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Out-of-field thermal neutron characterization with thin 3D-silicon detectors in Varian TrueBeam and Elekta Synergy LINACs

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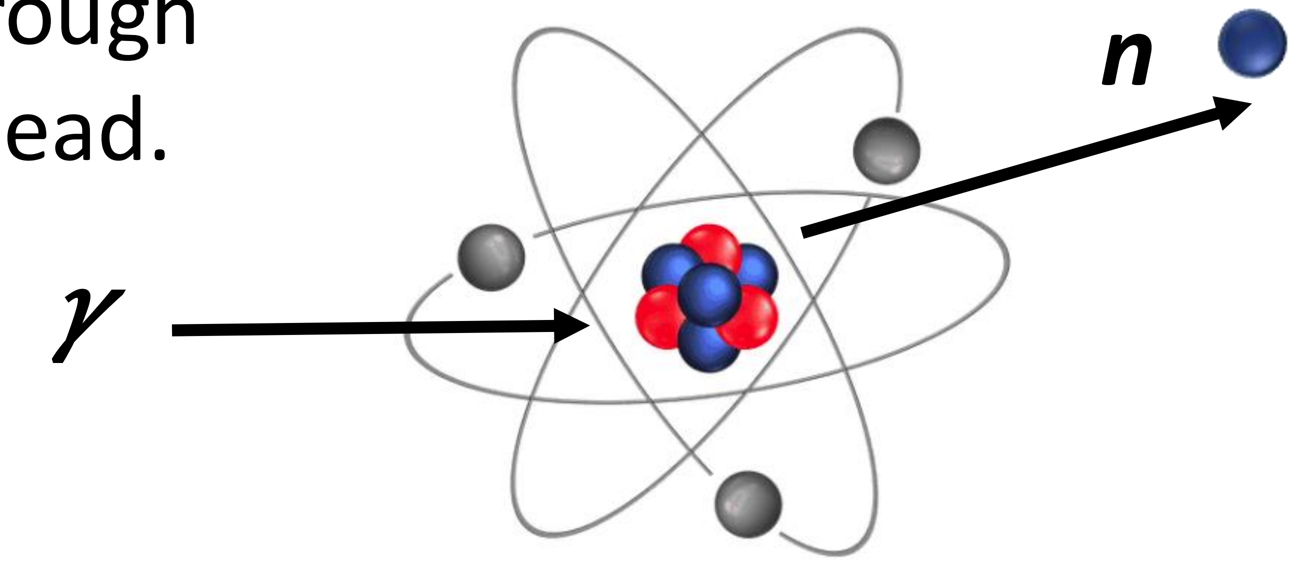
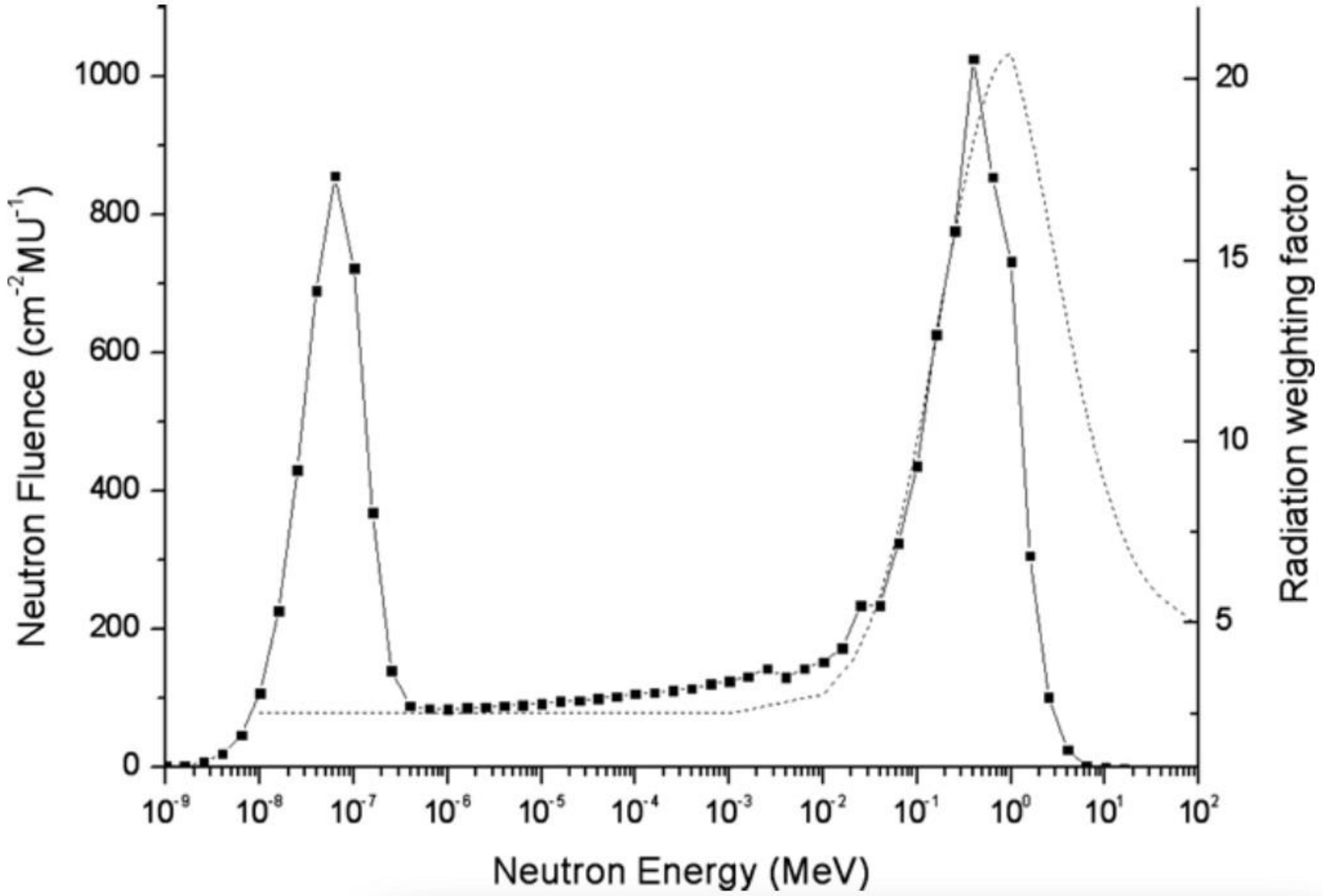
October 28th, 2025 – Valencia, Spain

Secondary neutrons in RT

- LINACs operating at E > 6 MV, generate neutrons through (γ,n) interactions with high-Z materials in the LINAC head.

- Secondary dose in pacients and workers
- *n* → high W_r → high impact





J. Pena *et al* (2005). Phys. Med. Biol. 50 (33),5921 and ICRP (2007) Publication 103

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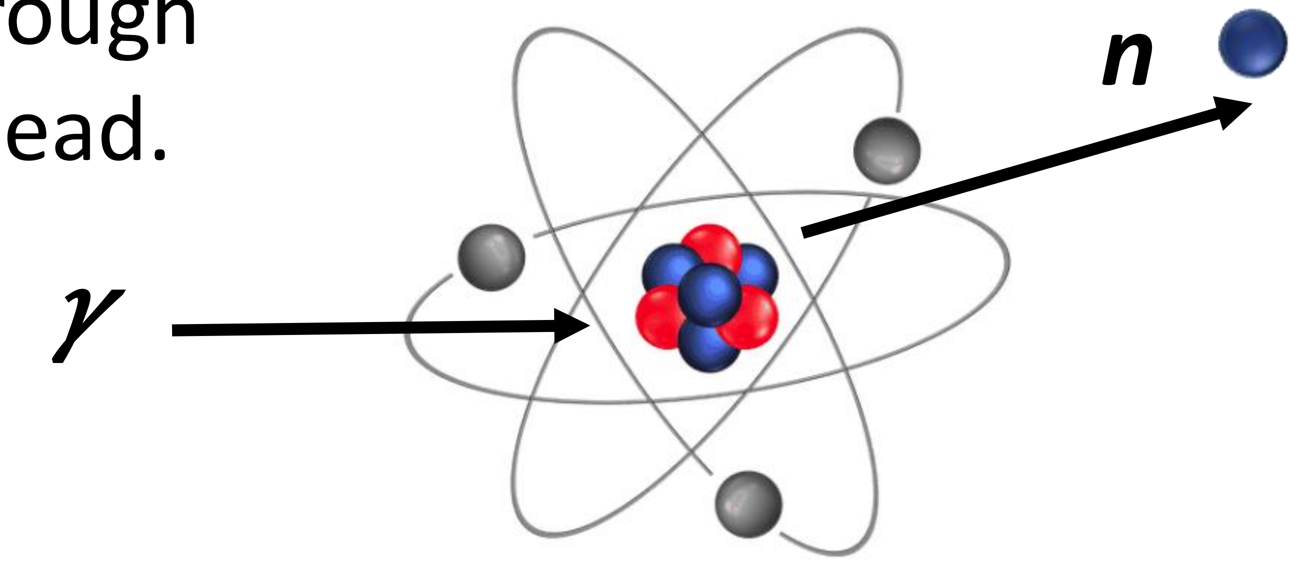

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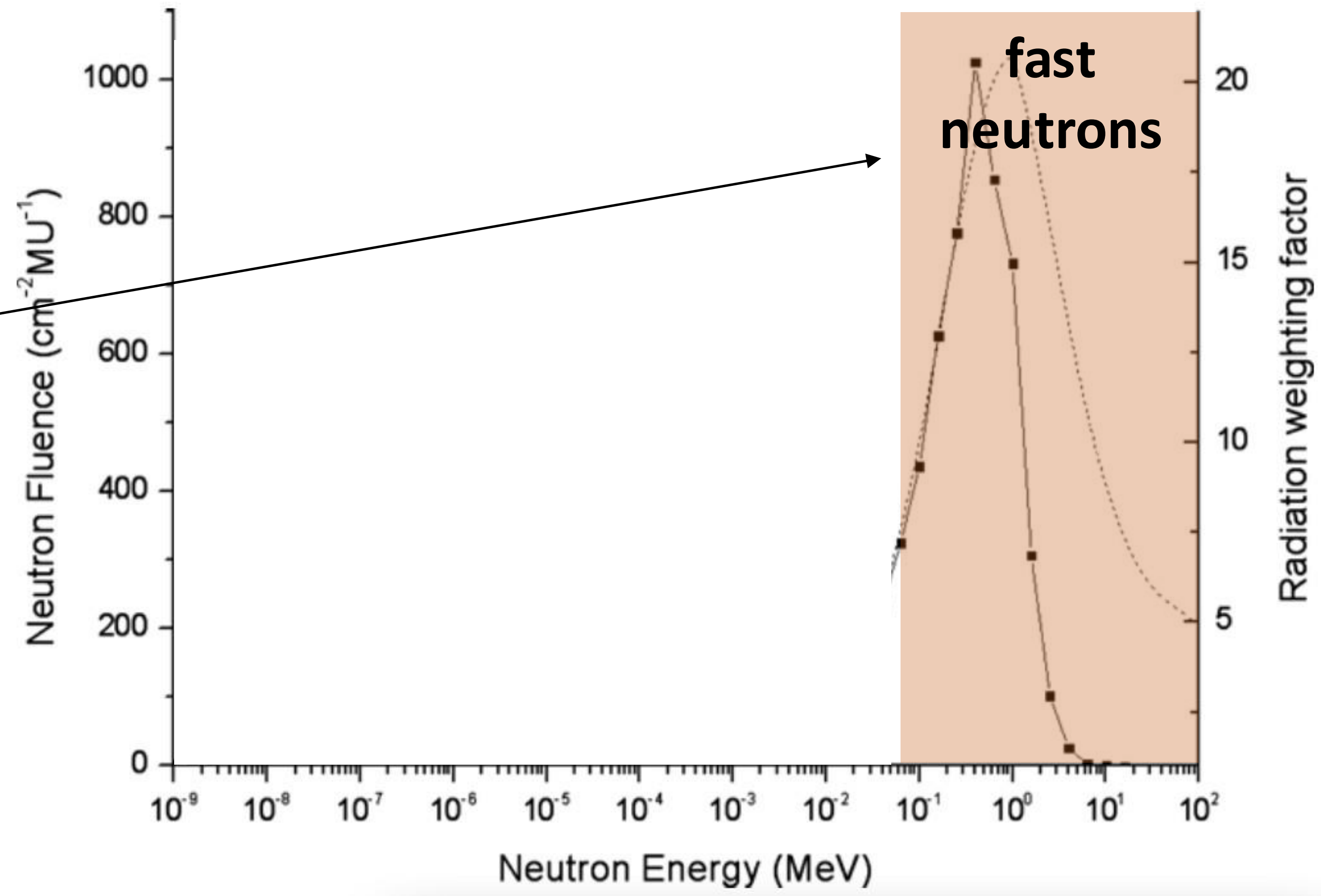

J. Pena *et al* (2005). Phys. Med. Biol. 50 (33),5921 and ICRP (2007) Publication 103

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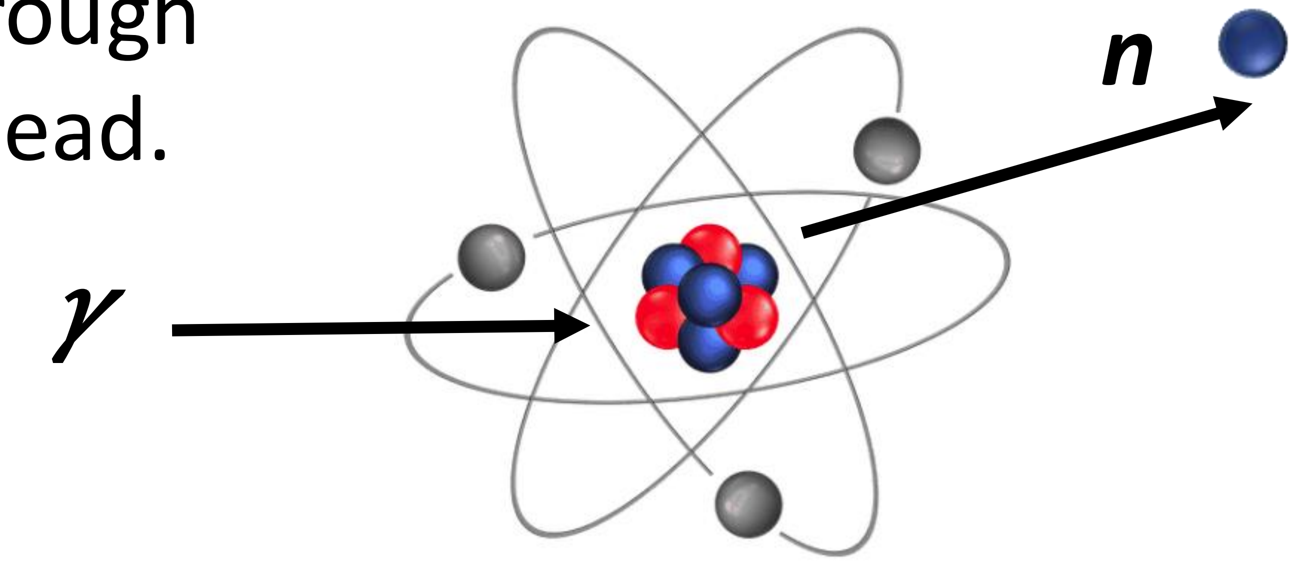

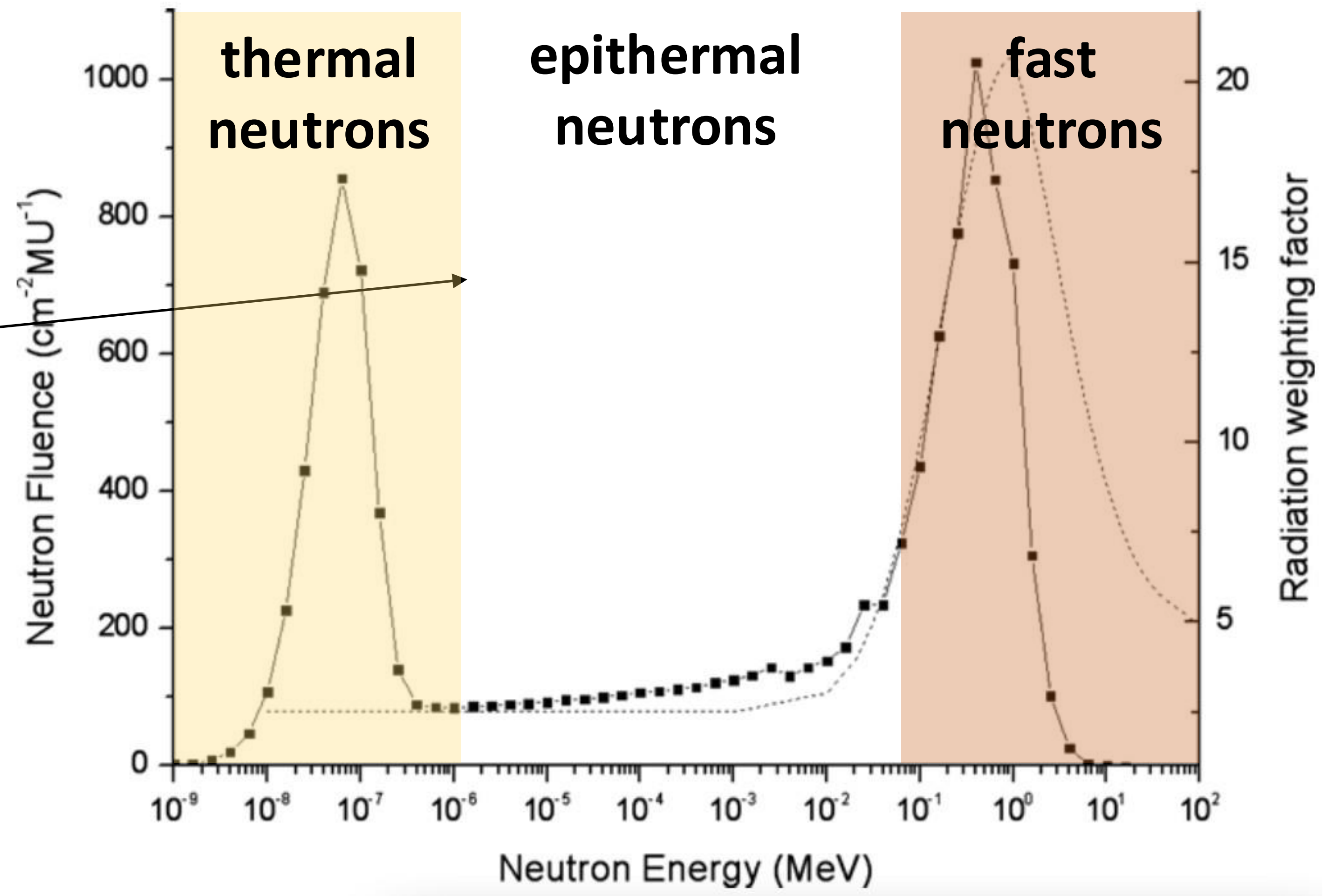

J. Pena *et al* (2005). Phys. Med. Biol. 50 (33),5921 and ICRP (2007) Publication 103

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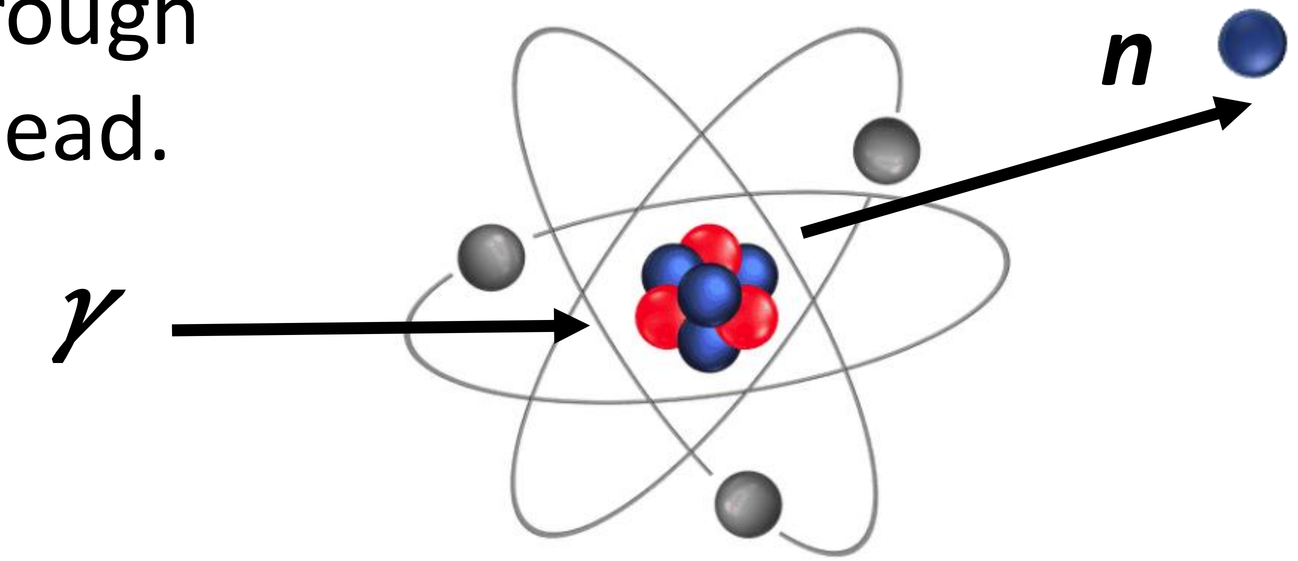

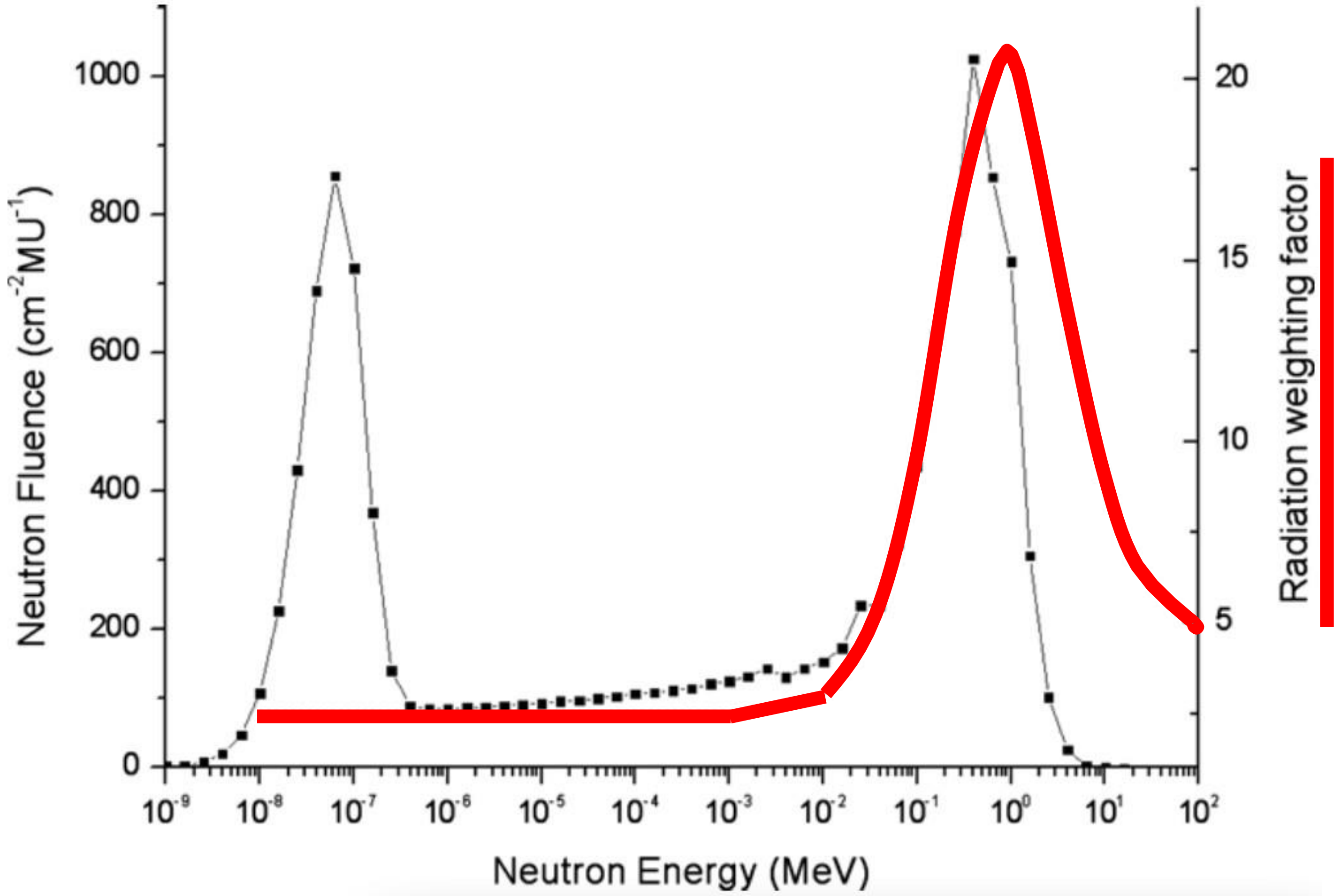

J. Pena *et al* (2005). Phys. Med. Biol. 50 (33),5921 and ICRP (2007) Publication 103

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Photoneutron yield

High variability between models and configurations

Field size

LINAC models

A comparison of the measured neutron dose for 10-MV, 15-MV, and 18-MV linacs with the current 15 MV measures using LB6411.

Medical accelerator	Measurement/ calculation method	Potential (MV)	Field size (cm^2)	Neutron dose to photon dose (mSv/ Gy)	Reference
Elekta Synergy	LB6411 Neutron probe	15	10 × 10 30 × 30	0.13 ± 0.002 0.188 ± 0.003	This work
Varian Clinac DHX	Au-foil	18	20 × 20	0.67 ± 0.04	Yücel et al. (2016)
Elekta Precise	Au-foil	18	15 × 15	1.95	Esposito et al., 2008
Varian 2100C/D	PC films	18	20 × 20	3.30 ± 0.50	Hashemi et al. (2011)

I. Ait Ouaggou *et al* (2023). Radiation Physics and Chemistry. 212, 111096.

Photoneutron yield

Table 1 – MC calculation of component contribution in photoneutrons from Varian 2100C/2300C linac.[32]				
Component	20 MeV	18 MeV	15 MeV	10 MeV
Target	17.2% (W,Cu)	16% (W,Cu)	9% (W,Cu)	0.01% (Cu)
Primary collimator	36% (W)	41% (W)	38% (W)	45% (W)
Flattening filter	10.4% (Fe,Ta)	9% (Fe,Ta)	22% (W)	0.03% (CU)
Jaws	36% (W)	35% (W)	29% (W)	56% (W)
Others (magnet, shielding, etc.)	1%	1.4%	1.2%	1%

Beam energy variation

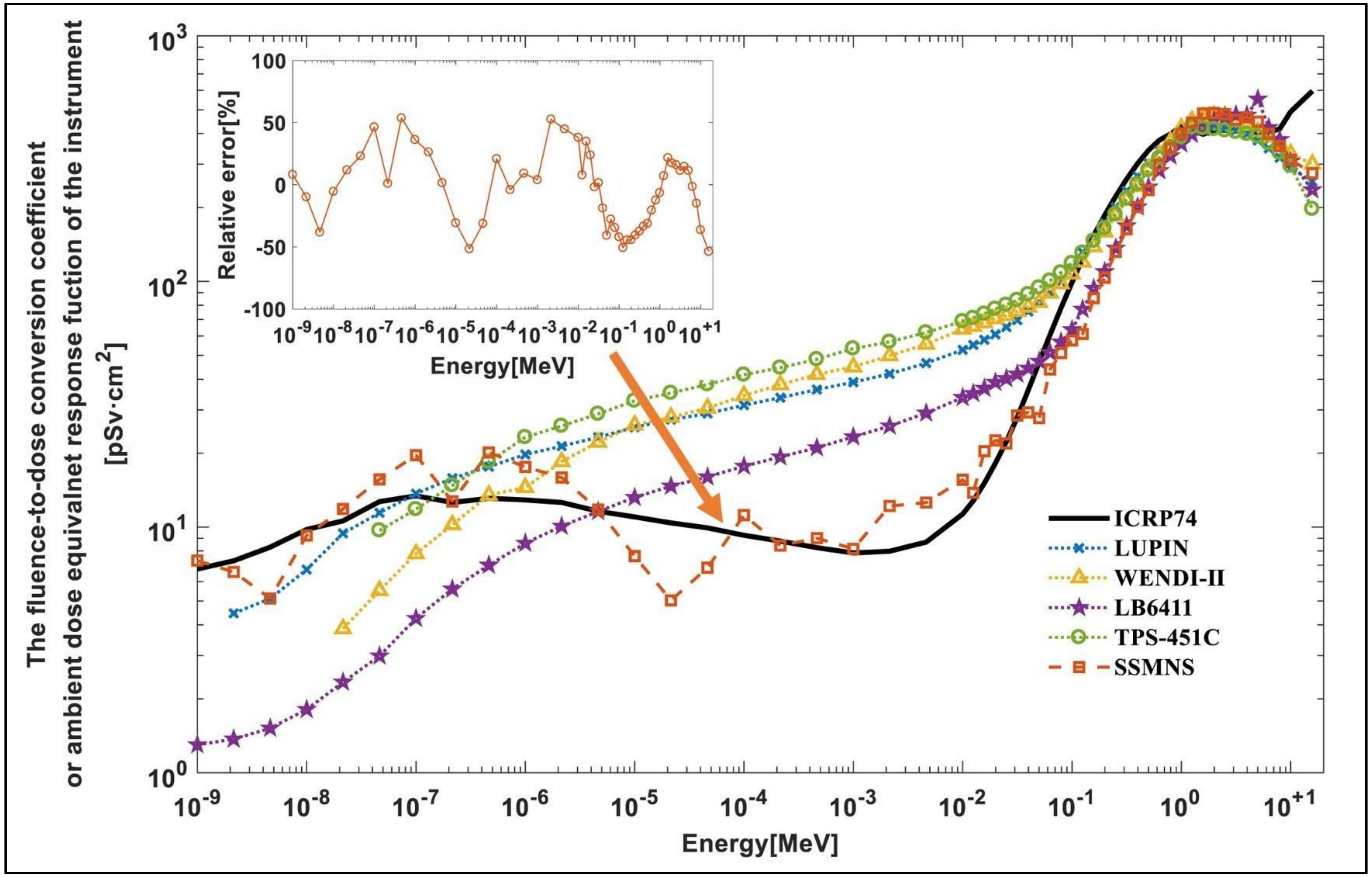
Different materials

A. Naseri & A. Mesbahi (2010). Reports of practical oncology and radiotherapy. 15(5), 138-144.

High variability between energy and configurations

How do we measure neutrons?

Z. Shen et al (2025). Nuclear Instruments and Methods in Physics Research Section A. 1076, 170473.4



Ambient dose rate meter

- Directly H*(10)
- Depends on response curve

Instruments currently used

Thermo Fisher Scientific. *TLD-600*™

WENDI

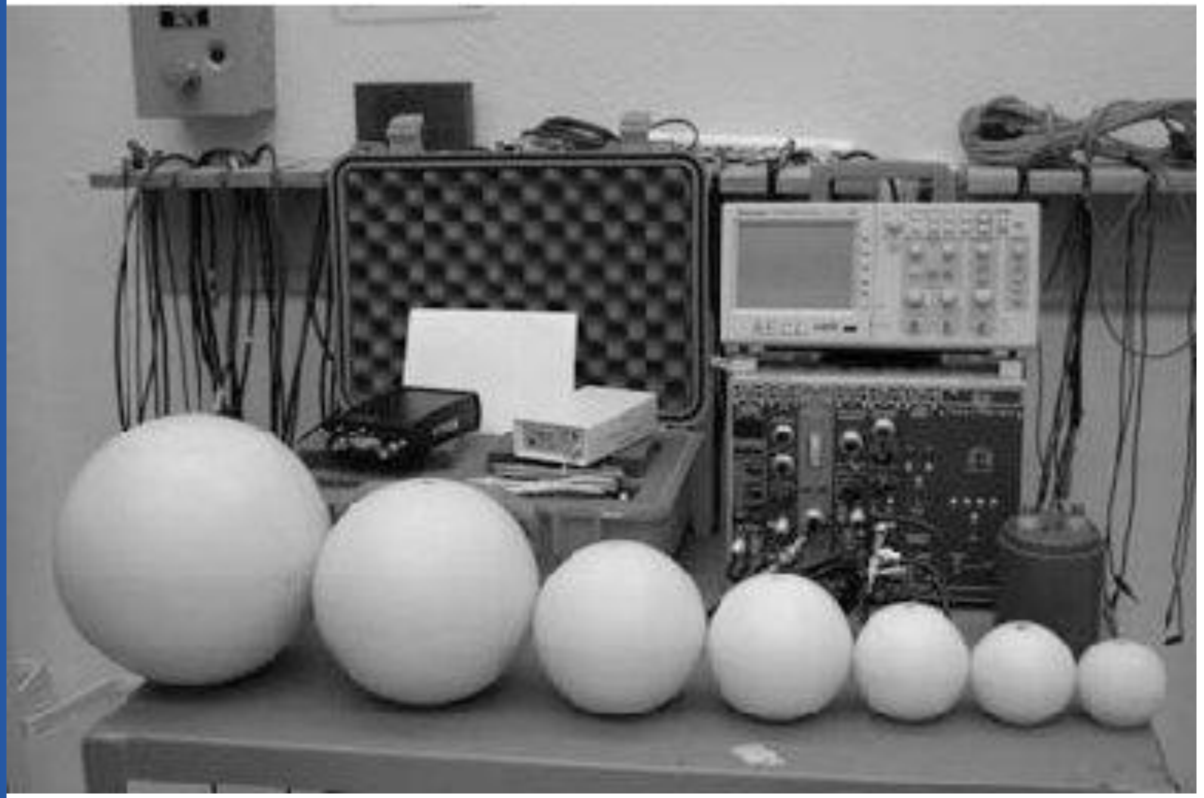
REM ball

Ludlum Measurements Inc. Model 3007 Series.

R.H. Olsher *et al* (2000). Health Physics. 79(2), 170-181.

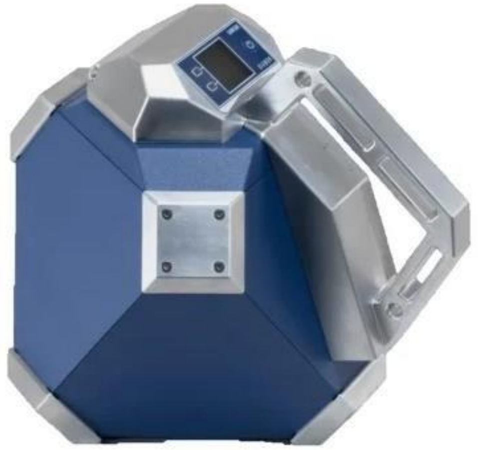
How do we measure neutrons?

Spectrometry



C. Domingo *et al* (2010). Radiation Measurements. 45(10), 1391-1397.

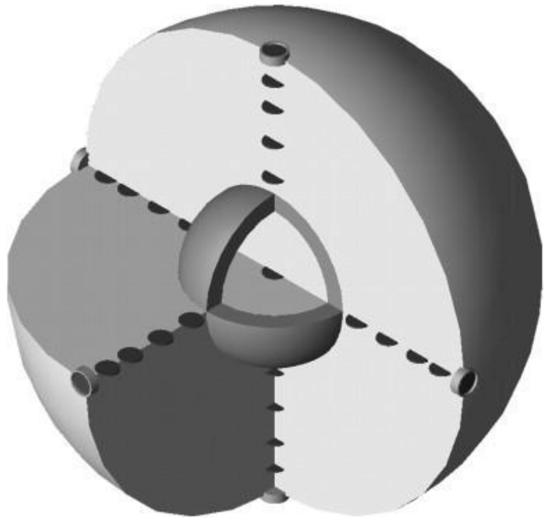
- Reference method BSS
- Requires multiple measurments
- ^{3}He restriction $$$



DIAMON
RAYLABS

SP2
ELSE NUCLEAR

R. Bedogni *et al* (2014). Nuclear Instruments and Methods in Physics Research Section A. 767, 159-162.



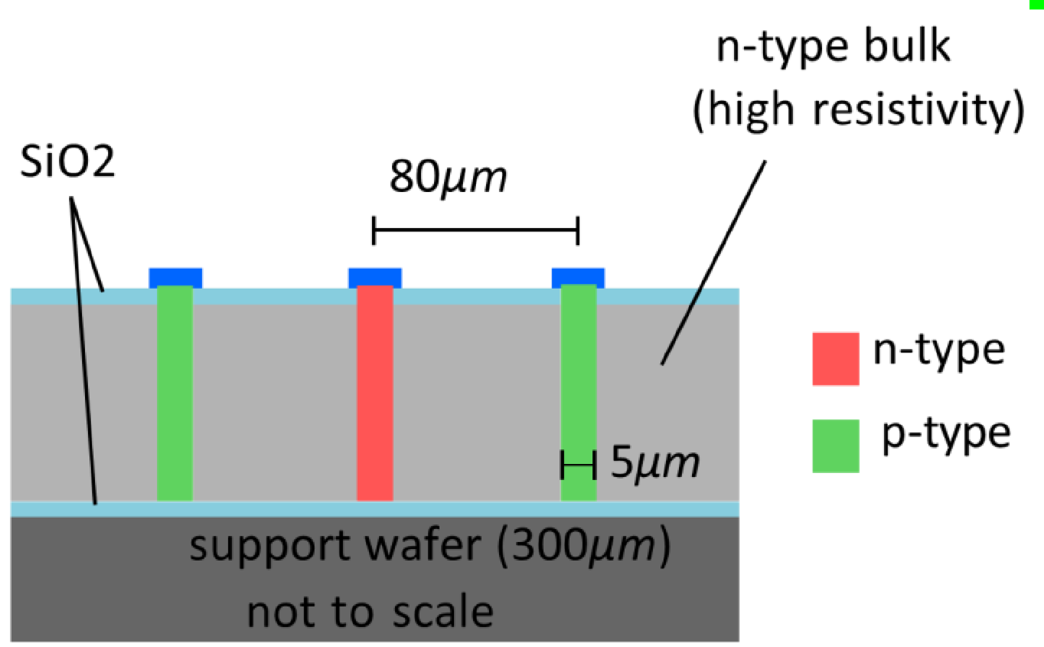
J. M. Gómez-Ros *et al* (2012). Nuclear Instruments and Methods in Physics Research Section A. 677, 4-9.

- Single-body
- Commercial Si detector (200-300 µm)

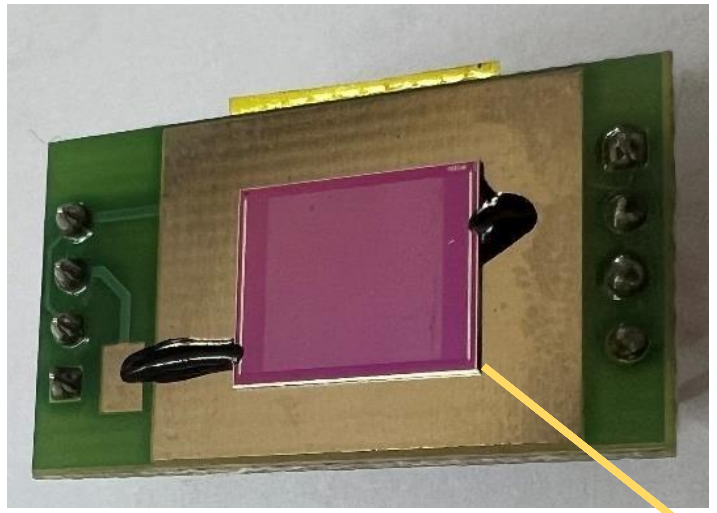
gamma rejection factor $10^{-4} – 10^{-5}$

Detector developed at CNM

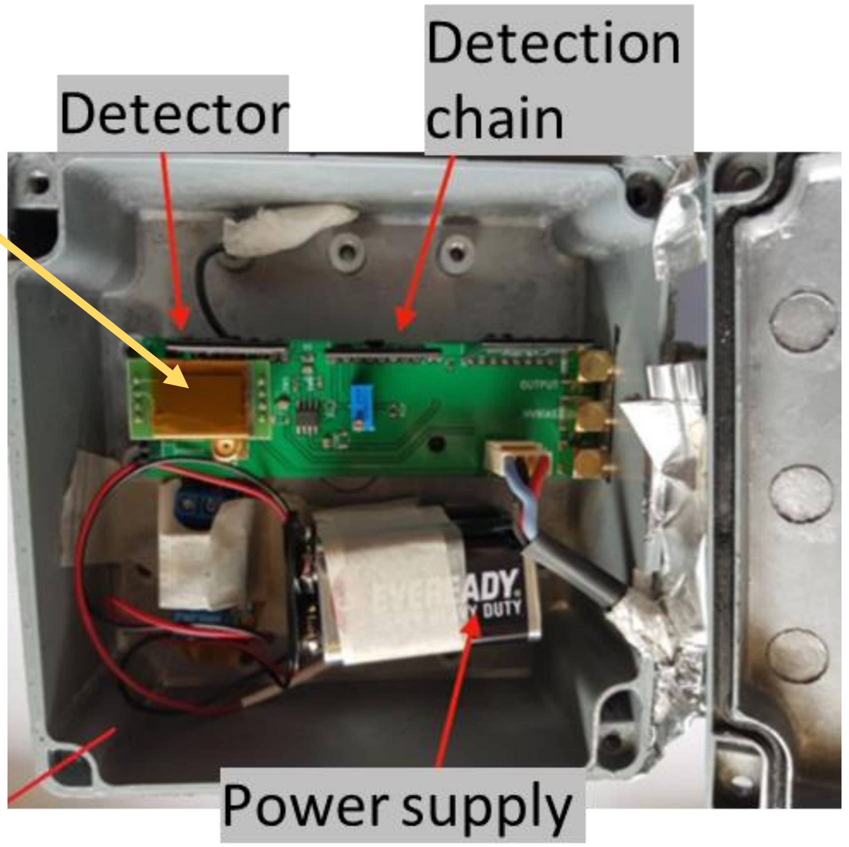
3D ultra-thin silicon detector (20 µm)

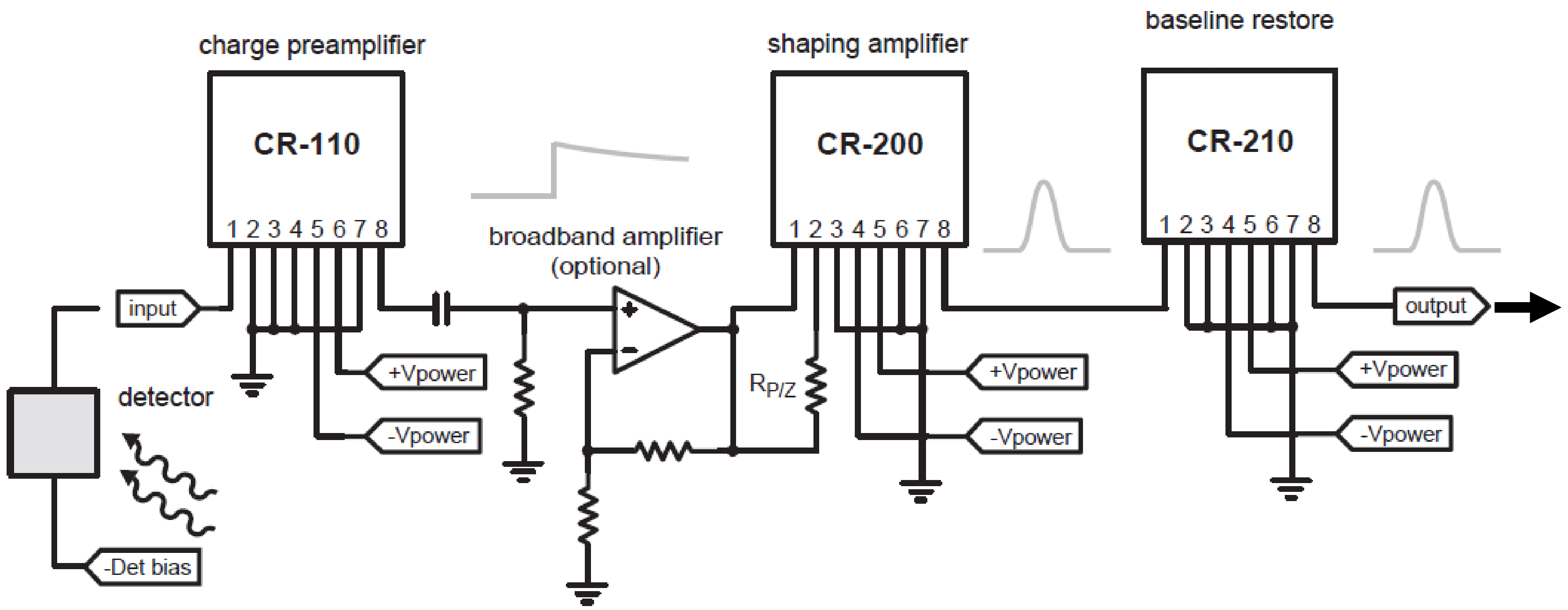


C. Guardiola *et al* (2013). Phys. Med. Biol. 58(10), 3227.



Active area
7.5x7.5 mm^2

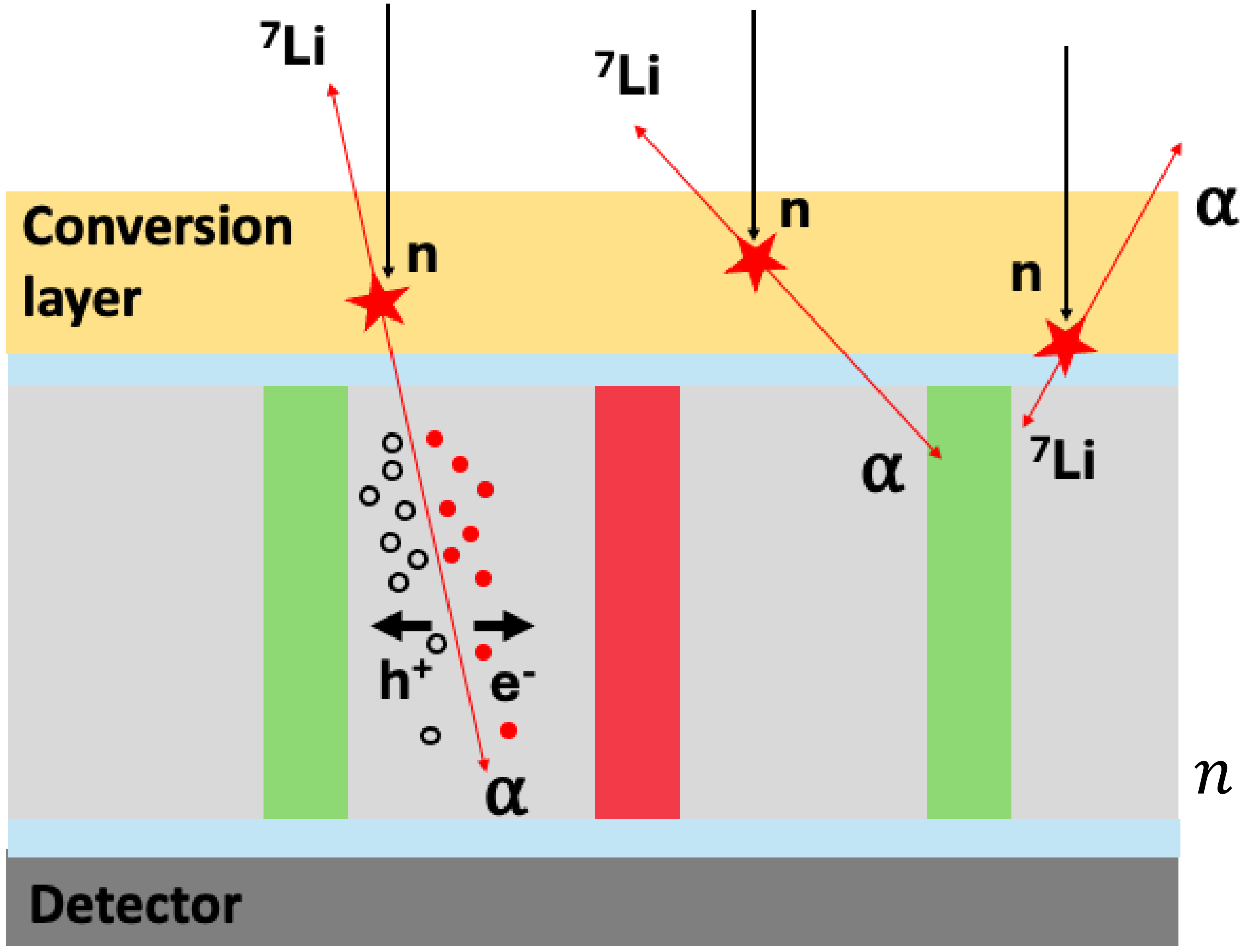


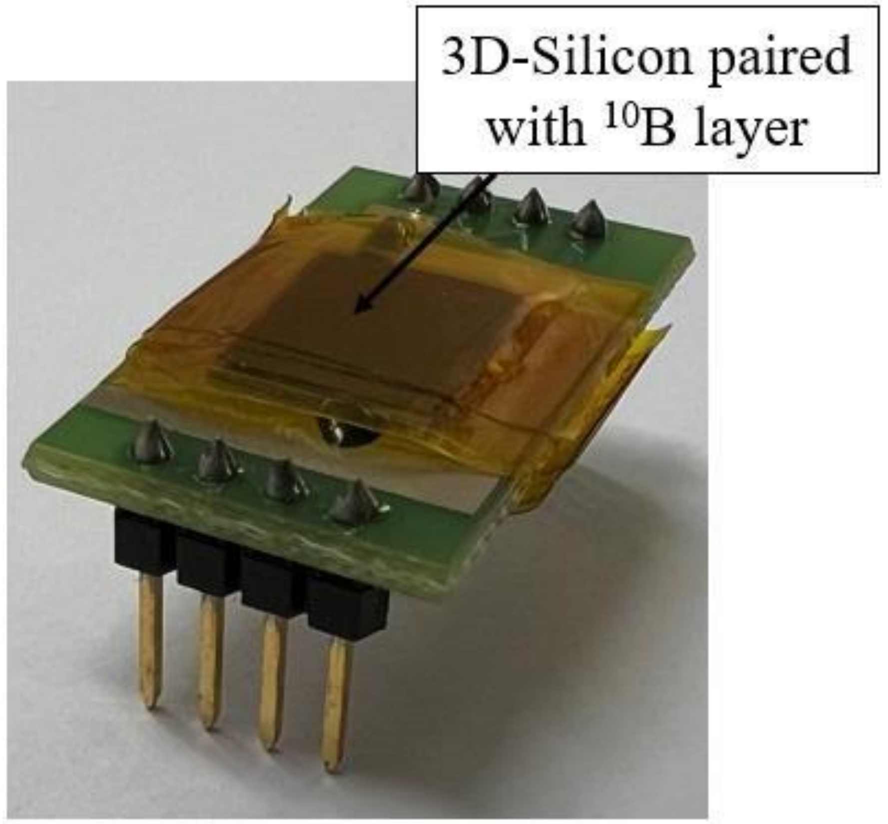


MCA, FPGA, mCU,...

Detector developed at CNM

3D ultra-thin silicon detector (20 µm)





$$n + 10B \rightarrow \alpha(1.47MeV) + {}^7Li\ (0.84MeV) + \gamma(0.48MeV)$$

Gamma rejection factor 10^{-8} - 10^{-9} (γ-rays 662 keV@ ^{137}Cs)

F. Zamorano *et al* (2025) Phys. Med. Biol. 70(16), 5001.

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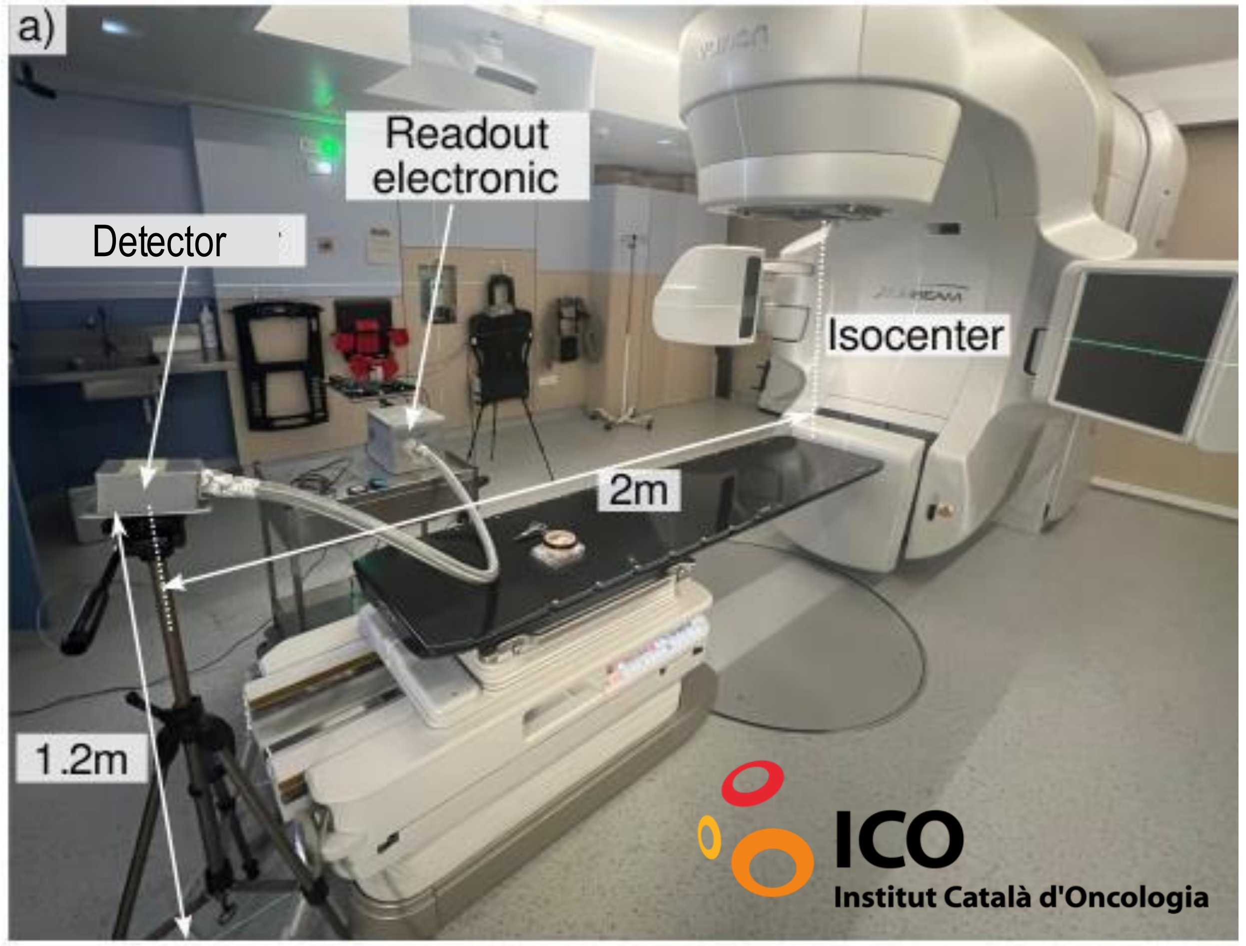
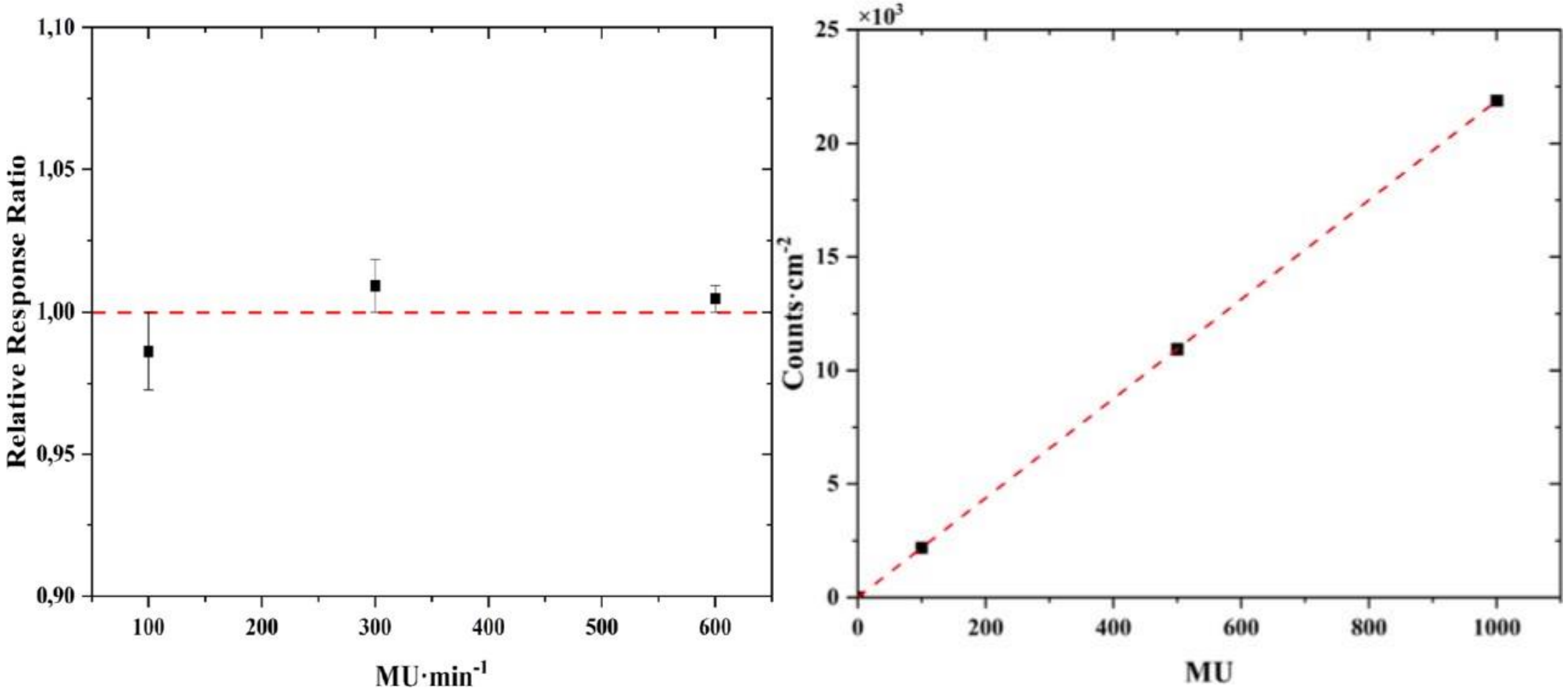
Experimental measurements

- Reproducibility < 2.3%
- Lineal up to 600 MU/min.
- No gammas @ LLD 660 keV.

F. Zamorano *et al* (2025) Phys. Med. Biol. 70(16), 5001.





LINAC: Varian TrueBeam

15 MV, 10x10 cm^2 , 0^o, FF, no phantom.

Dose rate: 100, 300 y 600 UM/min.

Total dose: (600 MU/min):

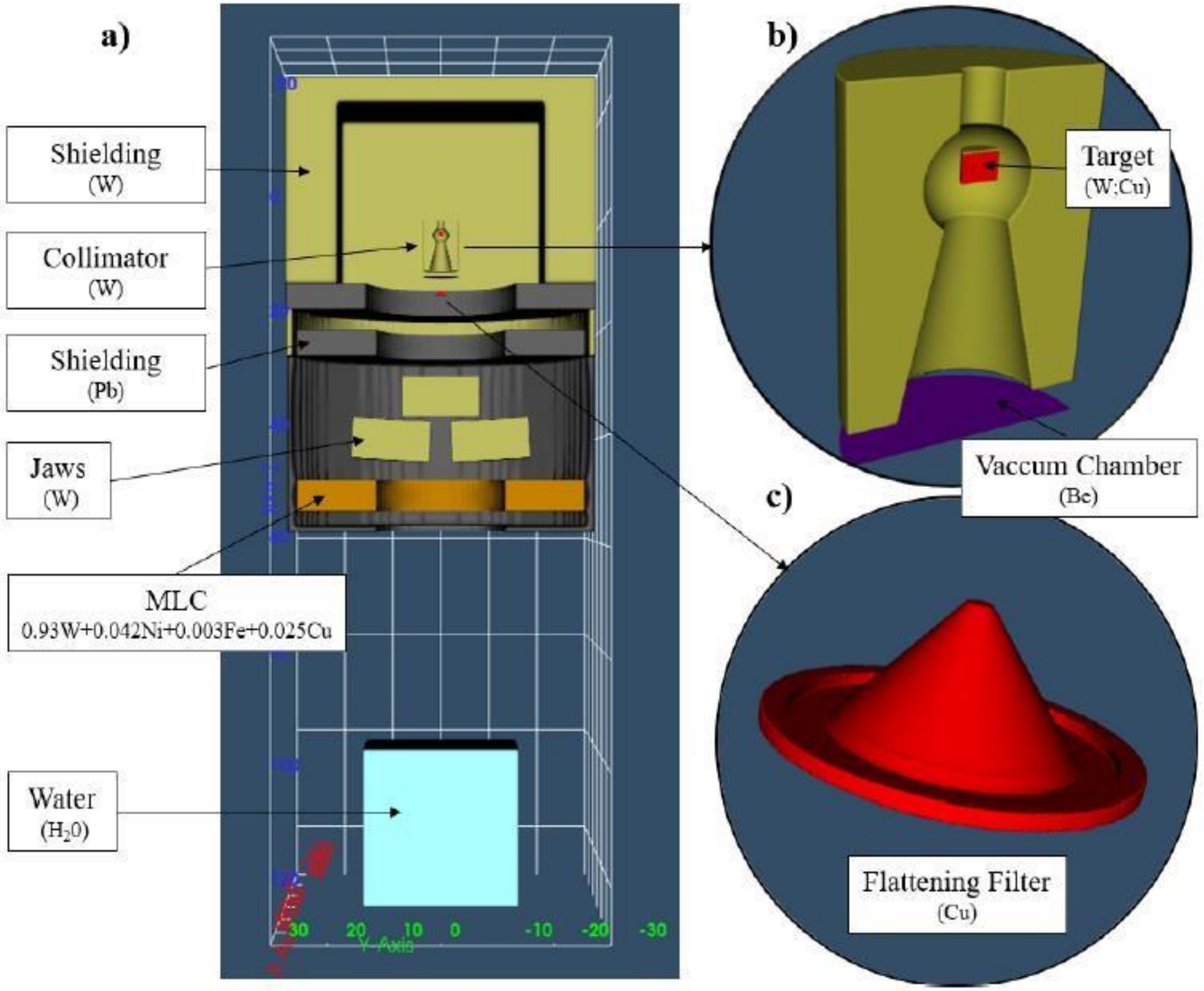
100, 500 y 1000 MU.

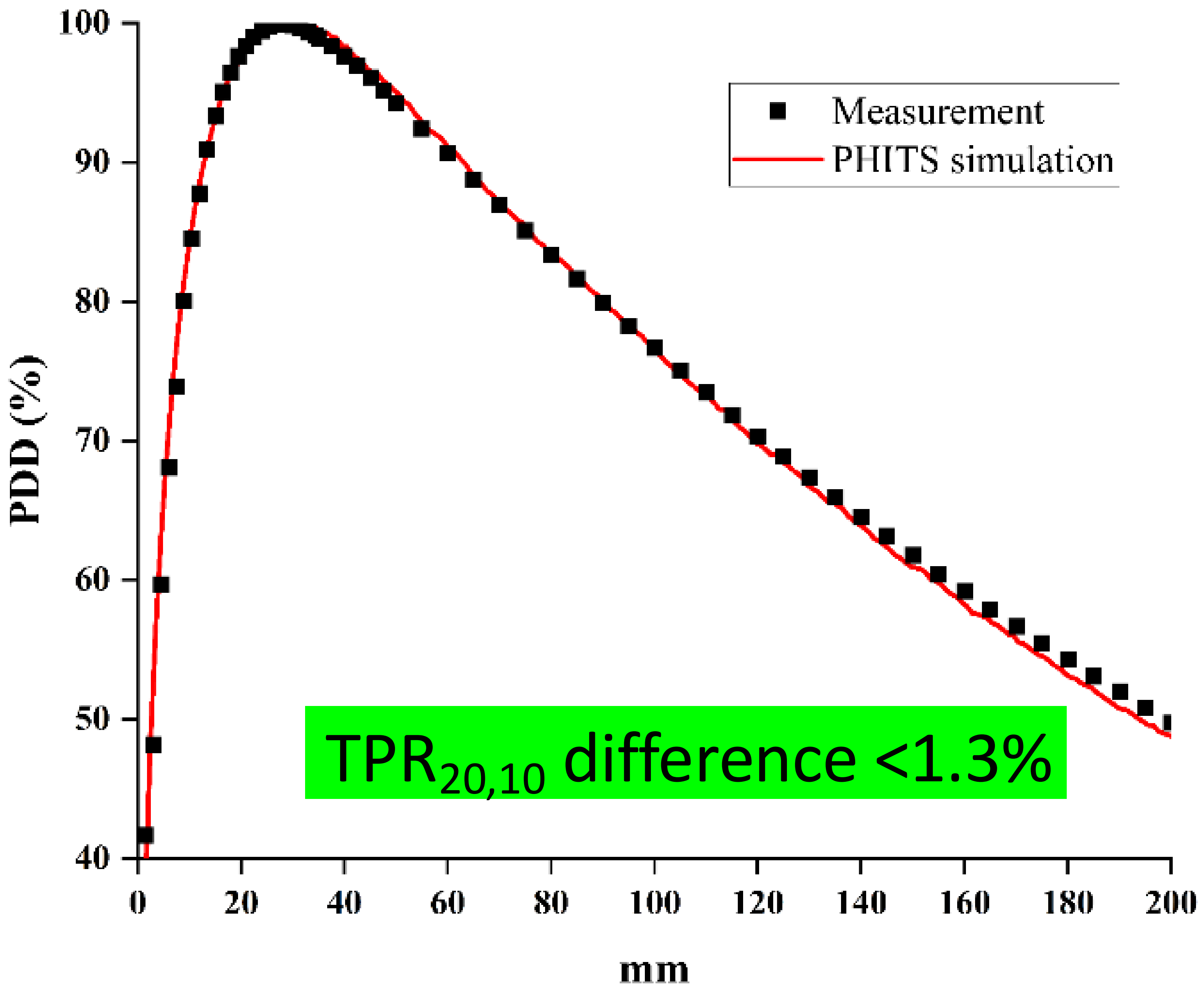
First LINAC head model of TrueBeam including shielding operating @15 MV

PHITS

Particle and Heavy Ion Transport code System

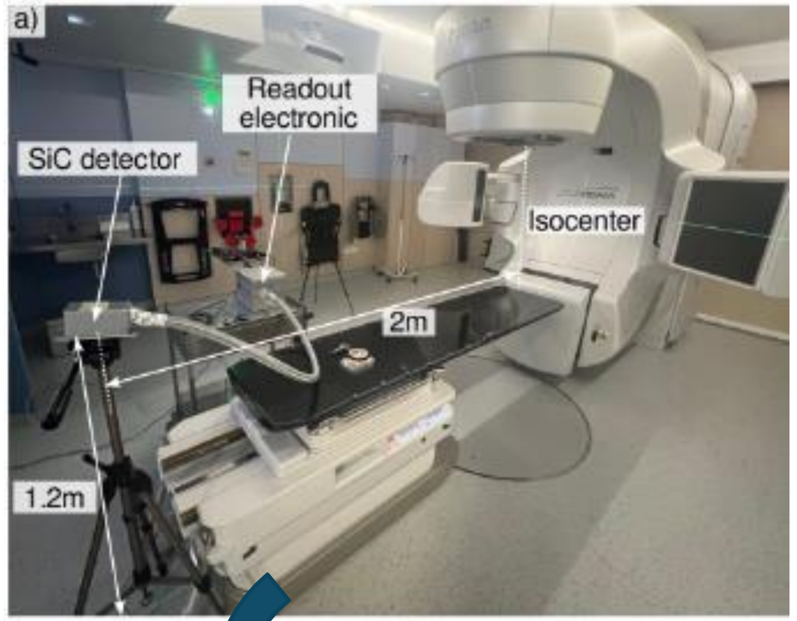
Monte Carlo code

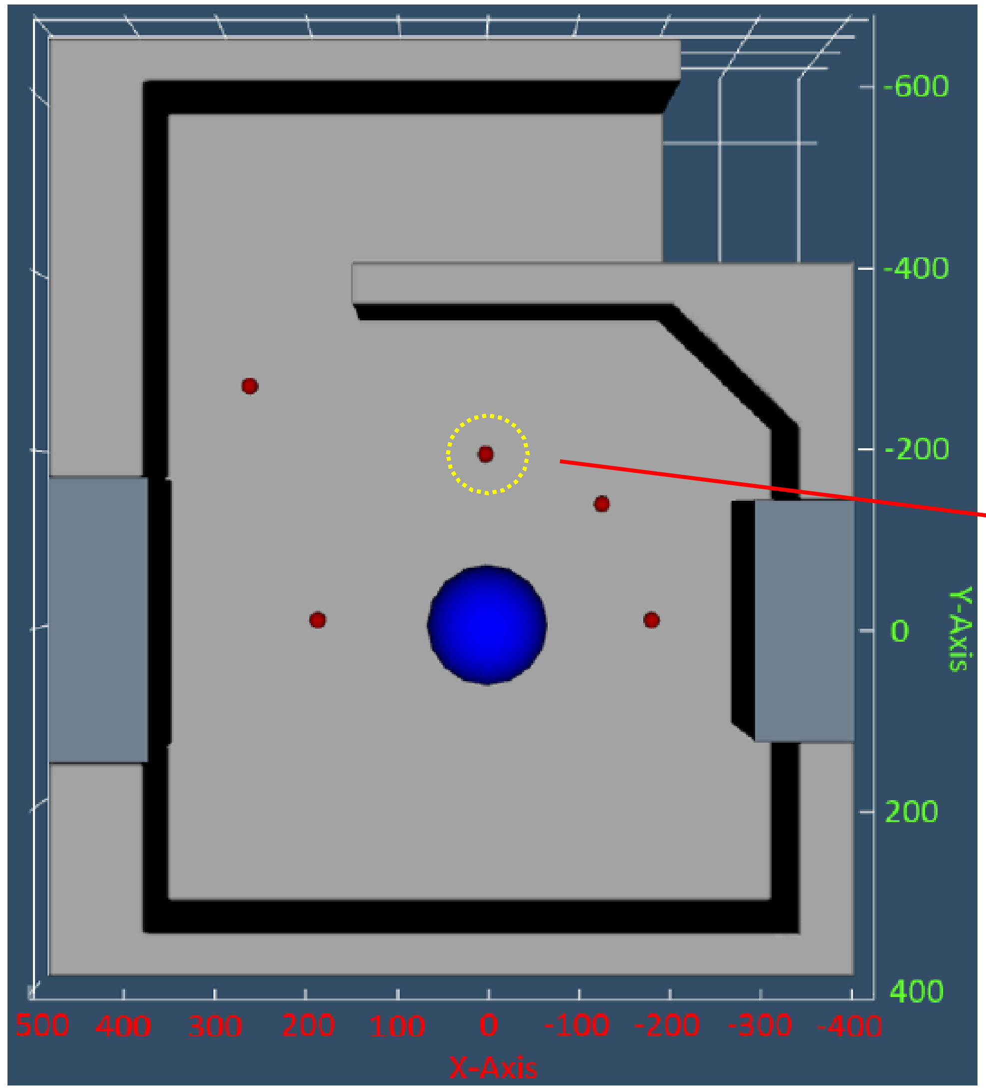


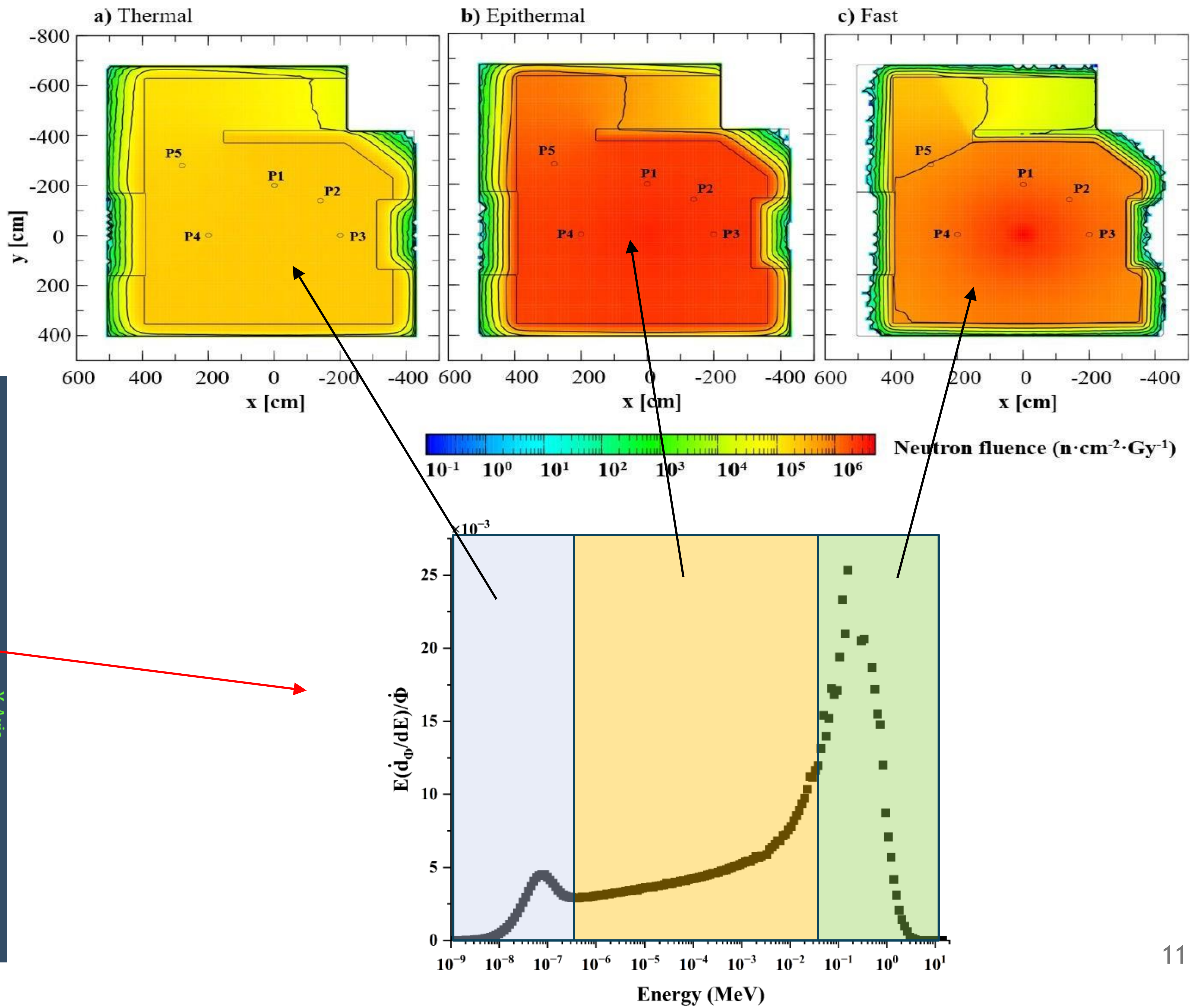


F. Zamorano *et al* (2025) Phys. Med. Biol. 70(16), 5001.

MC Simulations







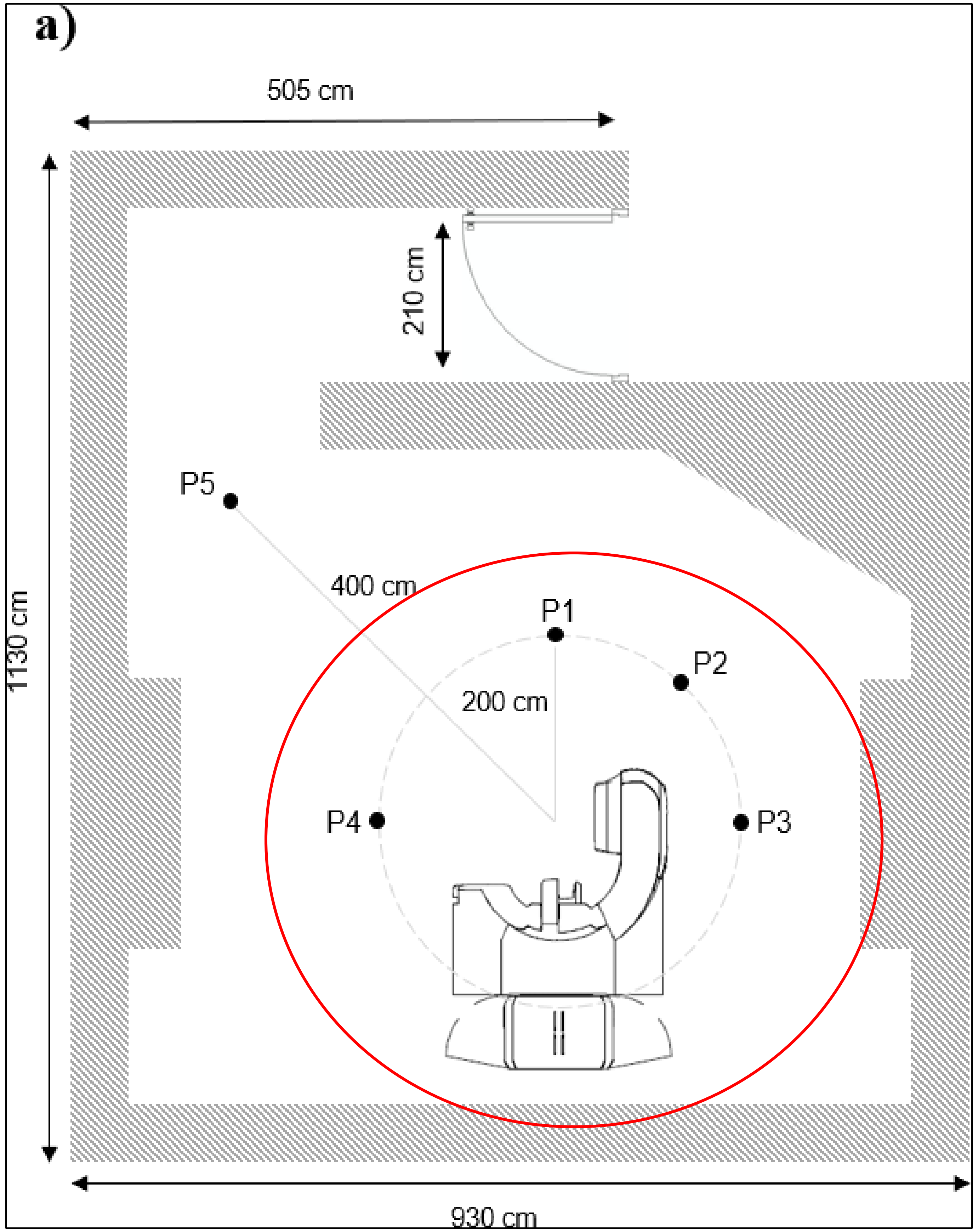
F. Zamorano *et al* (2025) Phys. Med. Biol. 70(16), 5001.

Experimental vs Simulation

Neutron fluence experimental vs simulated

LINAC	Thermal neutron fluence inside treatment room (neutron·cm^{-2}·Gy^{-1}) ·10^3			
	P1	P2	P3	P4
		Simulated		
Varian TrueBeam	(159.3 ± 0.3)	(160.4 ± 0.3)	(172.9 ± 0.3)	(147.8 ± 0.3)
		Measured		
Varian TrueBeam	(159.3 ± 3.2)	(160.3 ± 3.2)	(193.6 ± 3.9)	(141.6 ± 2.8)

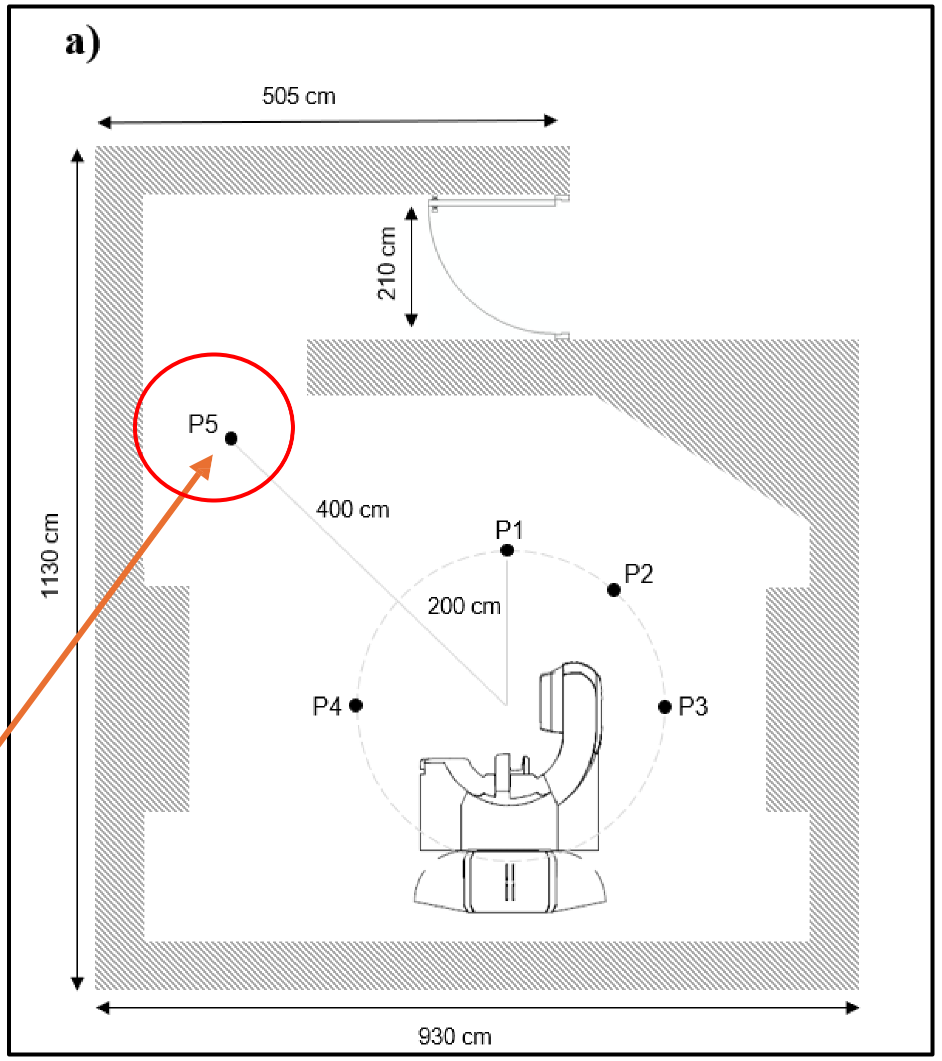
P1 - P4 < 4% difference



Experimental vs Simulation

Neutron fluence experimental vs simulated

LINAC	Thermal neutron fluence inside treatment room (neutron·cm^{-2}·Gy^{-1}) ·10^3				
	P1	P2	P3	P4	P5
	Simulated				
Varian TrueBeam	(159.3 ± 0.3)	(160.4 ± 0.3)	(172.9 ± 0.3)	(147.8 ± 0.3)	(128.1 ± 0.2)
	Measured				
Varian TrueBeam	(159.3 ± 3.2)	(160.3 ± 3.2)	(193.6 ± 3.9)	(141.6 ± 2.8)	(114.9 ± 2.3)



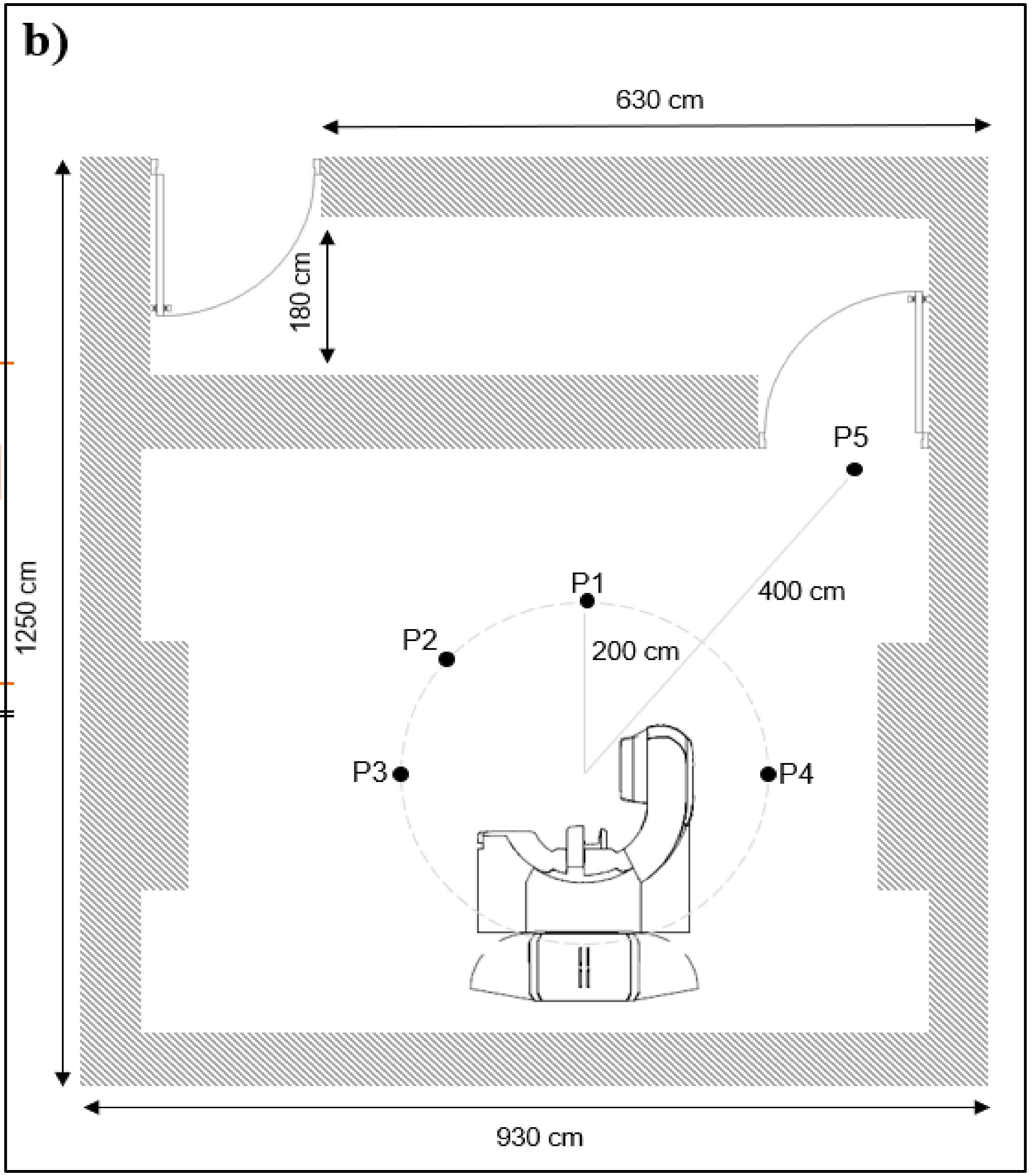
P5 < 12% difference

28% decrease
(less backscatter)

Comparative between 2 LINACs

2nd set of measurements using LINAC Elekta Synergy 15 MV

	Measured			
Varian TrueBeam	(159.3 ± 3.2)	(160.3 ± 3.2)	(193.6 ± 3.9)	(141.6 ± 2.8)
Elekta Synergy	(43.6 ± 0.9)	(39.5 ± 0.8)	(39.6 ± 0.8)	(41.2 ± 0.8)

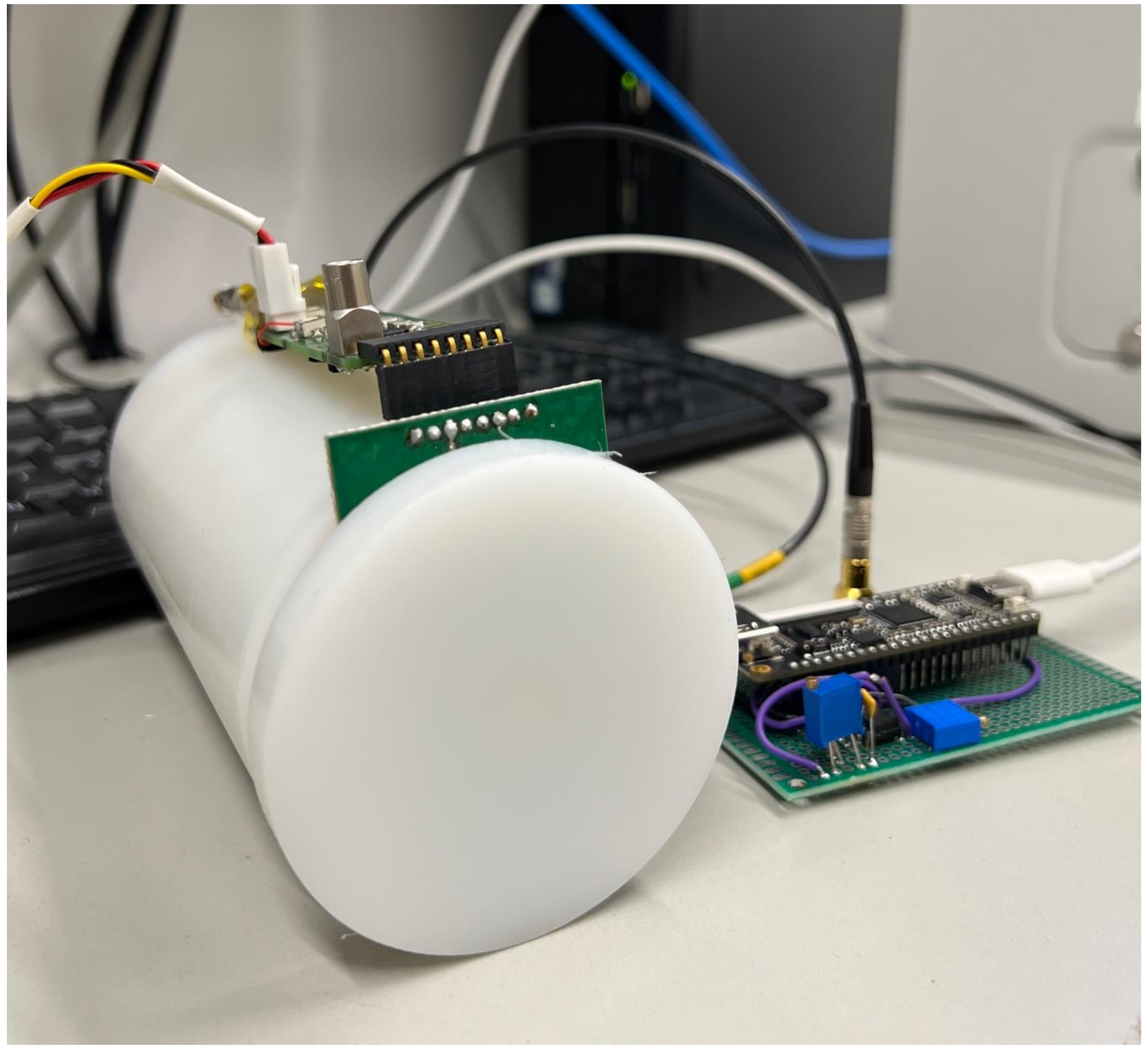


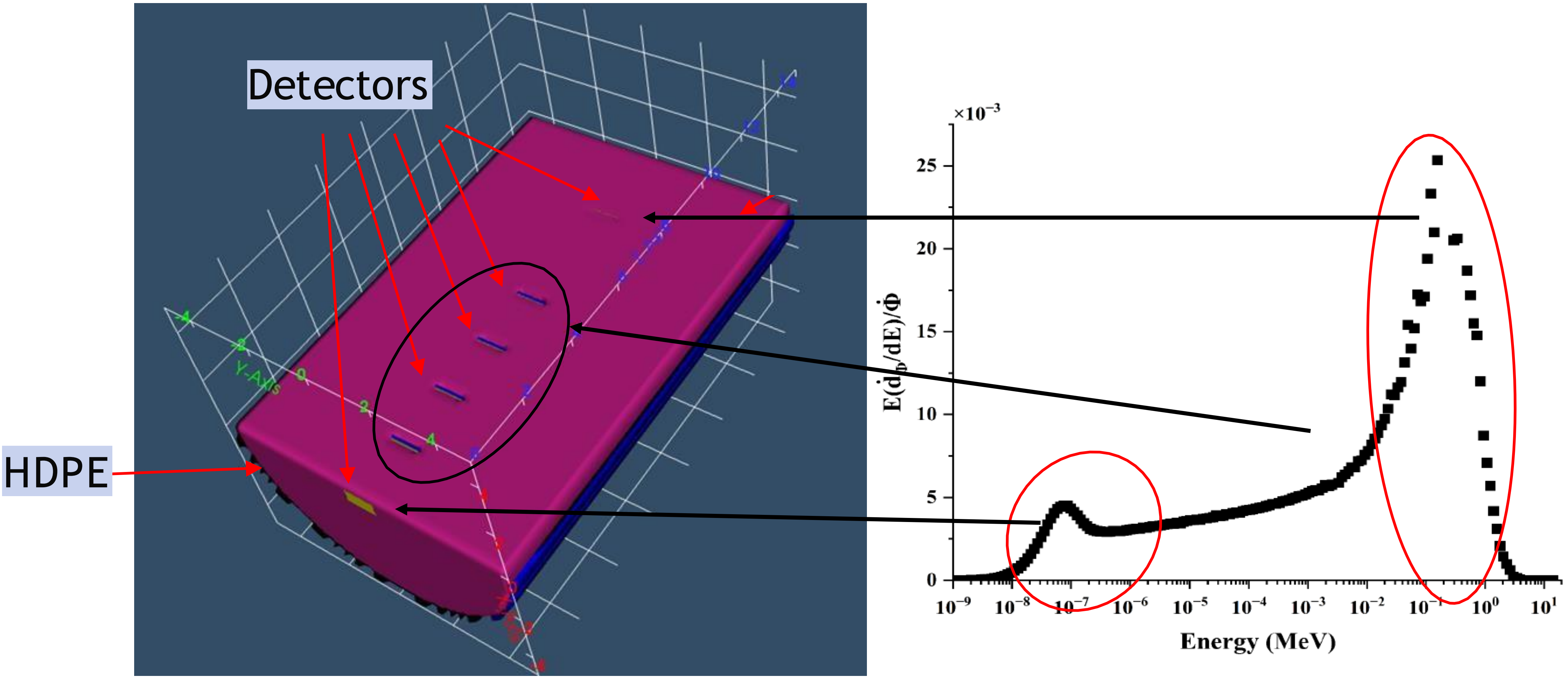
Elekta Synergy generates 4 times less neutrons compared to Varian TrueBeam operating at 15 MV

F. Zamorano *et al* (2025) Phys. Med. Biol. 70(16), 5001.

Conclusions & Ongoing

- Si (20 µm) SUITABLE for n_{th} detection
- 1st head model (PHITS) of the TrueBeam @15MV → $\boldsymbol{n}_{source}$
- Developing a *n*-spectroscopy system (high effiency & rejection factor)





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Acknowledgements

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‘María de Maeztu Unit of Excellence’ accreditation (CEX2023-001397-M)

Thanks for your attention!

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