Plastic scintillator based PET detector technique for proton therapy range monitoring: A Monte Carlo study

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On behalf of the J-PET collaboration

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The National Centre for Research and Development
LIDER
European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund

Context

- **Range monitoring would enable:**

  - Reduction of safety margins
  - Application of new irradiation fields
  - Dose escalation
  - Hypofractionation
  - Personalization: adaptive therapy

- **Clinically tested prototypes**

  - Prompt-gamma
    - OncoRay, Dresden and UPenn, Pennsylvania
    - MGH, Boston

  - Positron Emission Tomography
    - GSI, Darmstadt
    - HIT, Heidelberg
    - CNAO, Pavia

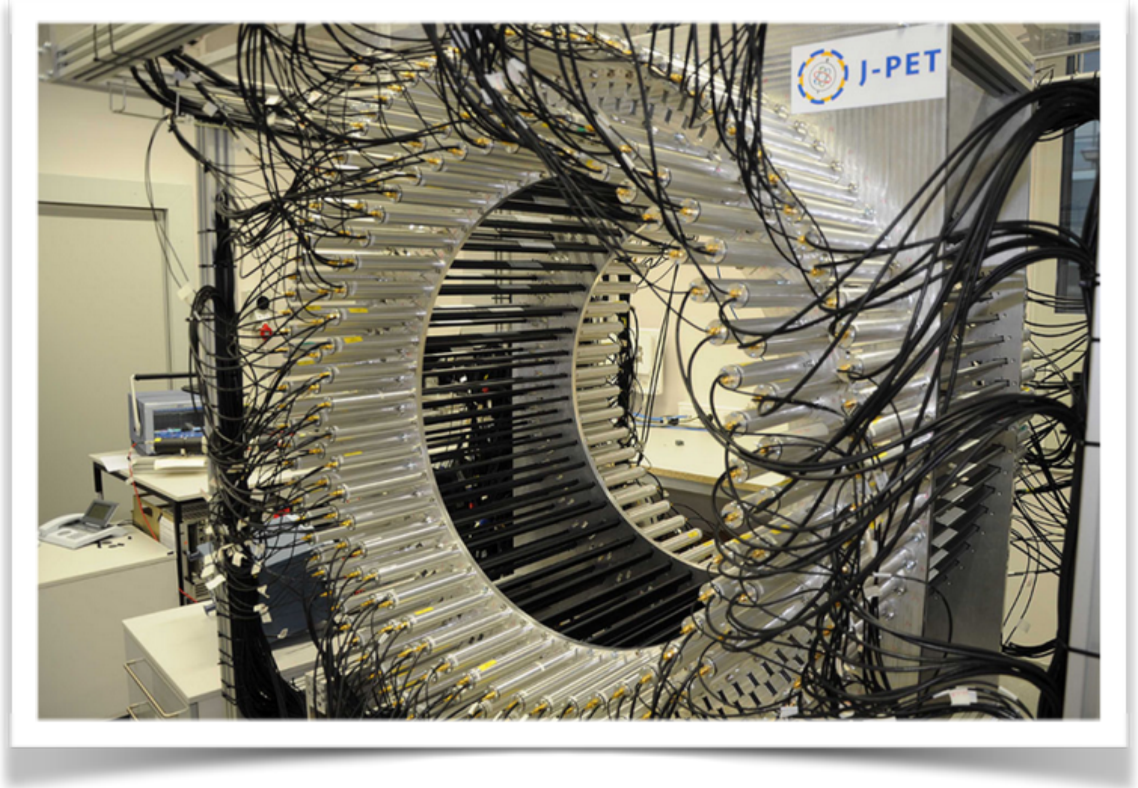
… other solutions are investigated pre-clinically

Outline

- Krakow proton therapy facility
- Jagiellonian-PET (J-PET)

- Simulation setup
- J-PET design
- Efficiency

- Conclusions and future steps



Krakow proton therapy facility

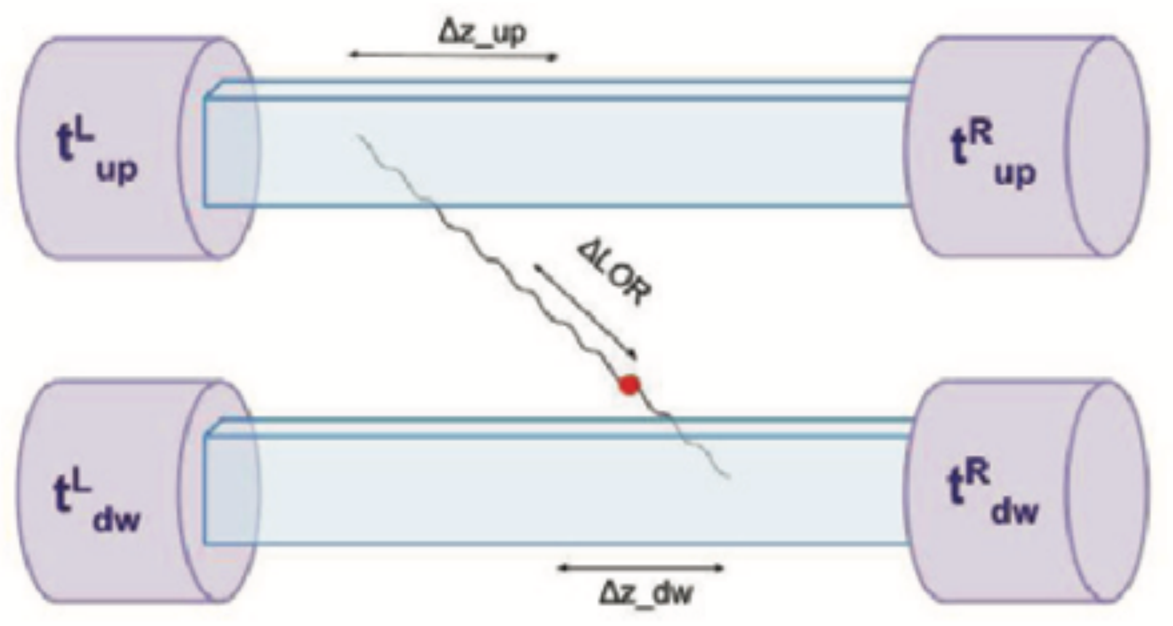
- IBA Proteus C-235
- 2x Gantry (scanning)
- Eye treatment room
- Experimental hall

- Clinical operation from Oct 2016
- >120 patients treated

Jagiellonian-PET (J-PET)

Cost effective method for the Total-body PET

Principle



CRT = 0.266 ns.

$$t_{hit}=(t^L+t^R)/2$$

$$\Delta LOR=(t_{hit}^{up}-t_{hit}^{dw})c/2$$

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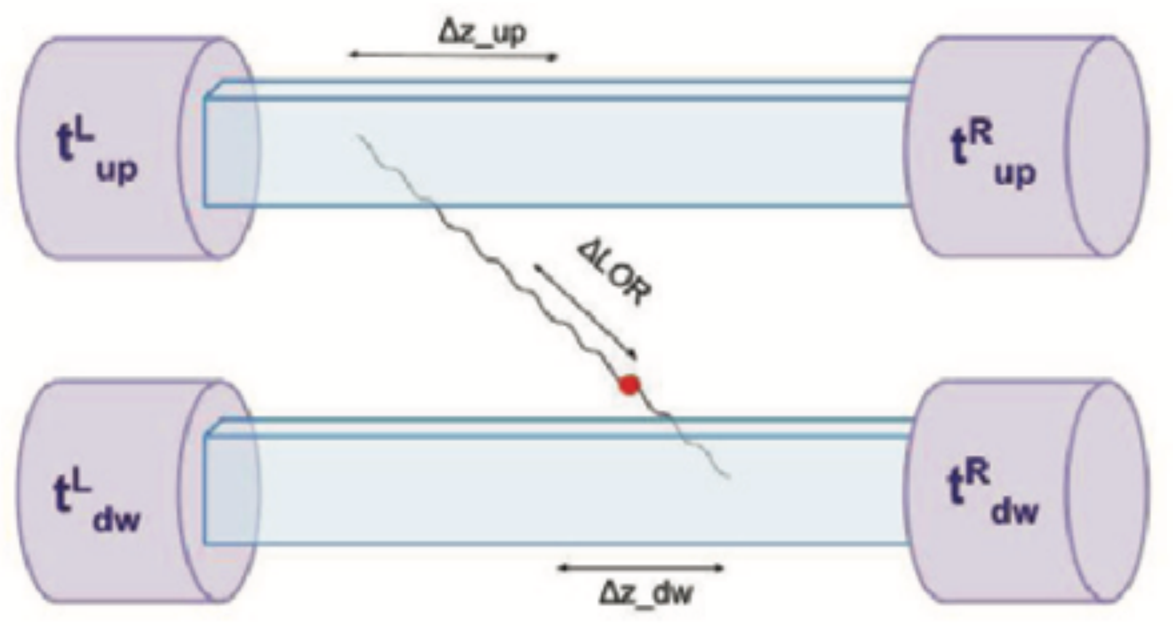

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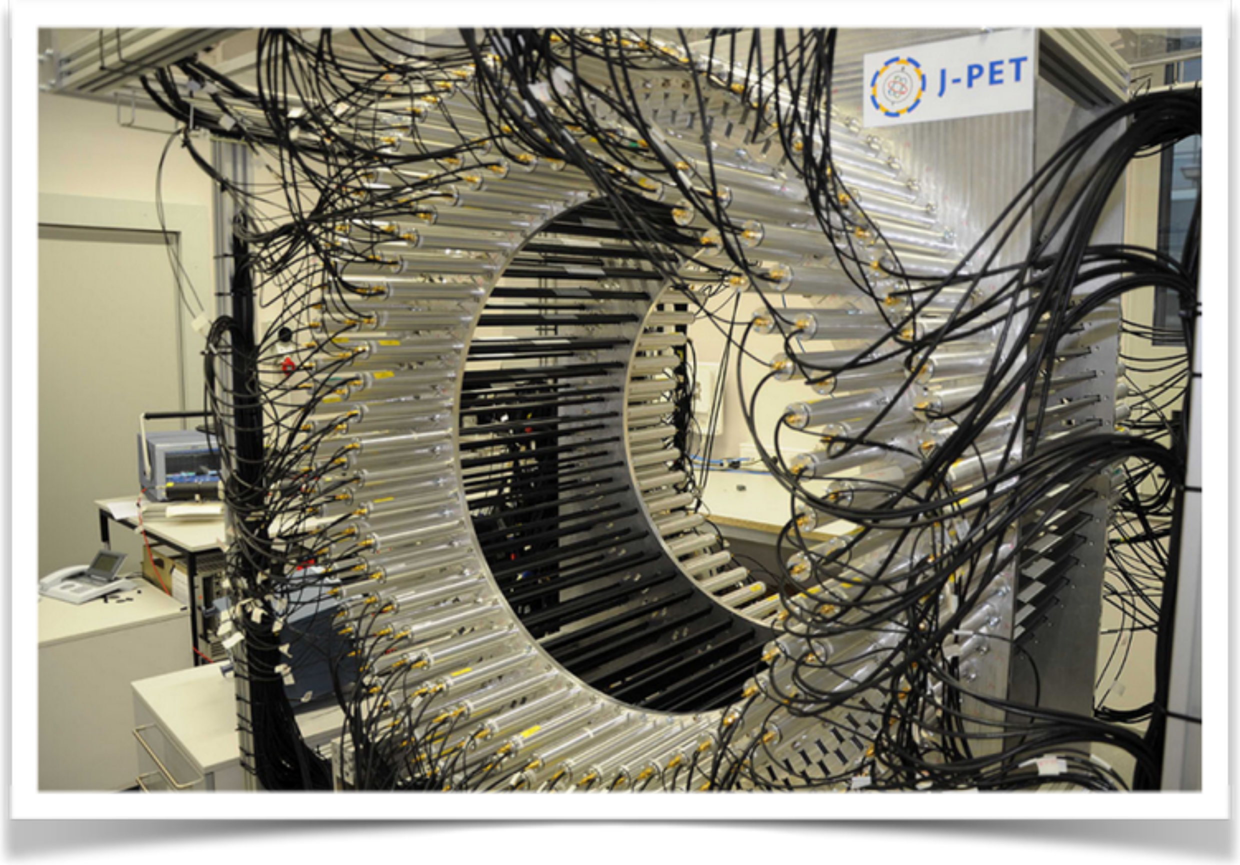
Prototype



- Three cylindrical layers of EJ-230 plastic scintillator strips (7×19×500mm3)
- Vacuum tube photomultipliers

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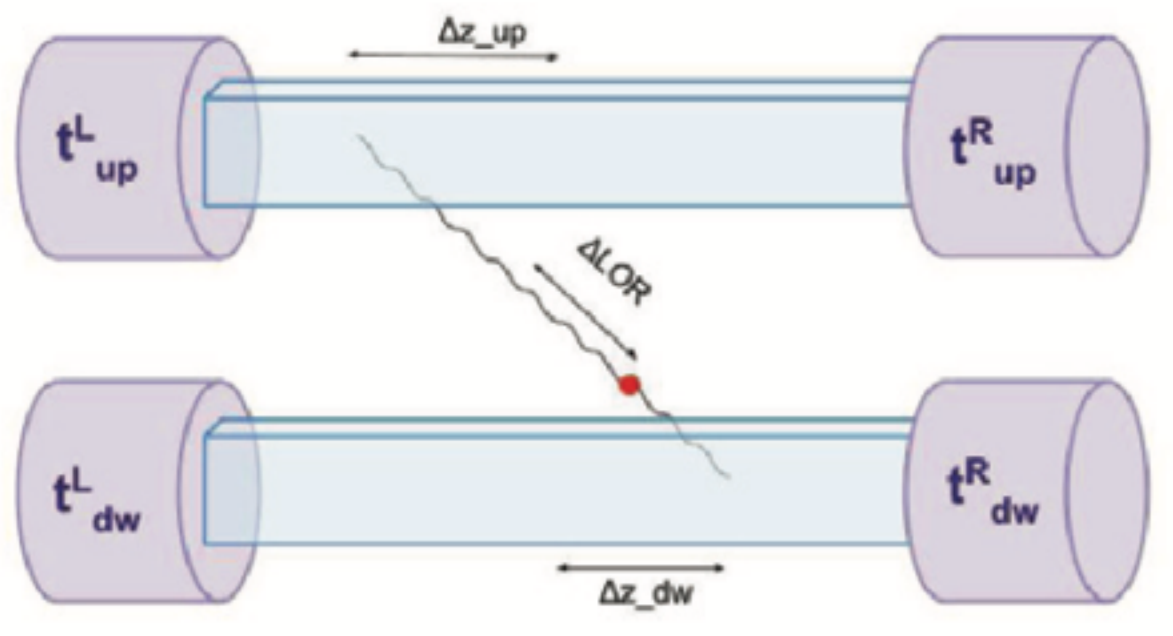

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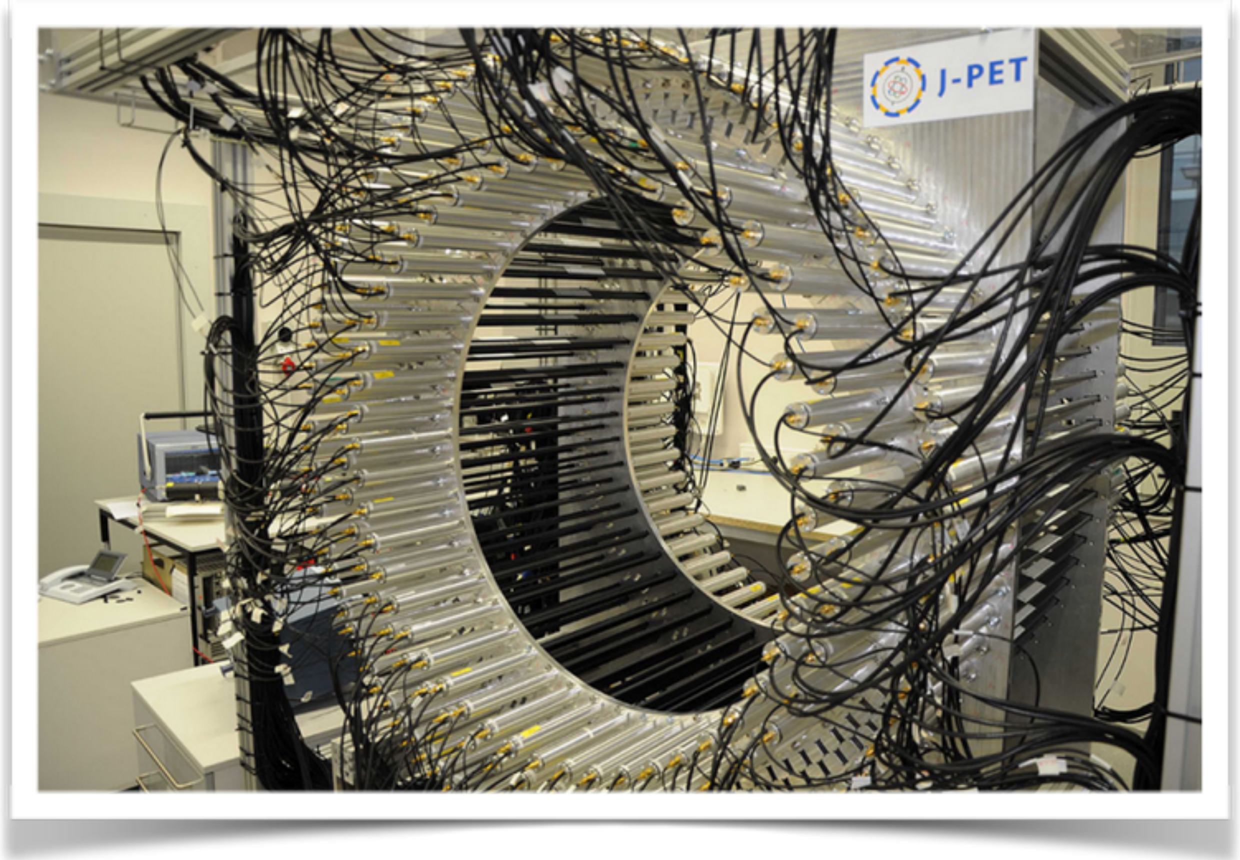

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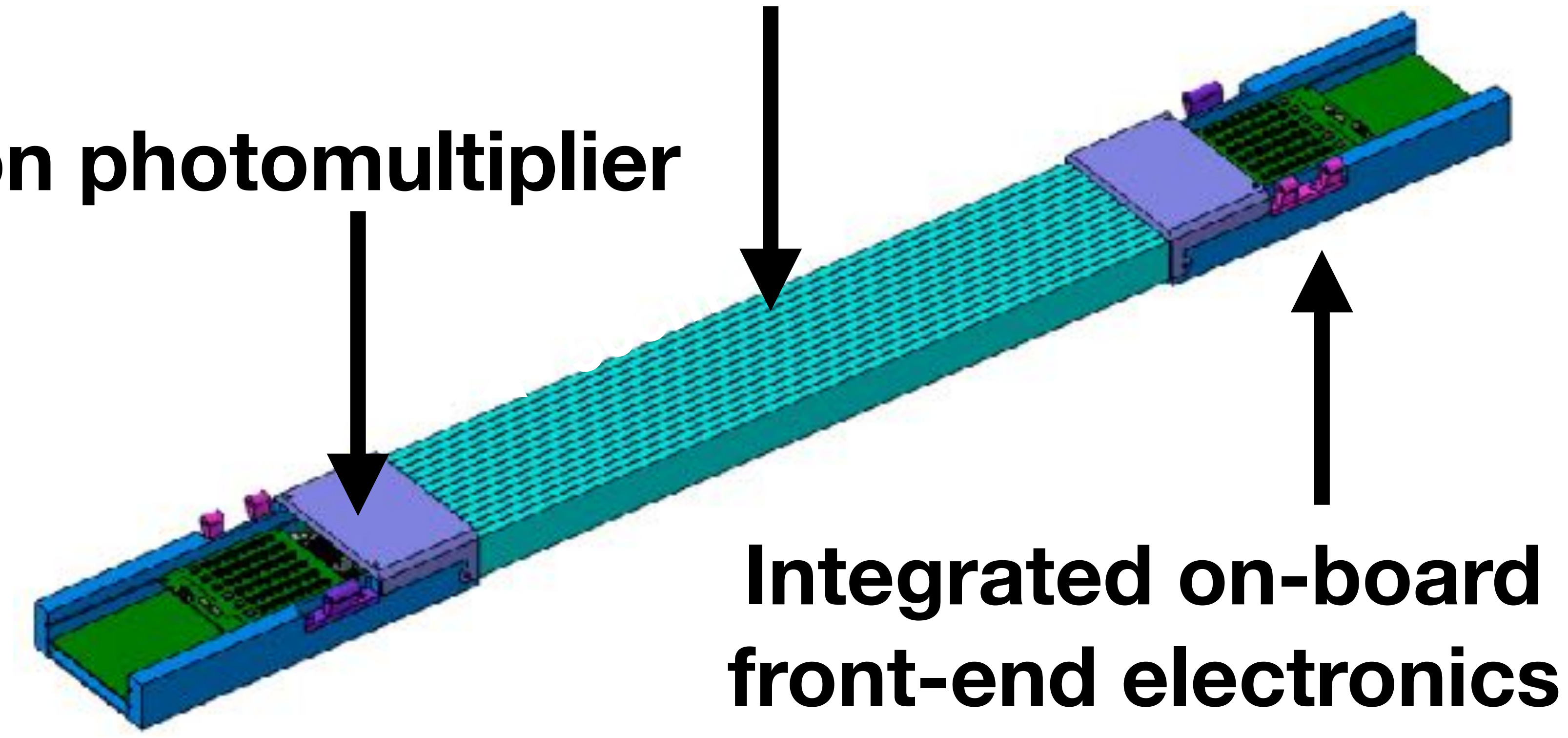
Modular Prototype

light weight, portable, reconfigurable



Jagiellonian-PET (J-PET)

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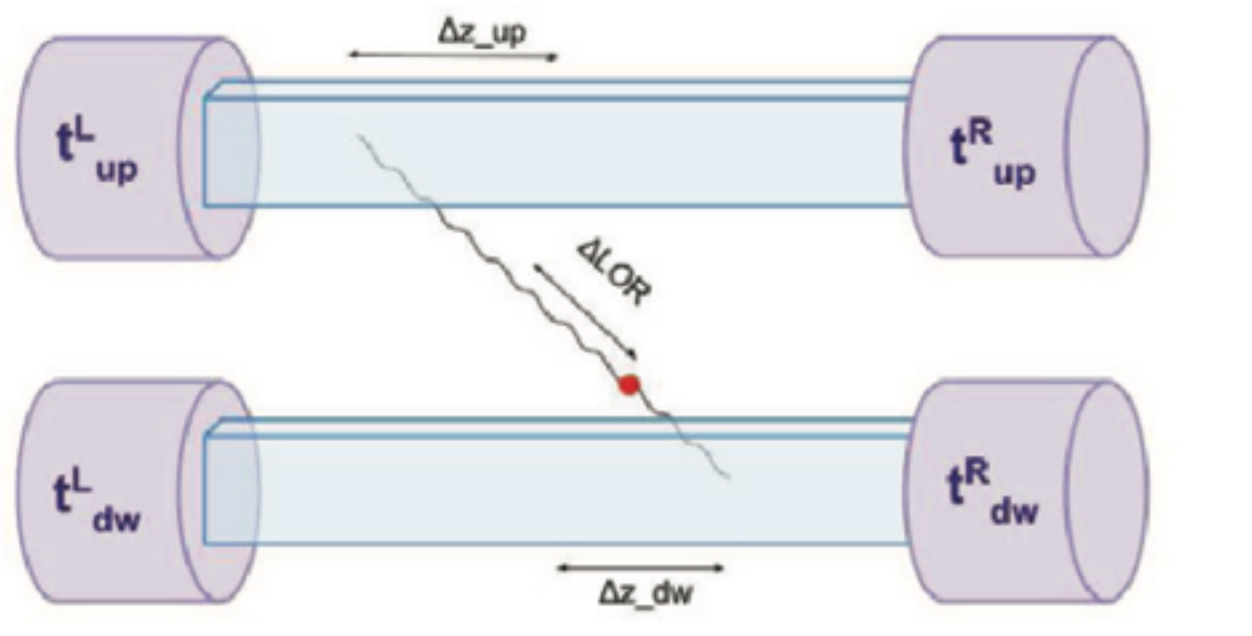

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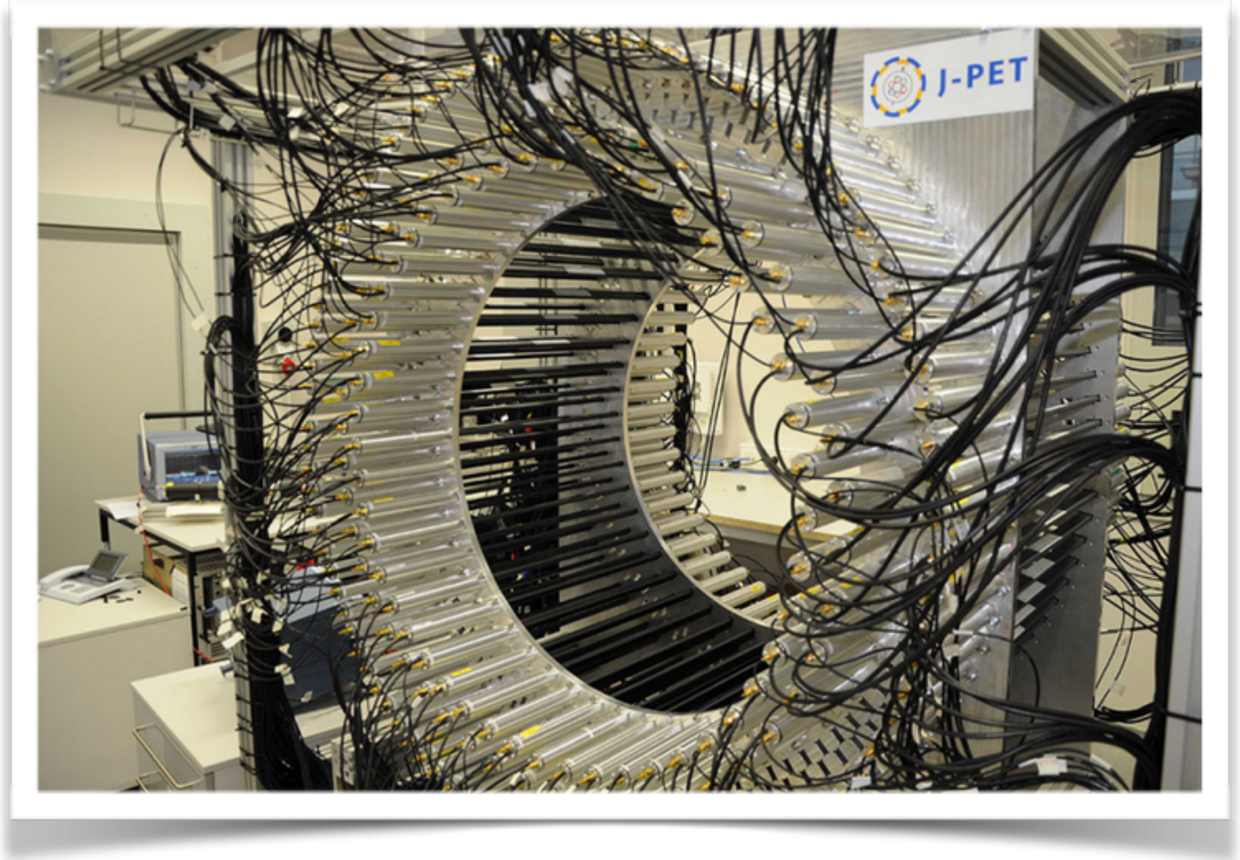

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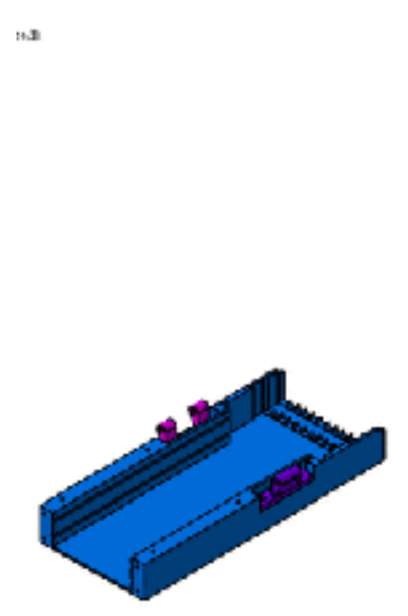

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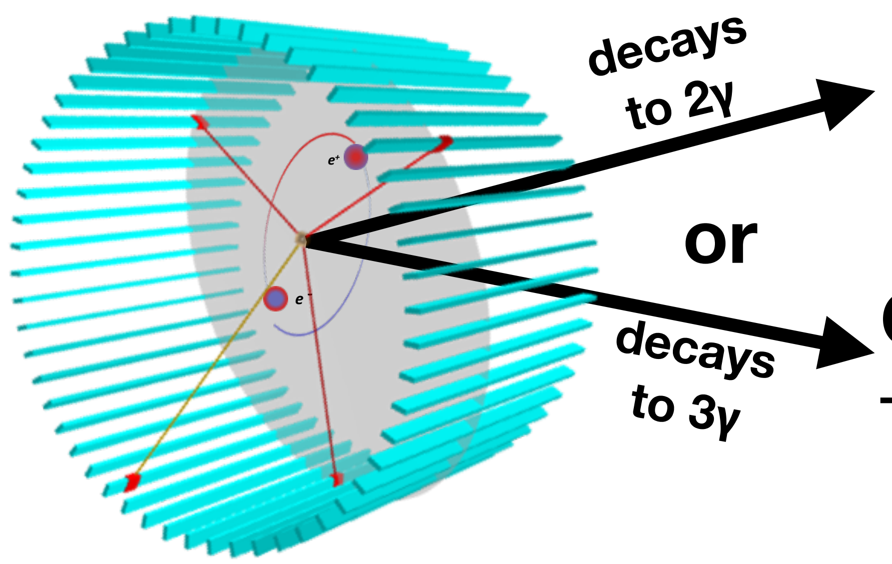
Research with J-PET

Positronium imaging:

In PET, in 30-40% cases e+e- annihilations proceed via production of positronium atom

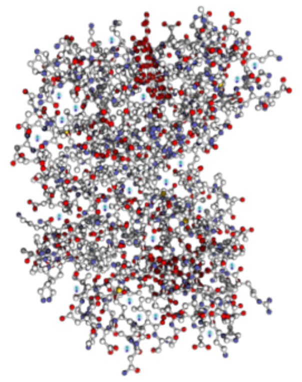


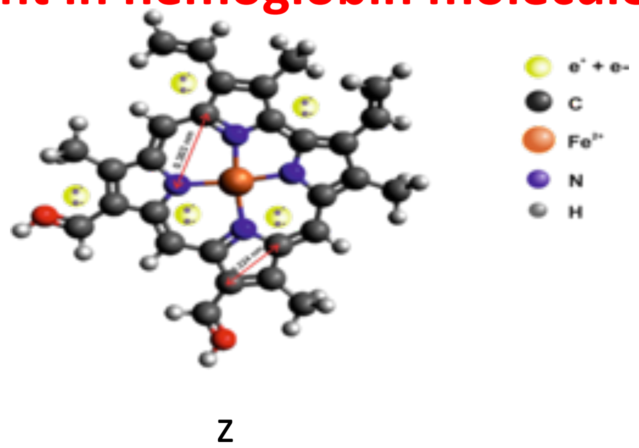
Para-positronium (p-Ps)
τ = 125ps, $^1S_0$

Ortho-positronium (o-Ps)
τ = 142ns, $^3S_1$

- J-PET for imaging of positronium properties inside human body
- Searching for the differences in properties of positronium atoms in healthy and cancerous tissues …and imaging of these properties in-vivo.

Heme group present in hemoglobin molecule in blood

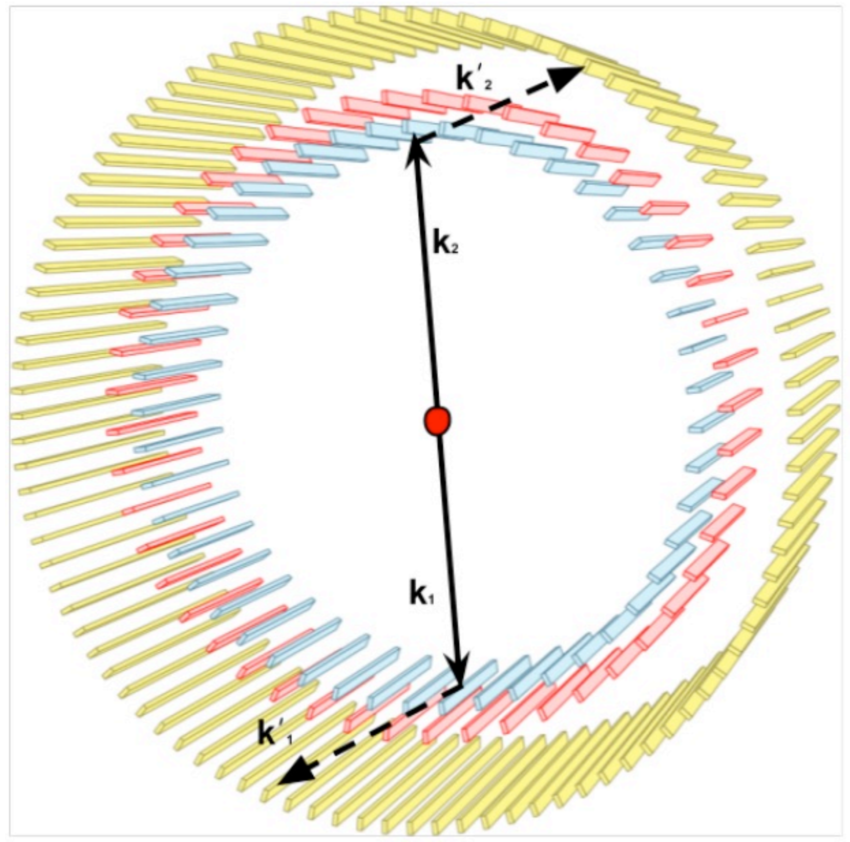


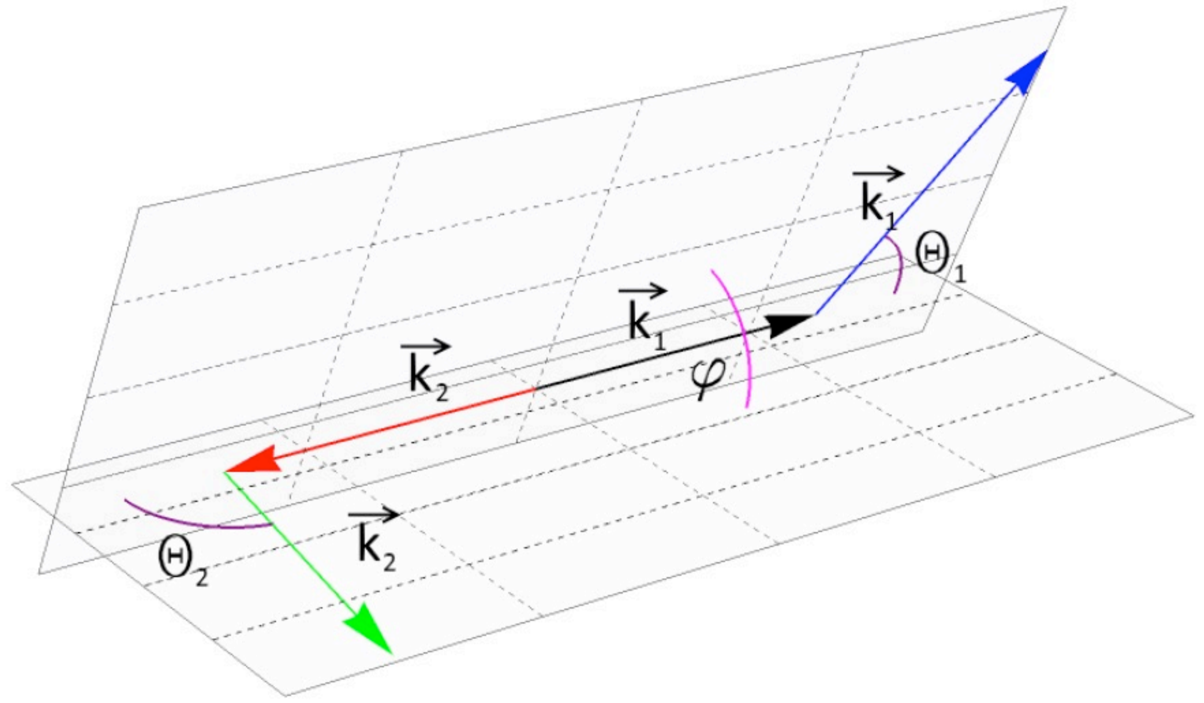


Ps trapped between atoms in Heme group

M-14-024 (#1831) Friday Nov 16 10:20am
P.Moskal *Pilot studies towards positronium imaging with the total-body PET scanners*

Quantum entanglement imaging:





- Determination of the linear polarisation direction of photon at the moment of its interaction with the detector and the quantum entanglement properties of photons.
- Correlation between the degree (type) of quantum entanglement and tissue properties.

[1] J-PET: Moskal P et al., arXiv:1805.11696, submitted to Phys. Med. Biol. (2018).
[2] J-PET: Moskal P et al., Patent No: US 9851456 (2017); PL 227658 (2013); PCT/EP2014/068374
[3] Hiesmayr B and Moskal P, arXiv:1807.04934, submitted to Scientific Reports (2018).
[5] J-PET: Moskal P et al., (2015) Nucl. Instr. Meth. A775, 54.
[6] J-PET: A. Gajos et al. (2016) Nucl. Instr. Meth. A819, 54.
[7] J-PET: Moskal P et al., (2016) Phys. Med. Biol. 61, 2025.
[8] J-PET: Moskal P et al., (2016) Acta Phys. Polon. B47, 509.
[9] J-PET: D. Kamińska et al., (2016) Eur. Phys. J. C76 (2016) 455.
[10] Hiesmayr B and Moskal P (2017) Scientific Reports 7, 15349.
[11] Jasinska B and Moskal P (2017) Acta Phys. Polon. B48, 1577.
[8] J-PET: Raczynski L et al., (2017) Phys. Med. Biol. 62, 5076.
[7] J-PET: Niedzwiecki Sz et al., (2017) Acta Phys. Polon. B48, 1567.
[12] J-PET: Jasinska B et al., (2017) Acta Phys. Polon. B48, 1737.
[13] J-PET: Kowalski P et al., (2018) Phys. Med. Biol. 63, 165008.
[14] Cern Courier, Oct(2018)
[15] G. Korcyl et. al., IEEE Transactions on Medical Imaging37(2018)11

Total-Body PET Imaging Workshop (#3000) Saturday Nov 17 3:30pm
P.Moskal *Towards total-body modular PET for positronium and quantum entanglement imaging*

Studies of discrete symmetries in Nature:

reflection in space (P), matter-antimatter symmetry (C), time reversal symmetry (T)

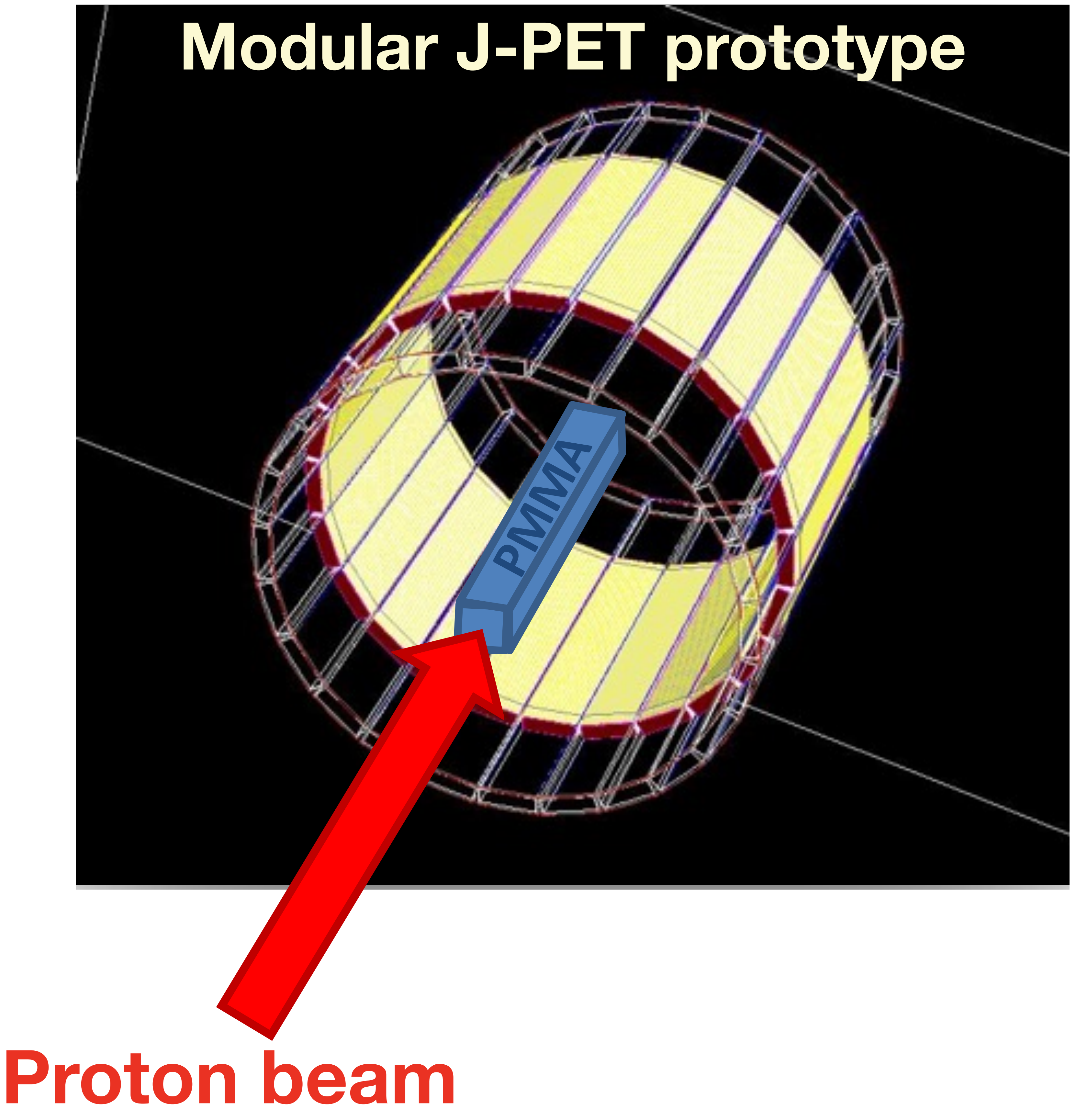
Pawel Moskal arrives tonight

Is J-PET feasible for in-room proton therapy range monitoring?

Efficiency: What would be the signal produced in the J-PET detector?

Design: Can we benefit from the modular configuration of the J-PET?

Simulation setup



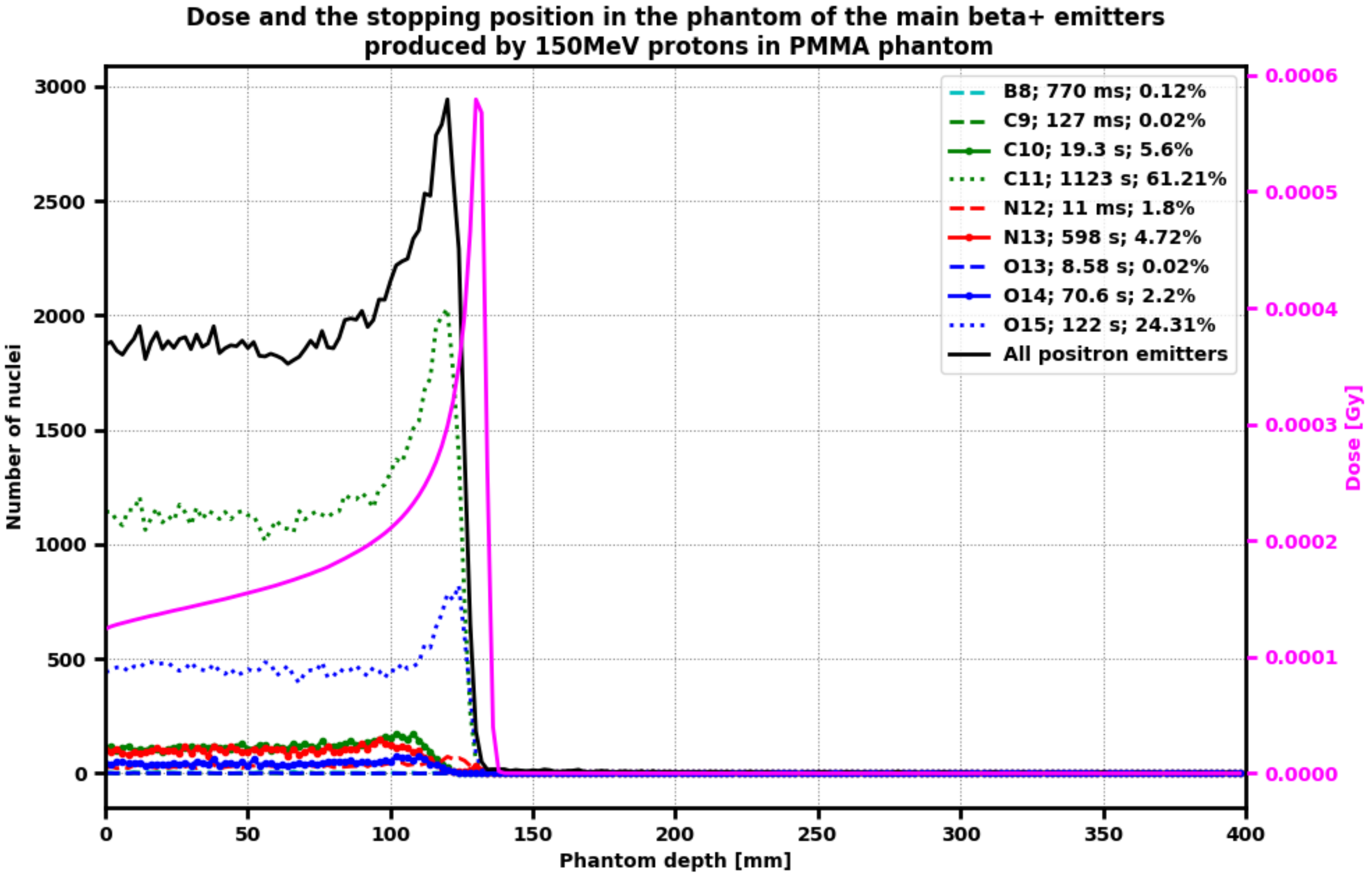
Settings:

- GATE/Geant4
- Physics list: QGSP_BIC_HP_EMY
- Full simulation
- in-room design
  (in-beam in the future)
- PMMA phantom 10x10x40cm^3
- Protons at 150 MeV
- 10^7 primary protons
- Clinical proton beam model
  used in Krakow for patient treatment

Scoring:

- # of annihilations in the PMMA
- # of detected singles
- # of detected coincidences

Production emission in PMMA



Signal / efficiency

- $\varepsilon_{total} = \varepsilon_{back\text{-}to\text{-}back} * \varepsilon_{det} * \Omega$

ε_{det}=0.1, Ω_{barrel}=0.44

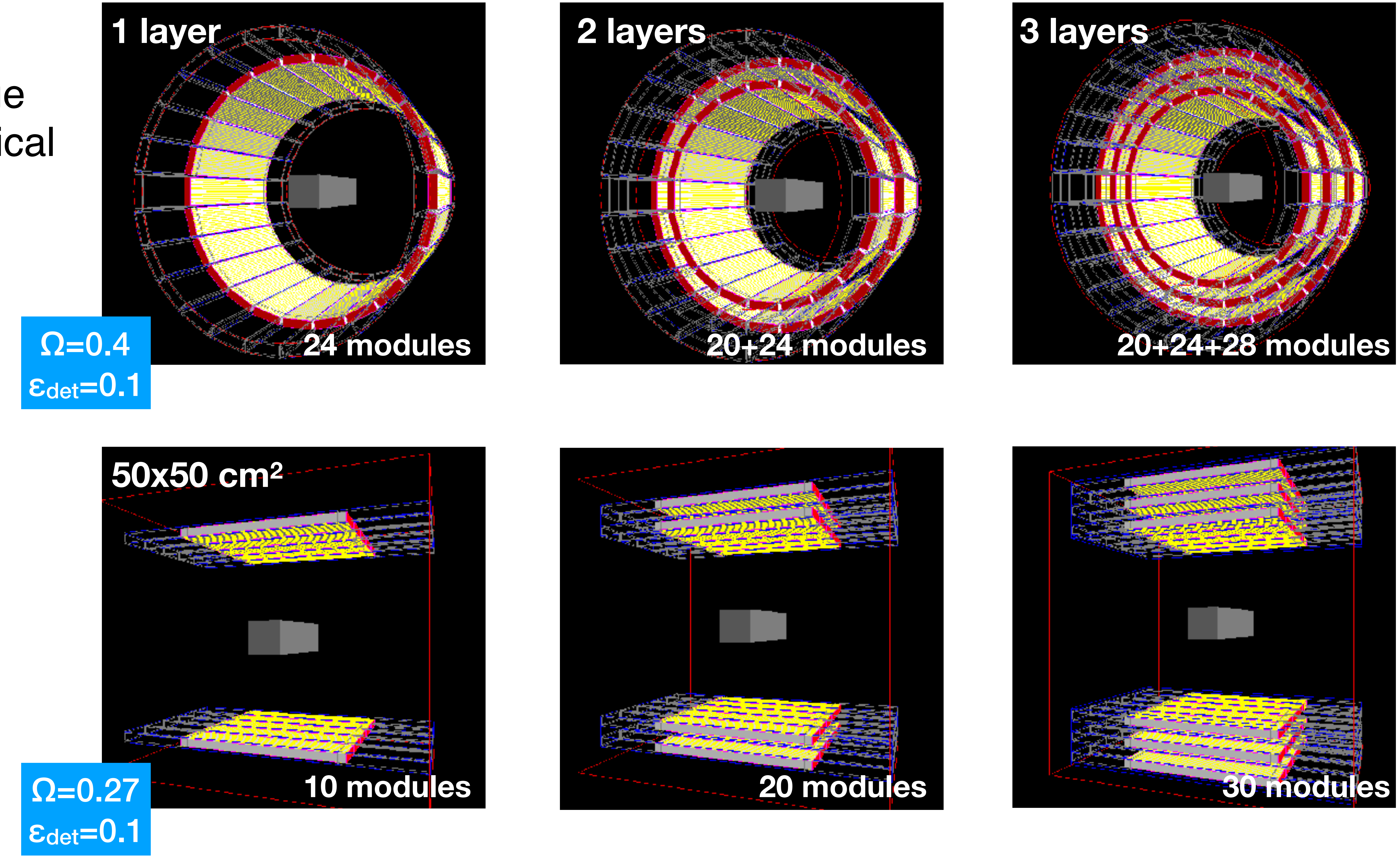
- Monte Carlo simulations:
    - What counts for proton therapy is:

      ε_{total} = # of coincidences / # of primary protons

      …accounting for the annihilation production distribution in the target

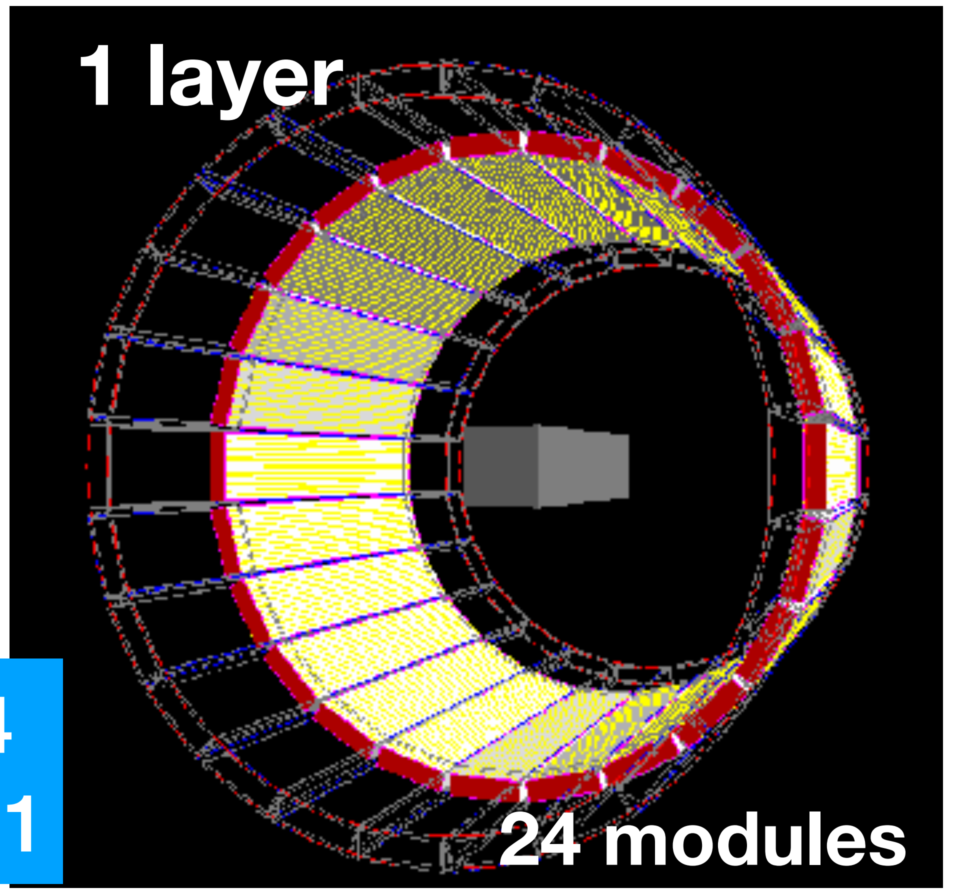
Design

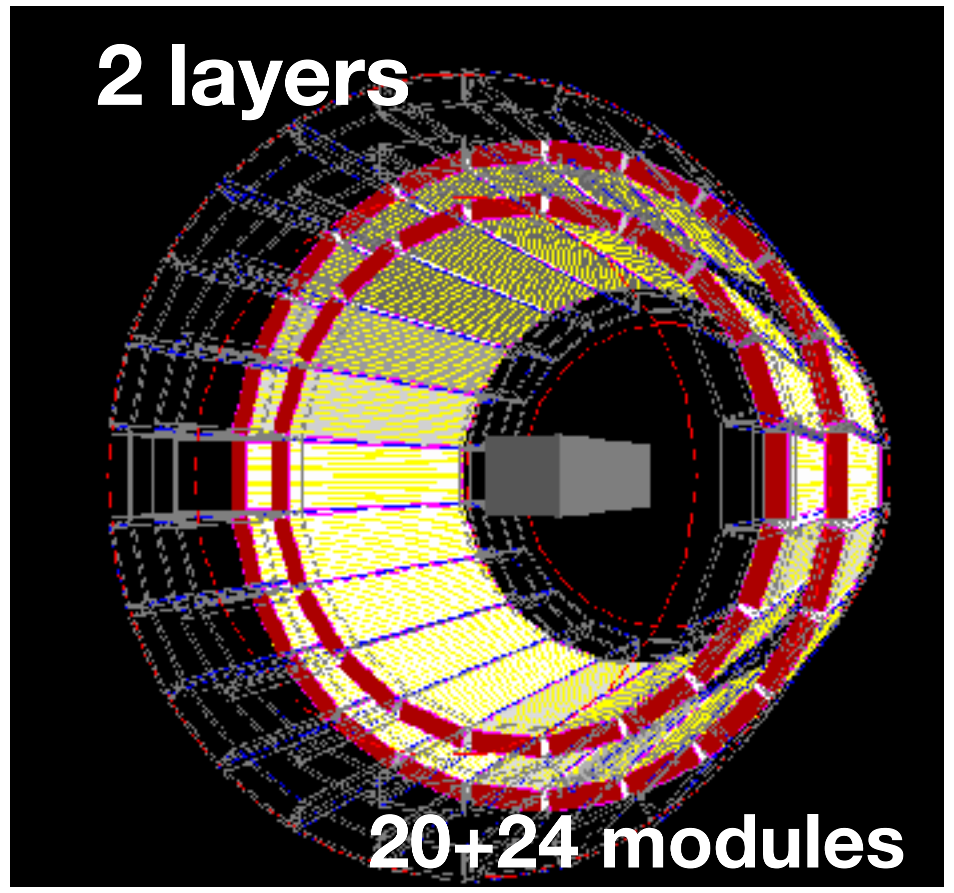
- The modular J-PET gives large freedom of choice of geometrical arrangement
- The number of layers should improve the efficiency
- Barrel could be integrated away from the gantry using e.g. rail-system
- Dual head can be integrated in the treatment position (studied in GSI and CNAO)

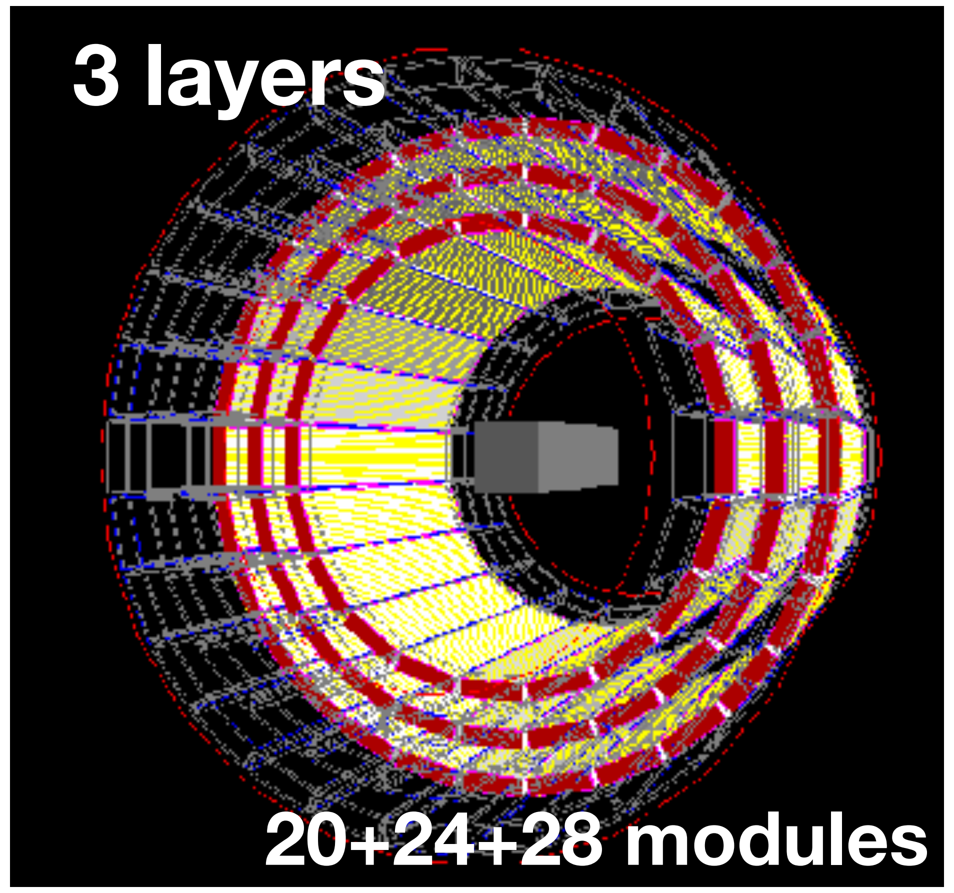


Signal

True + scattered

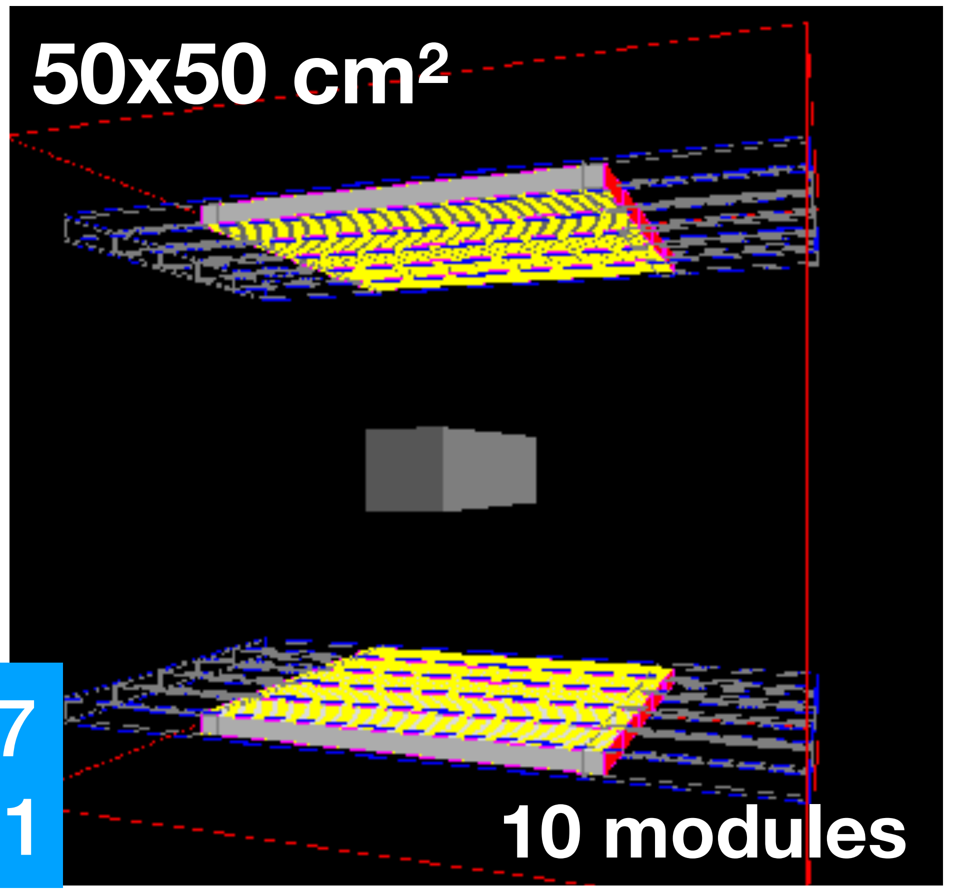


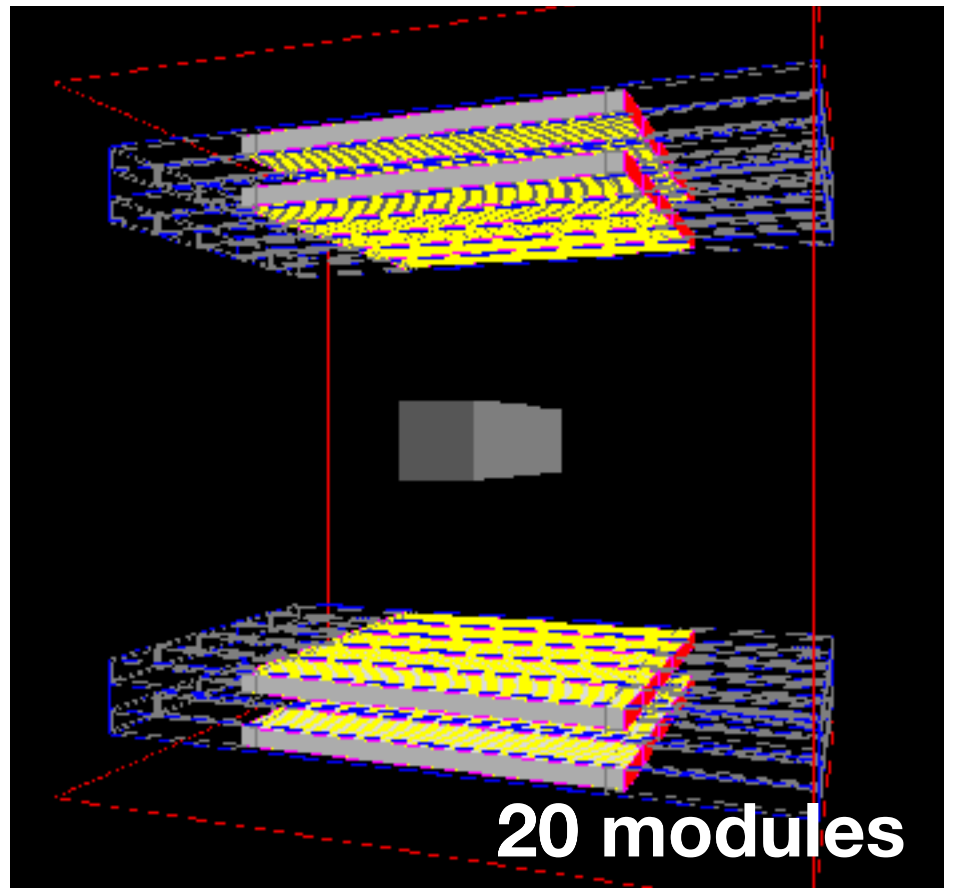


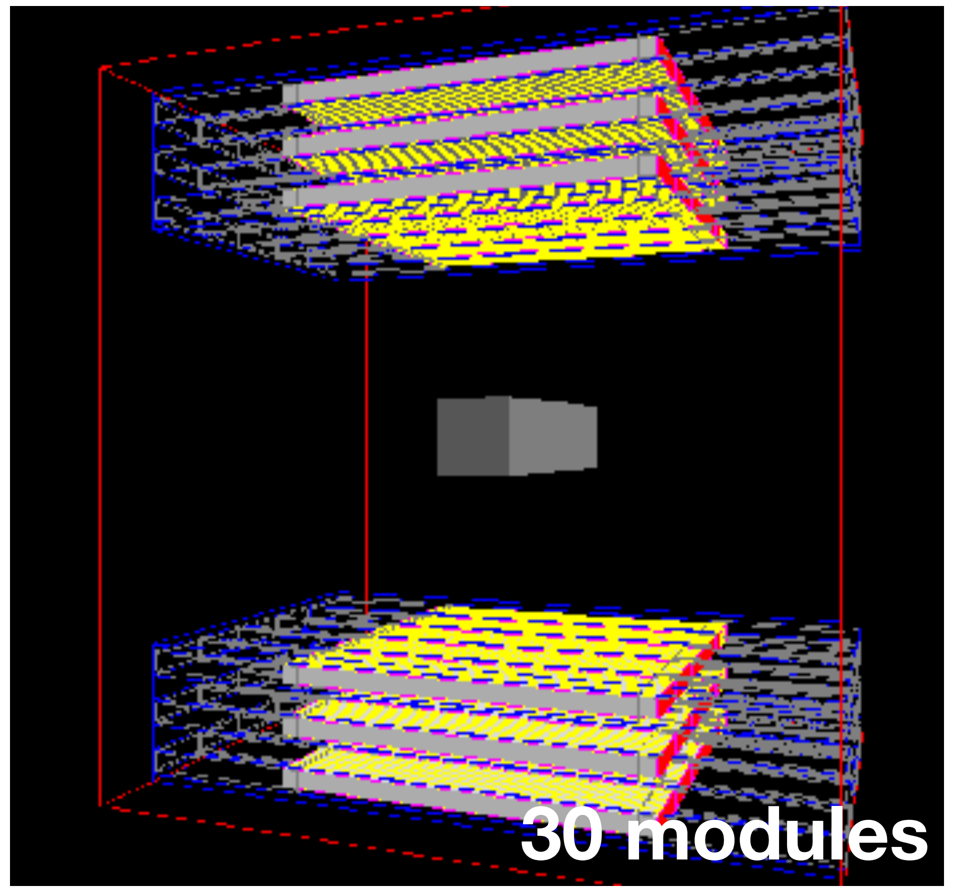


Ω=0.4
ε_{det}=0.1

coincidences/primary:	3.5E-05	1.4E-04	2.5E-04





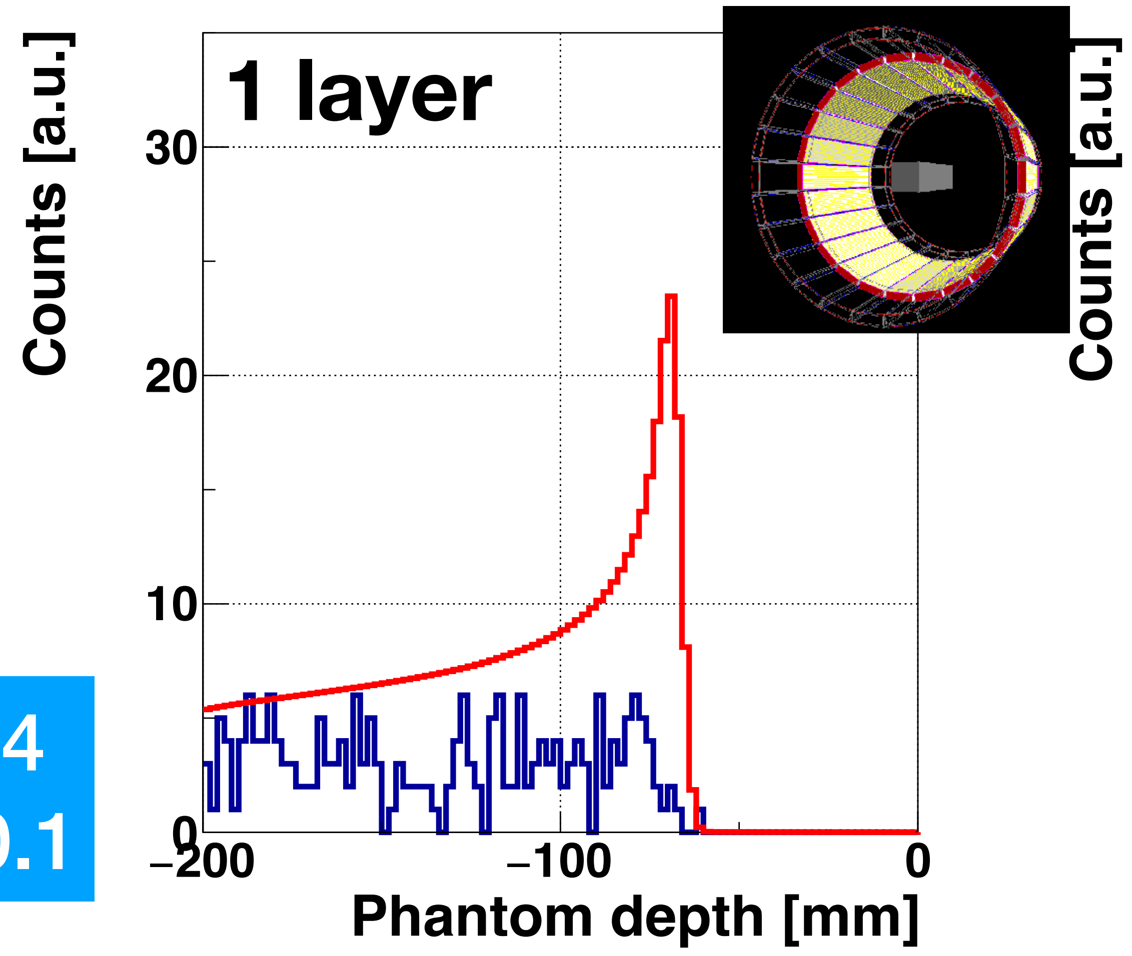


Ω=0.27
ε_{det}=0.1

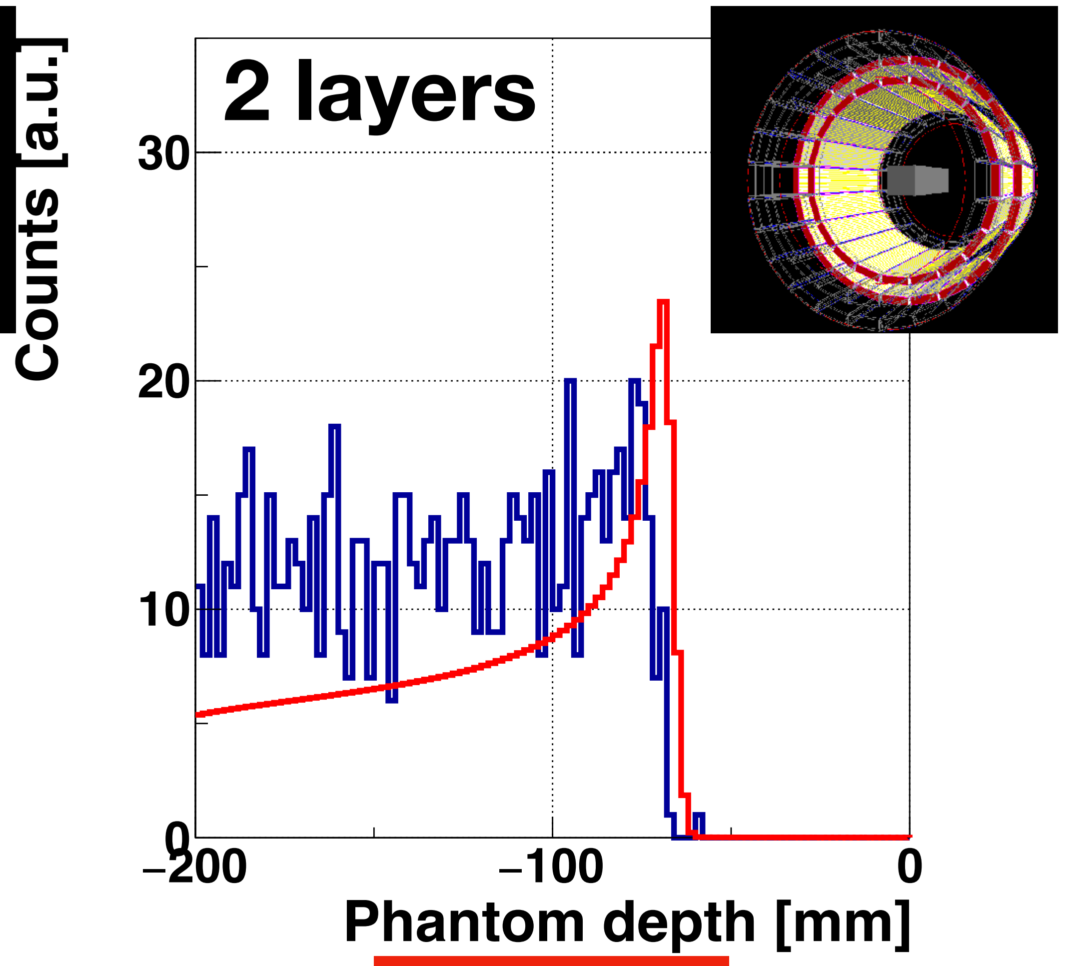
	1.9E-05	5.4E-05	1.0E-04

Signal

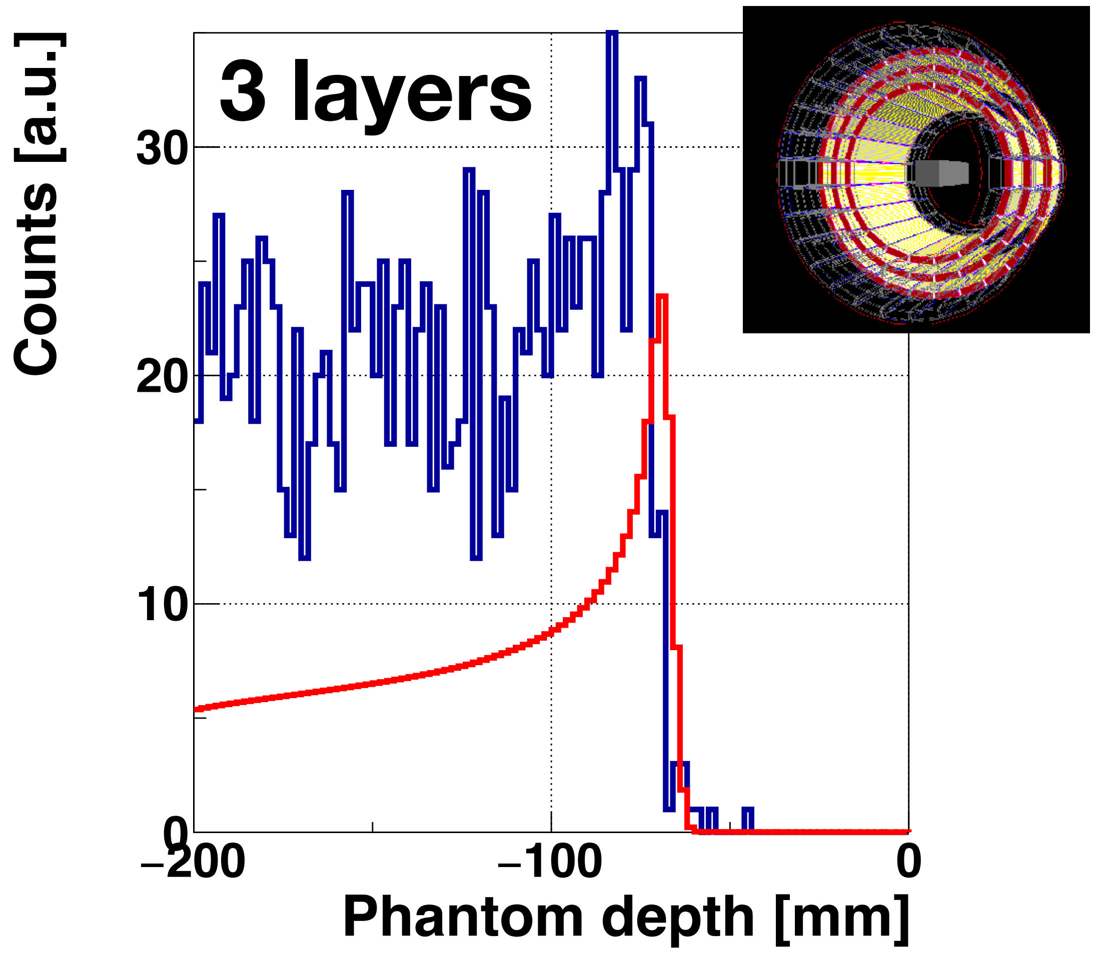
24 modules



20+24 modules



20+24+28 modules



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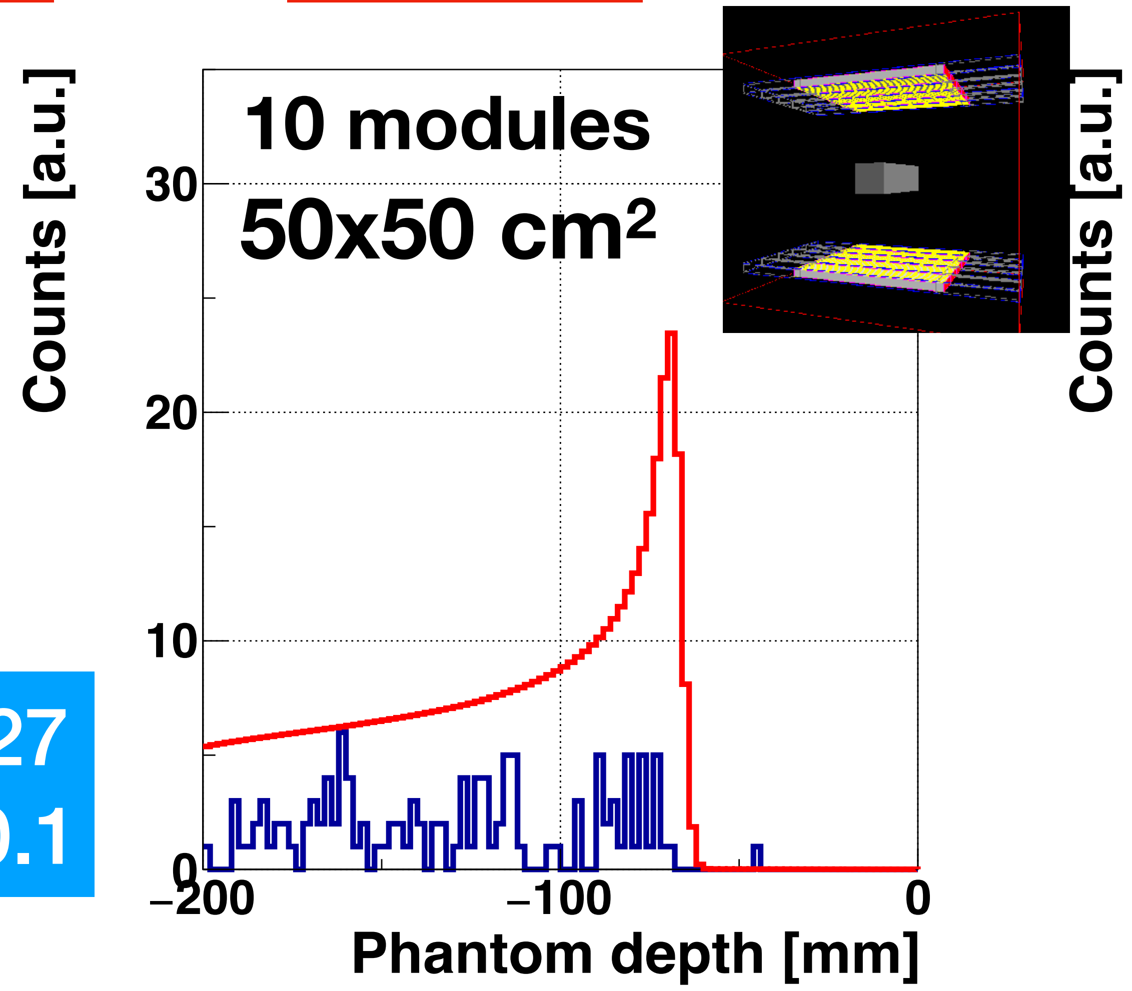

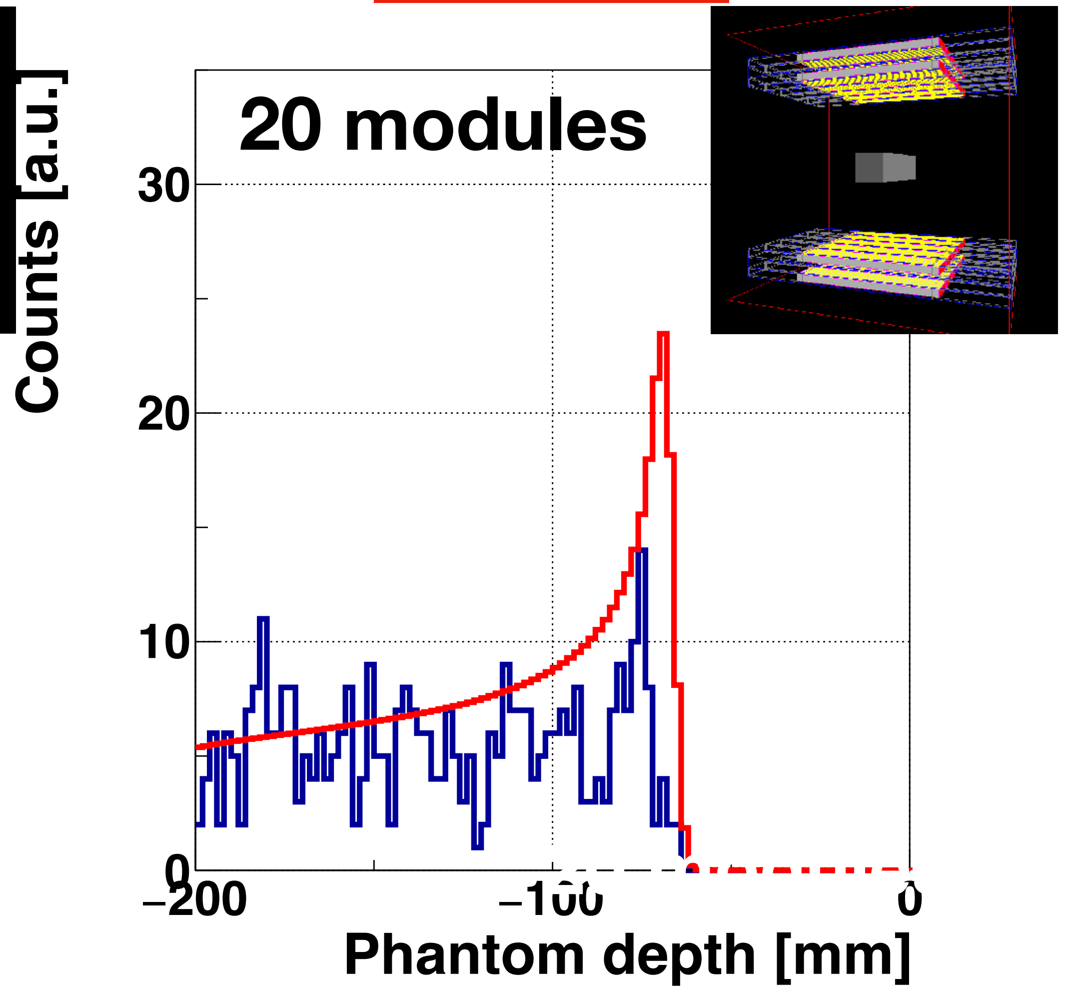

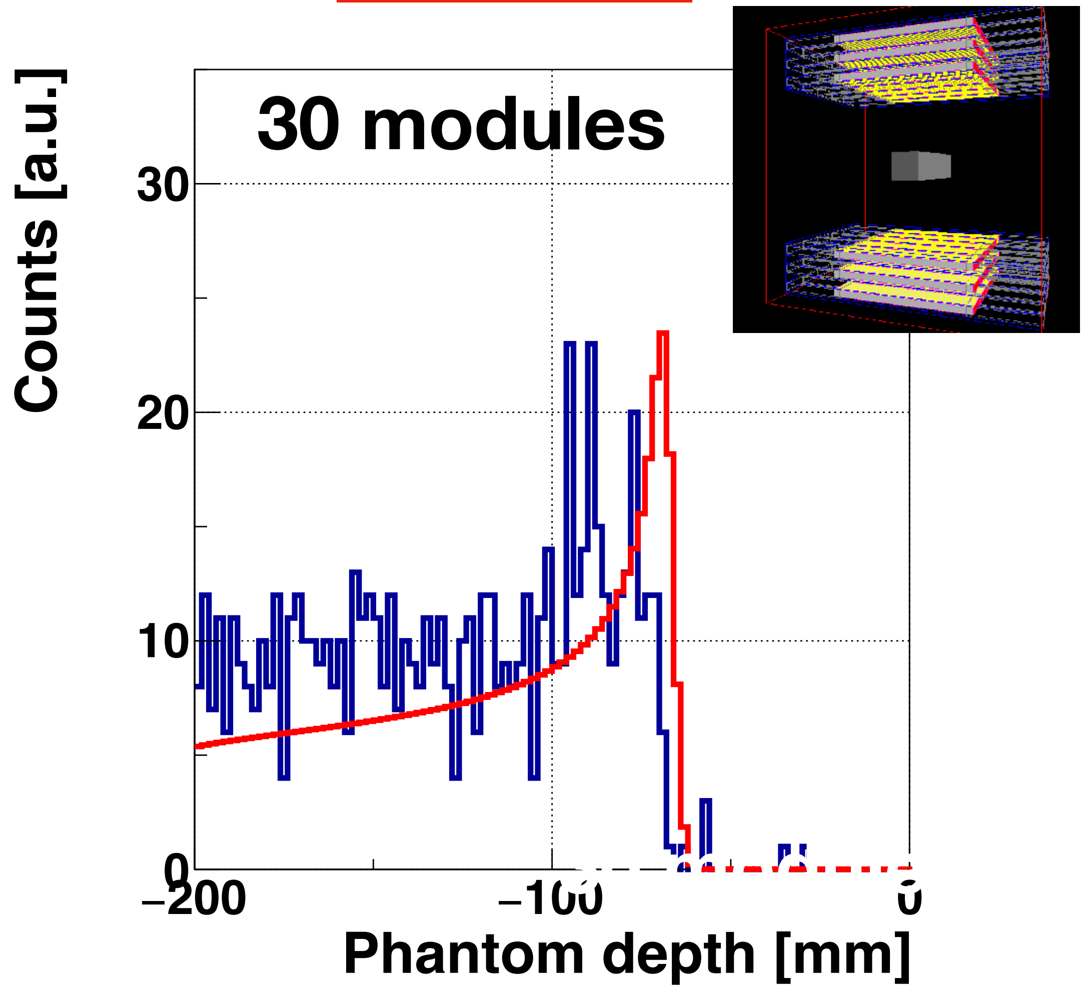

Ω=0.27
ε_{det}=0.1

1.9E-05 5.4E-05 1.0E-04

Summary

- **In Krakow**
  - PBT facility
  - J-PET

- **J-PET investigations for PBT**
  - Customized design out of cost effective J-PET modules
  - Efficiency per primary proton: $\varepsilon=10^{-5}$
    (efficiency increases with the number of layers)

Future plans

- Reconstruction
- In-beam simulation setup
- Experimental validation
- Pre-clinical tests in PBT centre in Krakow

Our group:

Jakub

Monika

Magda Jan Antoni Agata

...and the J-PET collaboration

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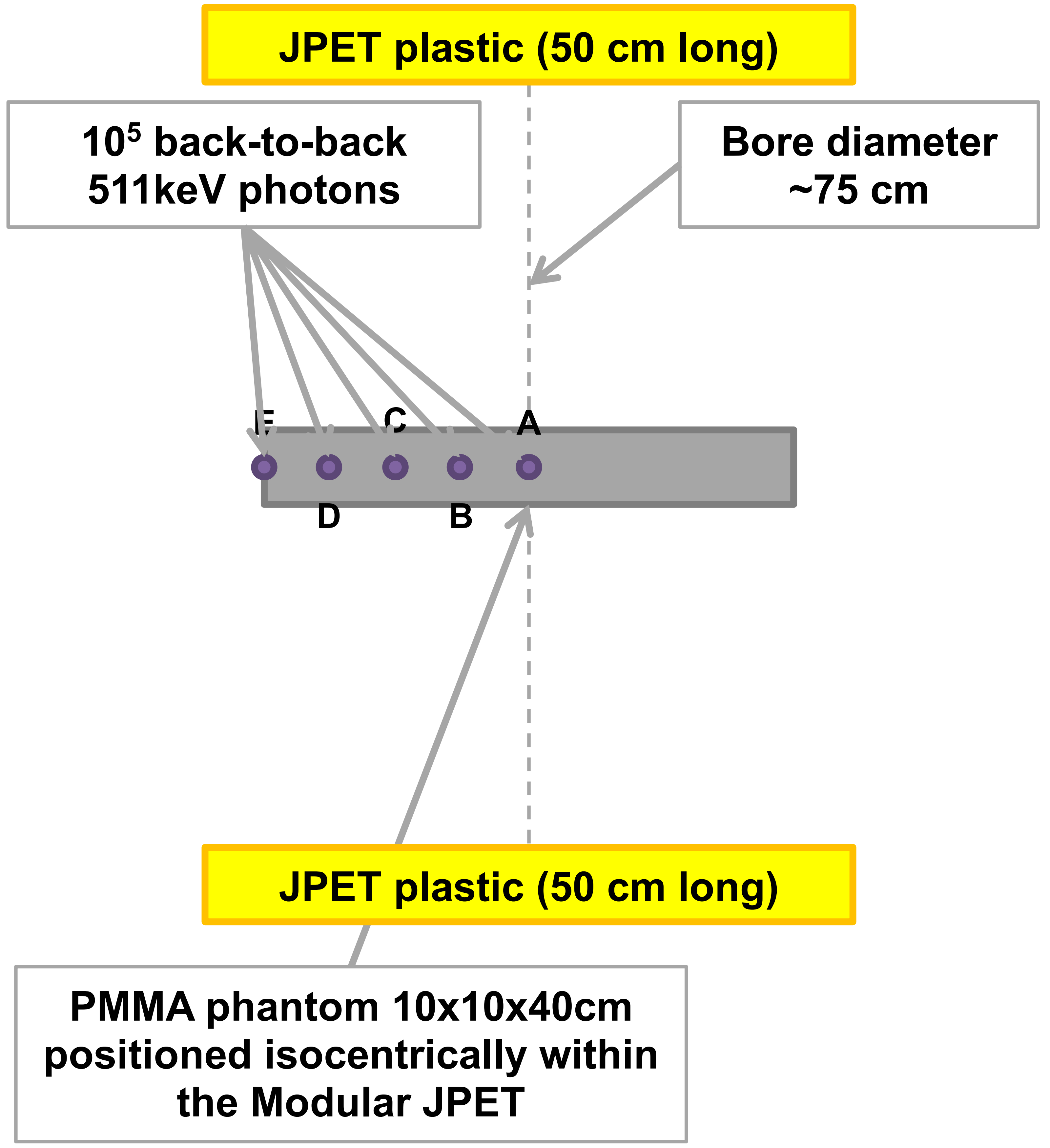
Spares

Modular JPET efficiency

Coincidence – two photons produced by the same annihilation, deposited energy higher than 200 keV each, within the plastics

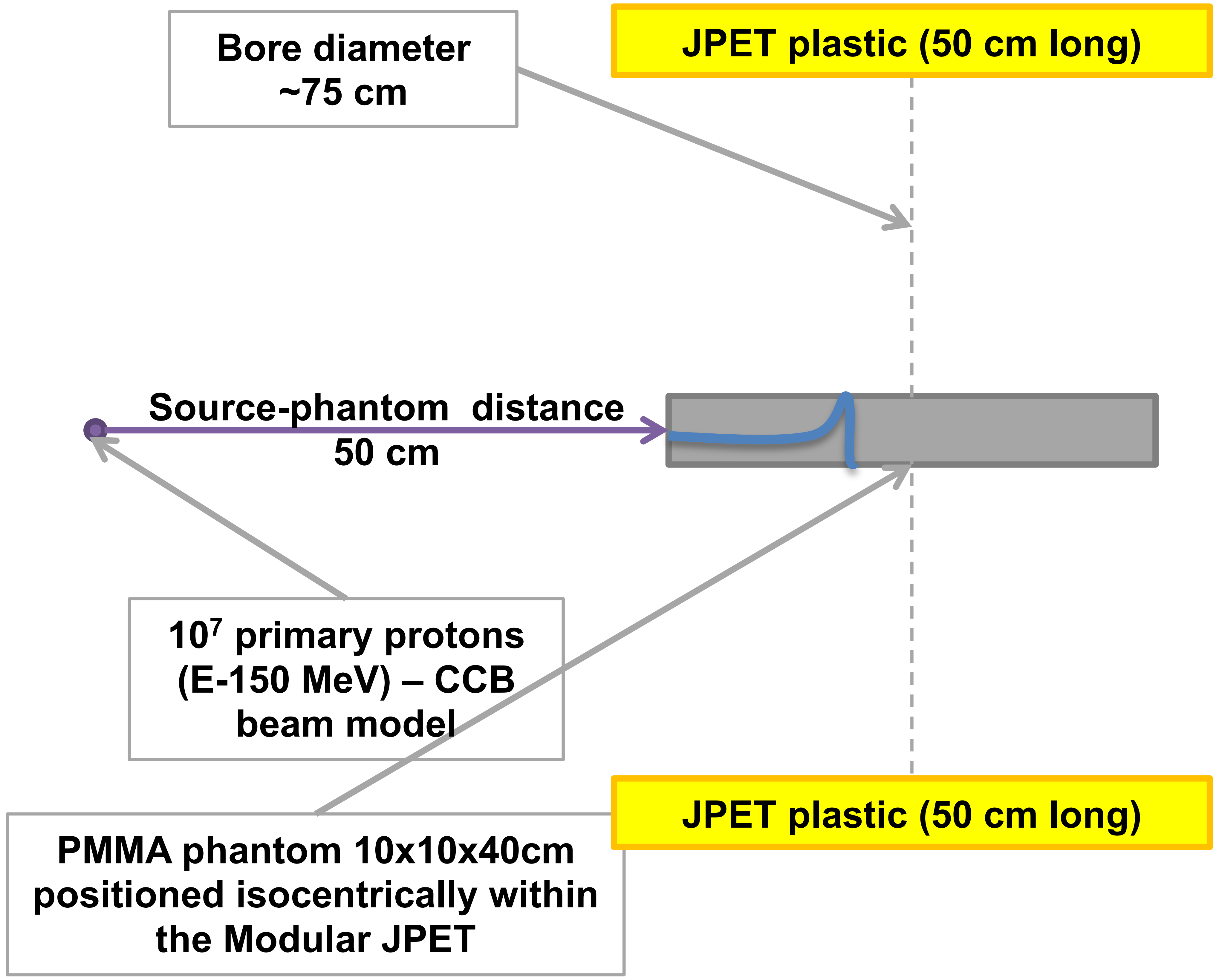
	A	B	C	D	E
Distance from the JPET center [cm]	0	5	10	15	20
Results in plastic					
Coincidences	**122**	**121**	**82**	**56**	**26**
Coincidences wrt annihilations (%)	**0.12%**	**0.12%**	**0.08%**	**0.06%**	**0.03%**



Proton beam simulation

Coincidence – two photons produced by the same annihilation, deposited energy higher than 200 keV each, within the plastics

Source	10^7 protons
Number of annihilations	$3.3 * 10^5$
Coincidences	187
Detected coincidences per annihilation (%)	0.05%
Detected coincidences per primary proton factor	$1.9*10^{-5}$



IMPORTANT: The proton range is approx. 14 cm.