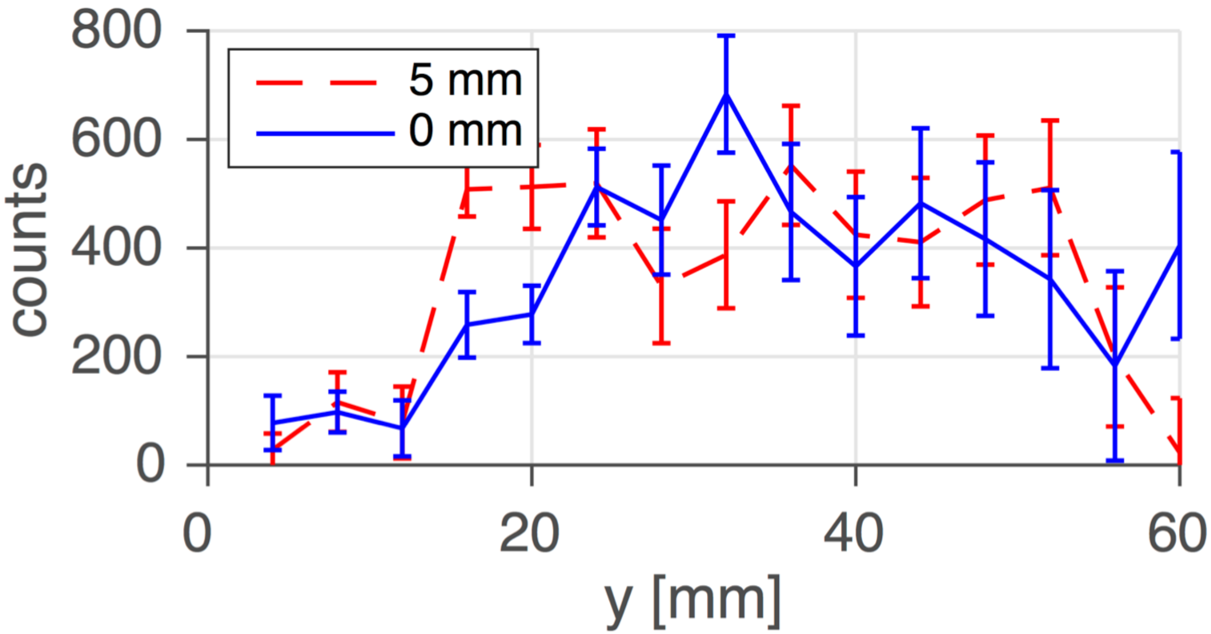
2D images



N-12-only imaging



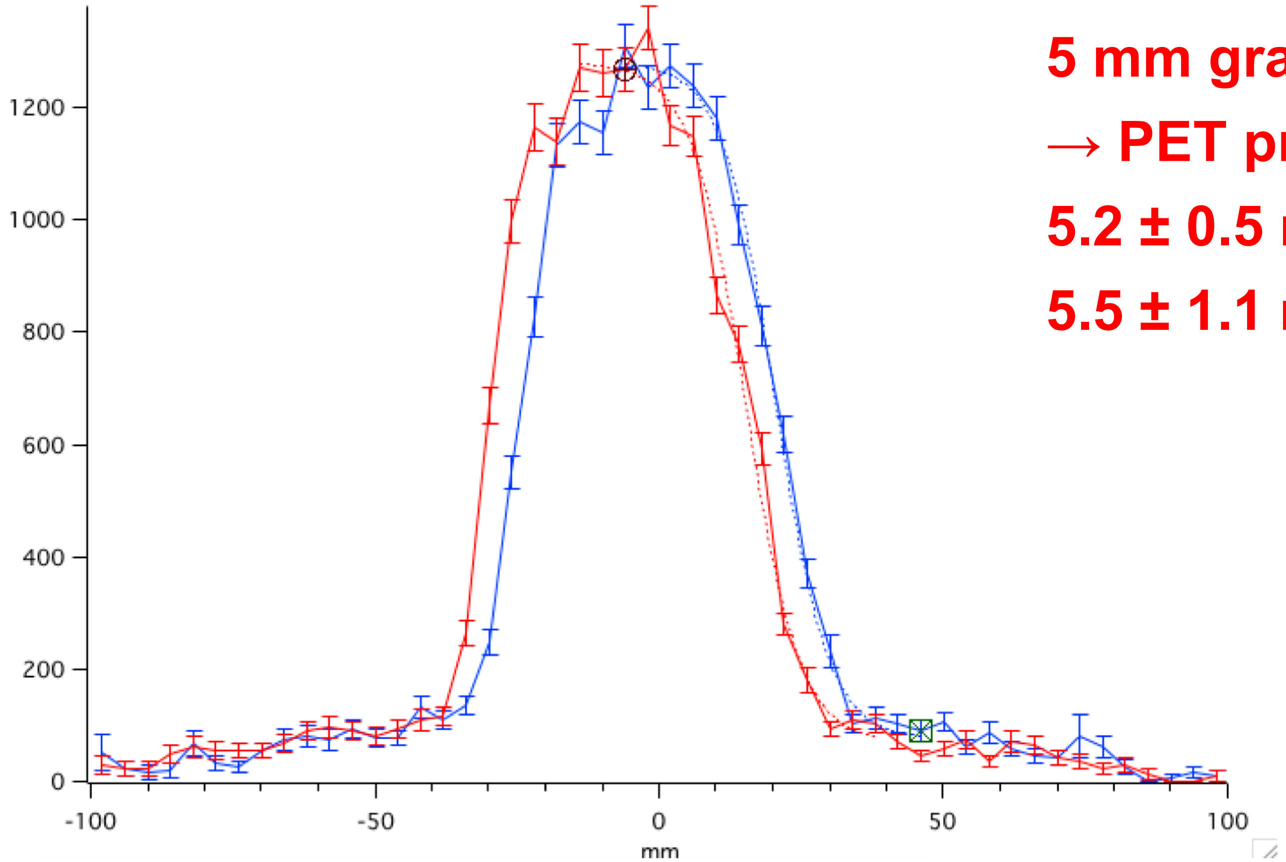
1D N-12 activity profiles in graphite



5 mm graphite target shift → 6 ± 3 mm PET profile shift

N-12 imaging during treatment: simulation

- 1 proton spot on a graphite target
- no long-lived contribution
- large dual-panel PET scanner

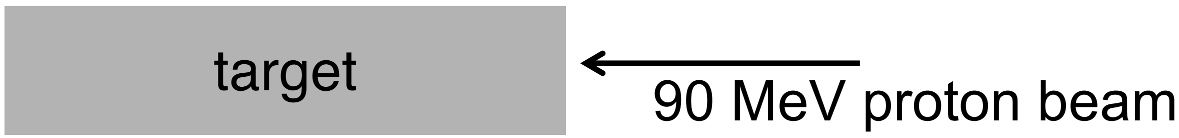


5 mm graphite target shift

→ PET profile shift:

5.2 ± 0.5 mm for 5 x 10^8 protons

5.5 ± 1.1 mm for 10^8 protons



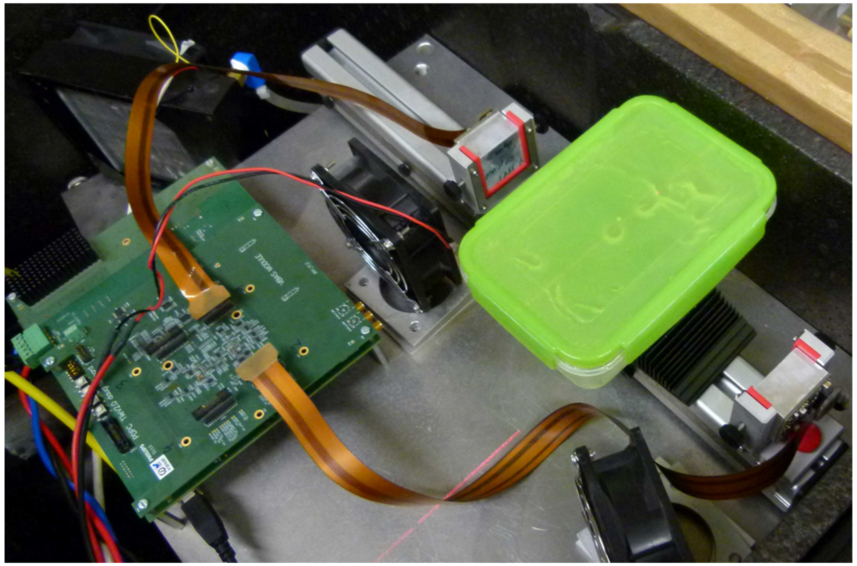
Radiation hardness dSiPM

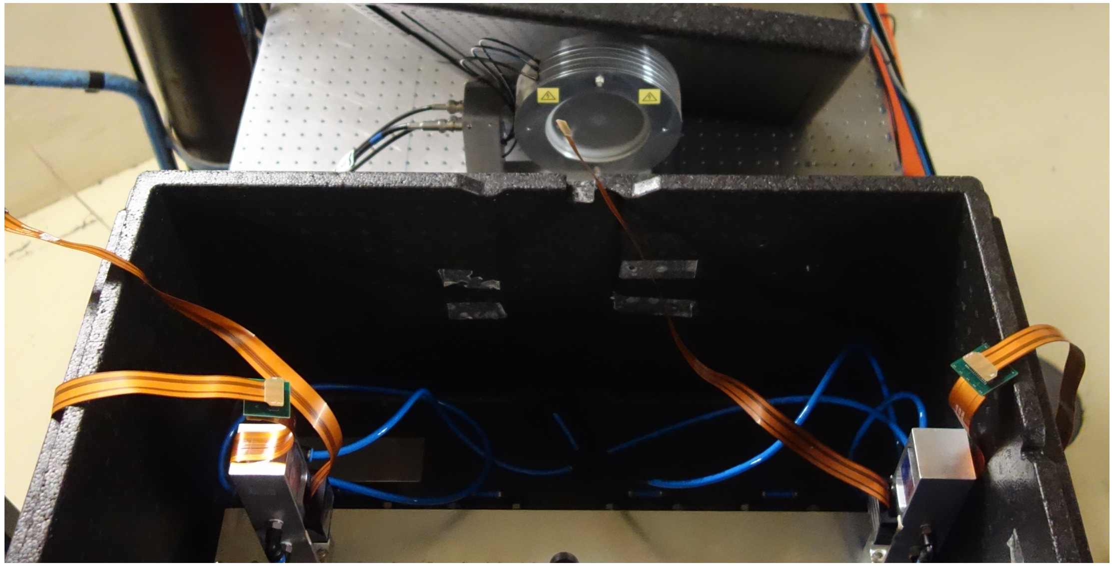
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 7, JULY 2017

Radiation Hardness of dSiPM Sensors in a Proton Therapy Radiation Environment

Faruk Diblen, Tom Buitenhuis, Torsten Solf, Pedro Rodrigues, Emiel van der Graaf, Marc-Jan van Goethem, Sytze Brandenburg, and Peter Dendooven, *Member, IEEE*

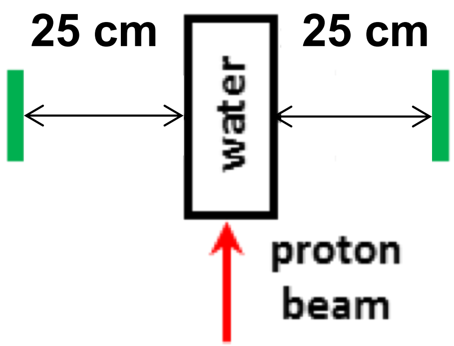
PHILIPS



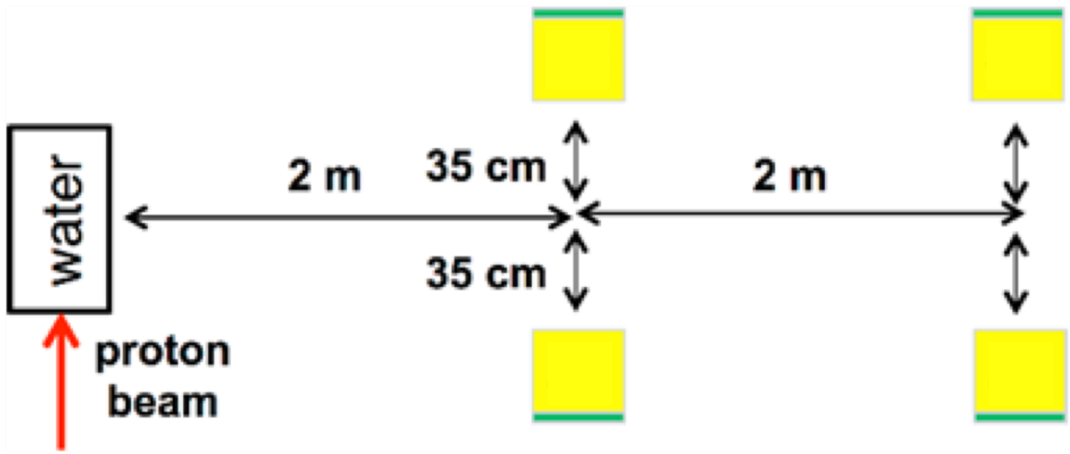


In-situ and in-room installations

in-situ bare sensors



in-room PET detectors



bare dSiPM sensor tiles
temperature about 8 °C

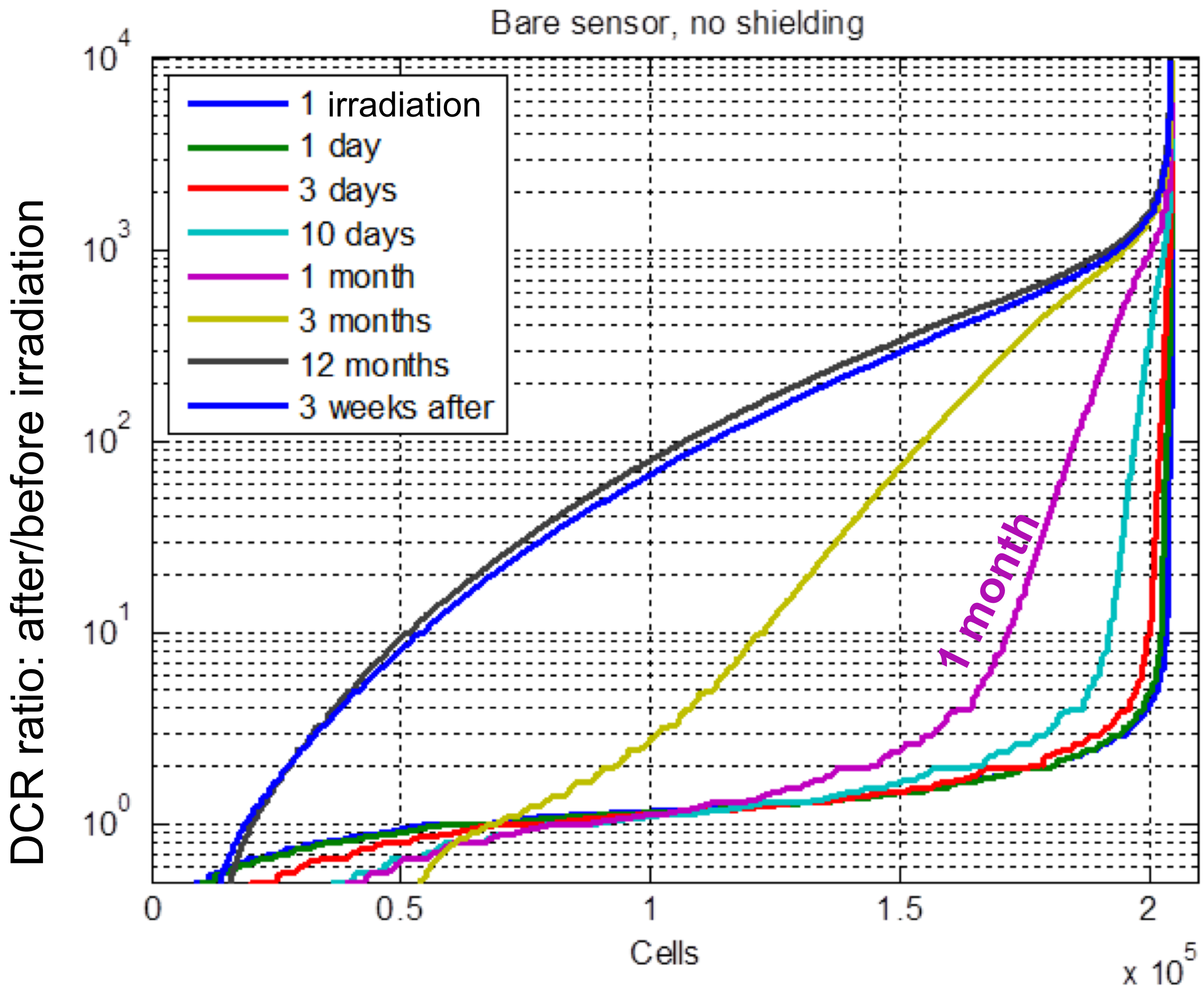
from 1 patient irradiation
(3 x 10^{11} protons)
to 1 year of patient irrad.
(10^{15} protons)

PET detectors:
- **dSiPM sensor tile**
- **8x8 array**
- **4x4x22 mm^3 LYSO**

3 years of patient irradiations
(3 x 10^{15} protons)

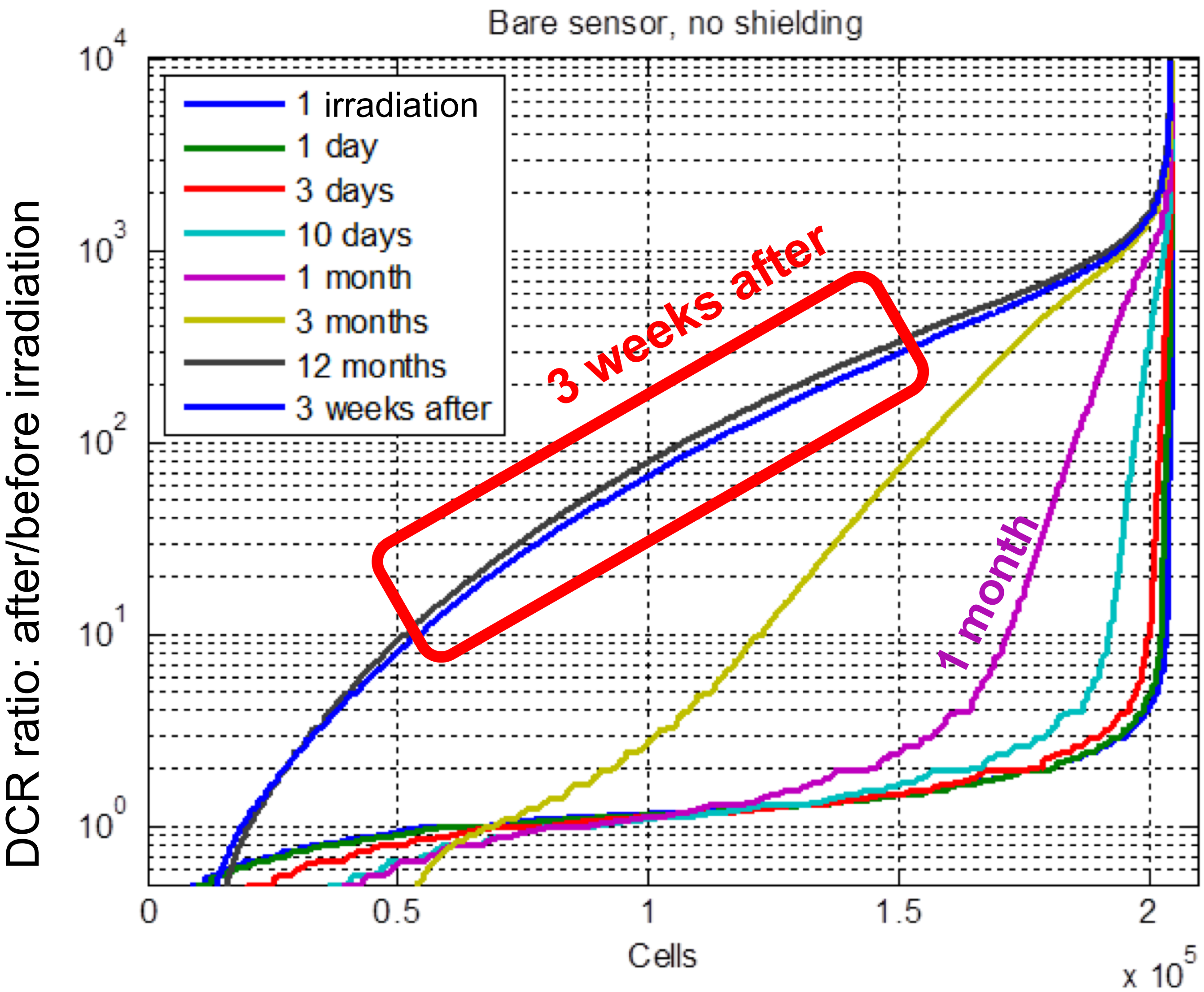
In-situ: DCR ratio after/before irradiation

- **dark count rate (DCR) is used to assess radiation damage**
- **DCR ratio** for every cell, ~2 x 10^5 per 32x32 mm^2 tile

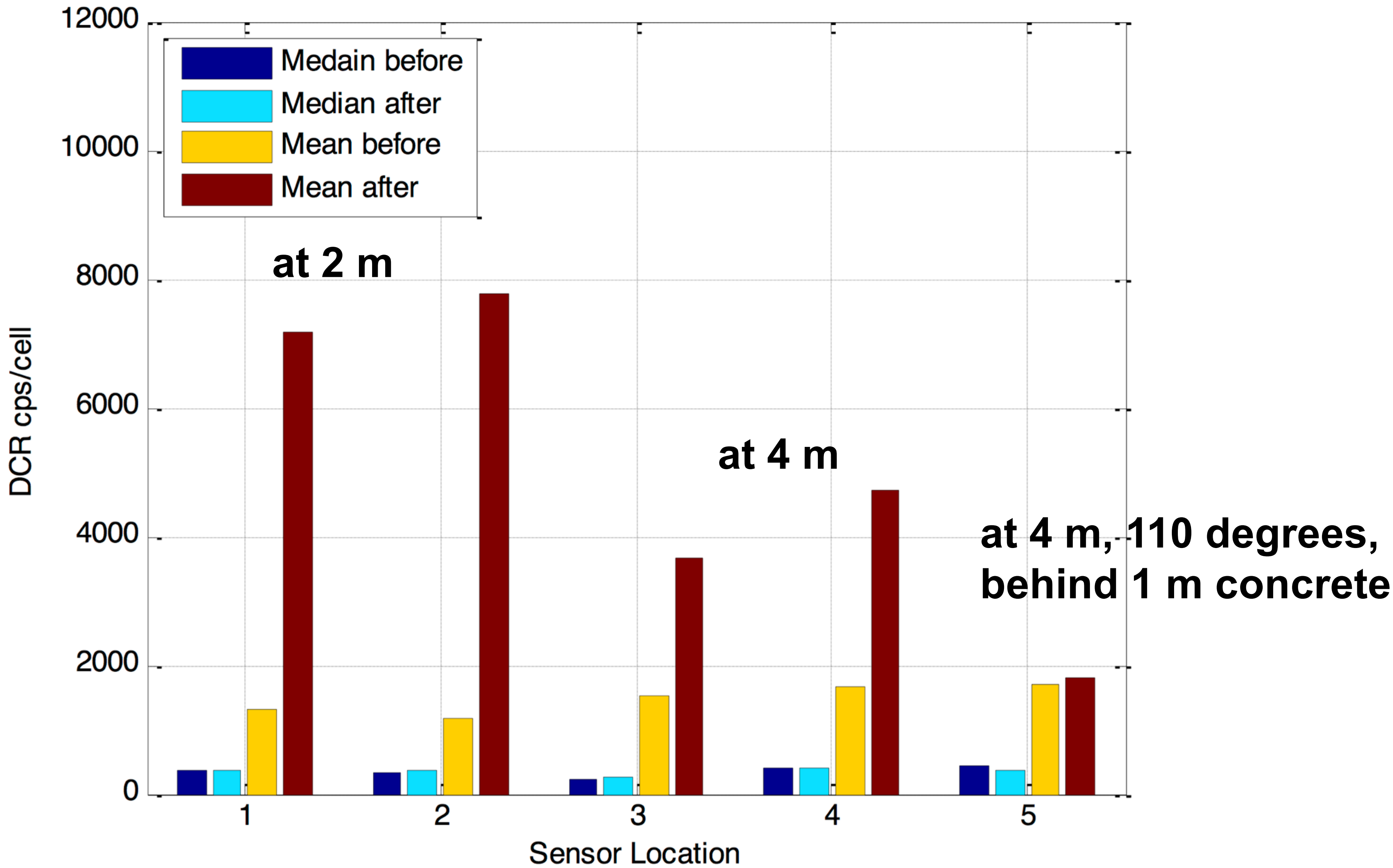


In-situ: recovery of damage

- **dark count rate (DCR) is used to assess radiation damage**
- **DCR ratio** for every cell, ~2 x 10^5 per 32x32 mm^2 tile

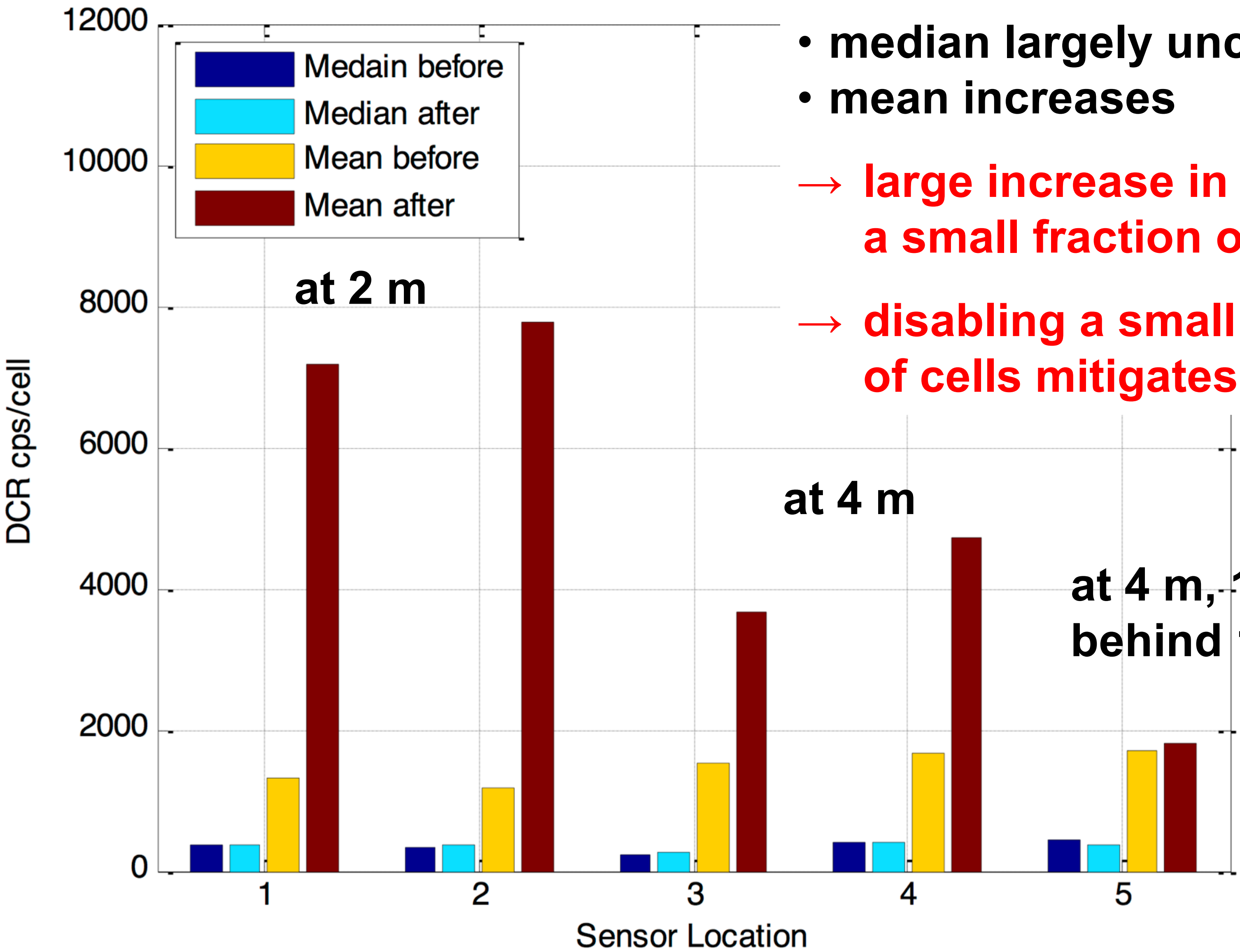


In-room: DCR



12000
10000
8000
6000
4000
2000
0
DCR cps/cell
Medain before
Median after
Mean before
Mean after
at 2 m
at 4 m
at 4 m, 110 degrees, behind 1 m concrete
1
2
3
4
5
Sensor Location

In-room: DCR



- **median largely unchanged**
- **mean increases**

→ large increase in DCR in a small fraction of cells

→ disabling a small fraction of cells mitigates damage

In-room: effect on PET performance

before or after	fraction cells enabled	$\Delta E/E$ [%]	CRT [ps] trig. scheme 2	counts rel. to trig. scheme 4 [%]
		detectors at 2 m		
before	90%	11.2 / 11.3	306	
after	90%	11.2 / 11.3	304	
after	80%			
		detectors at 4 m		
before	90%	11.7 / 12.0	310	
after	90%	11.7 / 12.7	315	
after	80%			
		detector behind concrete wall		
before	90%	11.6	308	
after	90%	11.7	306	
after	80%			

In-room: effect on PET performance

before or after	fraction cells enabled	ΔE/E [%]	CRT [ps] trig. scheme 2	counts rel. to trig. scheme 4 [%]
		detectors at 2 m		
before	90%	11.2 / 11.3	306	95
after	90%	11.2 / 11.3	304	56
after	80%			
		detectors at 4 m		
before	90%	11.7 / 12.0	310	89
after	90%	11.7 / 12.7	315	80
after	80%			
		detector behind concrete wall		
before	90%	11.6	308	89
after	90%	11.7	306	86
after	80%			

In-room: effect on PET performance

before or after	fraction cells enabled	ΔE/E [%]	CRT [ps] trig. scheme 2	counts rel. to trig. scheme 4 [%]
		detectors at 2 m		
before	90%	11.2 / 11.3	306	95
after	90%	11.2 / 11.3	304	56
after	80%	11.5 / 11.4	309	91
		detectors at 4 m		
before	90%	11.7 / 12.0	310	89
after	90%	11.7 / 12.7	315	80
after	80%	12.7 / 12.8	335	95
		detector behind concrete wall		
before	90%	11.6	308	89
after	90%	11.6 / 11.7	306	86
after	80%	11.8	328	97

Conclusions radiation hardness

- experiments using digital SiPM from PHILIPS
  - **in-situ geometry:** - significant increase in DCR
    - digital infrastructure of the sensor unaffected
    ➔ too severe sensitivity loss after 1-2 weeks of clinical operation of a proton therapy treatment room
  - **in-room geometry:** - moderate increase in DCR
    - disabling damaged cells mitigates drop in PET performance

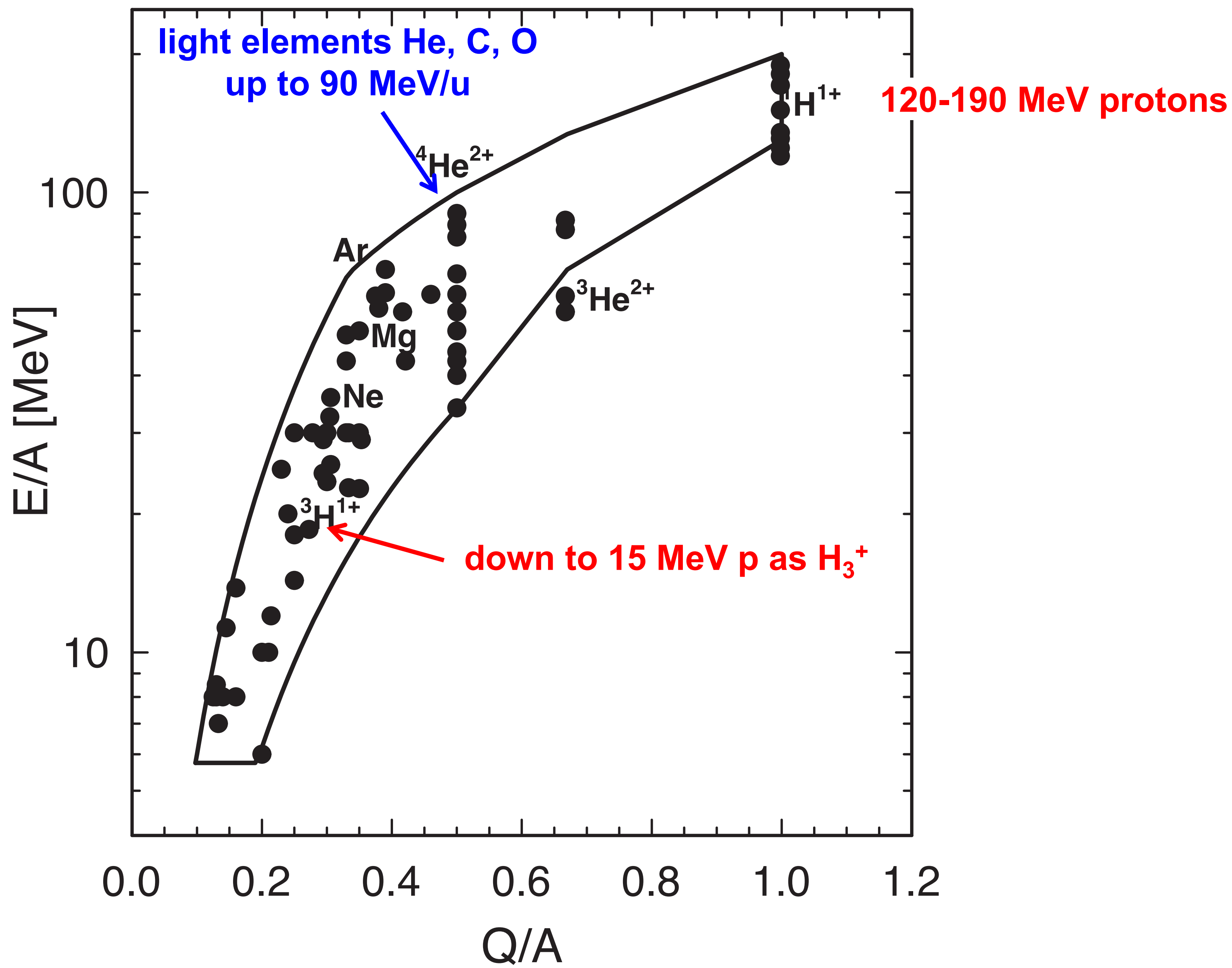
  ➔ PET performance expected to be maintained for over 3 years of clinical operation of a proton therapy treatment room

- **how about other types of SiPM ?**

Experiments at KVI-CART - AGOR

www.rug.nl/kvi-cart/research/facilities/agor/

AGOR operating diagram / available beams



Financing for experiments at KVI-CART

- **ENSAR2**
- 1 March 2016 to 29 February 2020
- **KVI-CART trans-national access: 700 hours**

- **INSPIRE: INfraStructure in Proton International REsearch**
  cordis.europa.eu/project/rcn/213378_en.html
- 1 March 2018 to 28 February 2022
- links clinical proton therapy centres in 11 European countries and 2 centres in the US; IBA and Varian participate
- **KVI-CART trans-national access: 600 hours**

- **CORA-IBER**: Continuously Open Research Announcement for Investigating the **Biological Effects of Space Radiation**
- KVI-CART as ESA Ground-Based Facility
- up to €50 000 for each proposal selected after peer review
  www.esa.int/Our_Activities/Human_Spaceflight/Research/New_radiation_research_programme_for_human_spaceflight/(print)
  esamultimedia.esa.int/docs/hsf_research/cora/CORA-IBER-information-package.pdf

www.rug.nl/kvi-cart/research/facilities/agor/access