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Photoneutron production at electron LINACs: testing performance of Monte-Carlo simulations and impact on relevant applications.

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list

Photoneutron production at electron LINACs: testing performance of Monte-Carlo simulations and impact on relevant applications

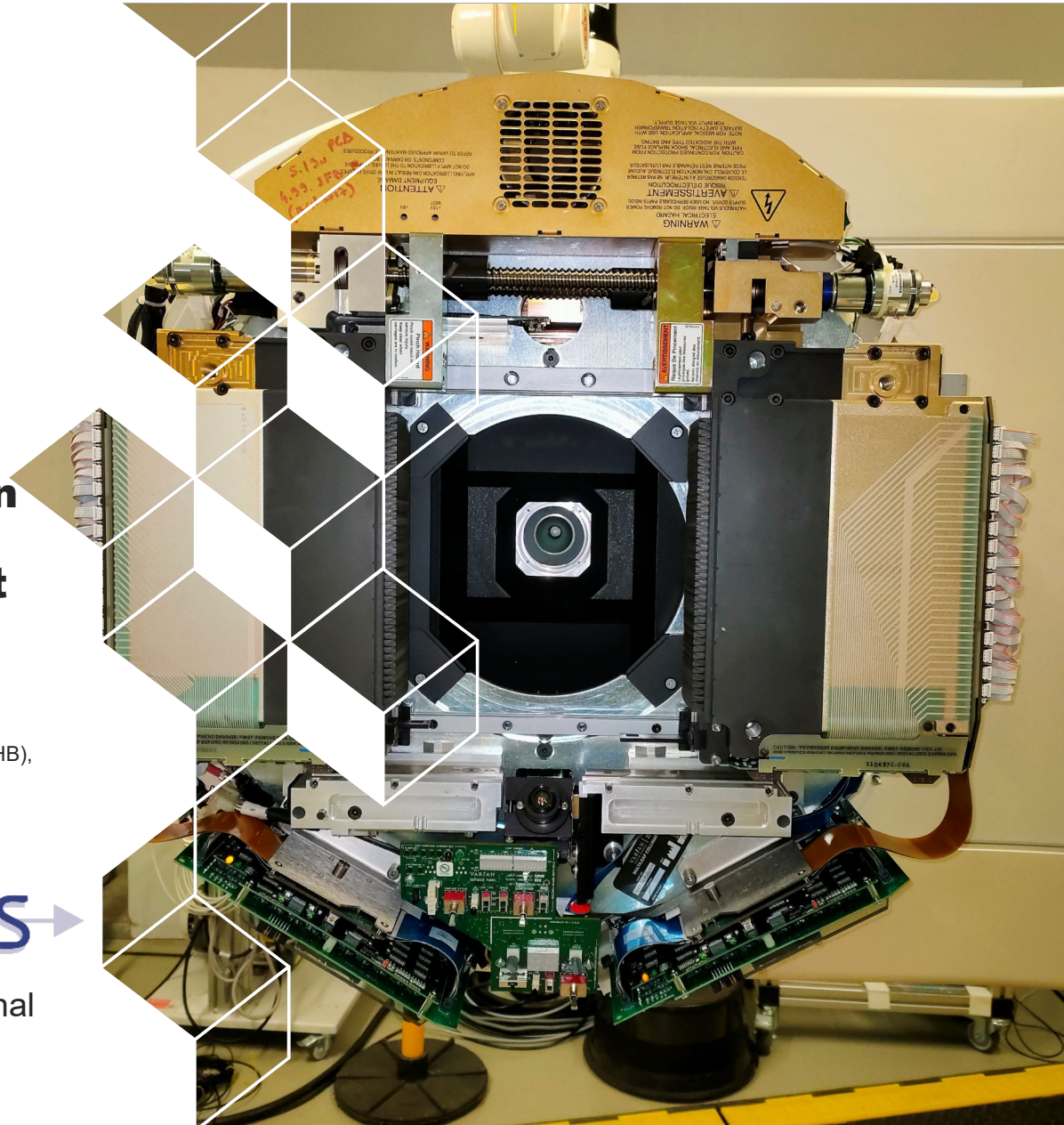
V. Blideanu¹, C. Besnard-Vauterin¹, B. Rapp¹

¹ Université de Paris-Saclay, CEA, LIST, Laboratoire National Henri Becquerel (LNE-LNHB), F-91129, Palaiseau, France



EURADOS

WG6 – Computational dosimetry



Introduction

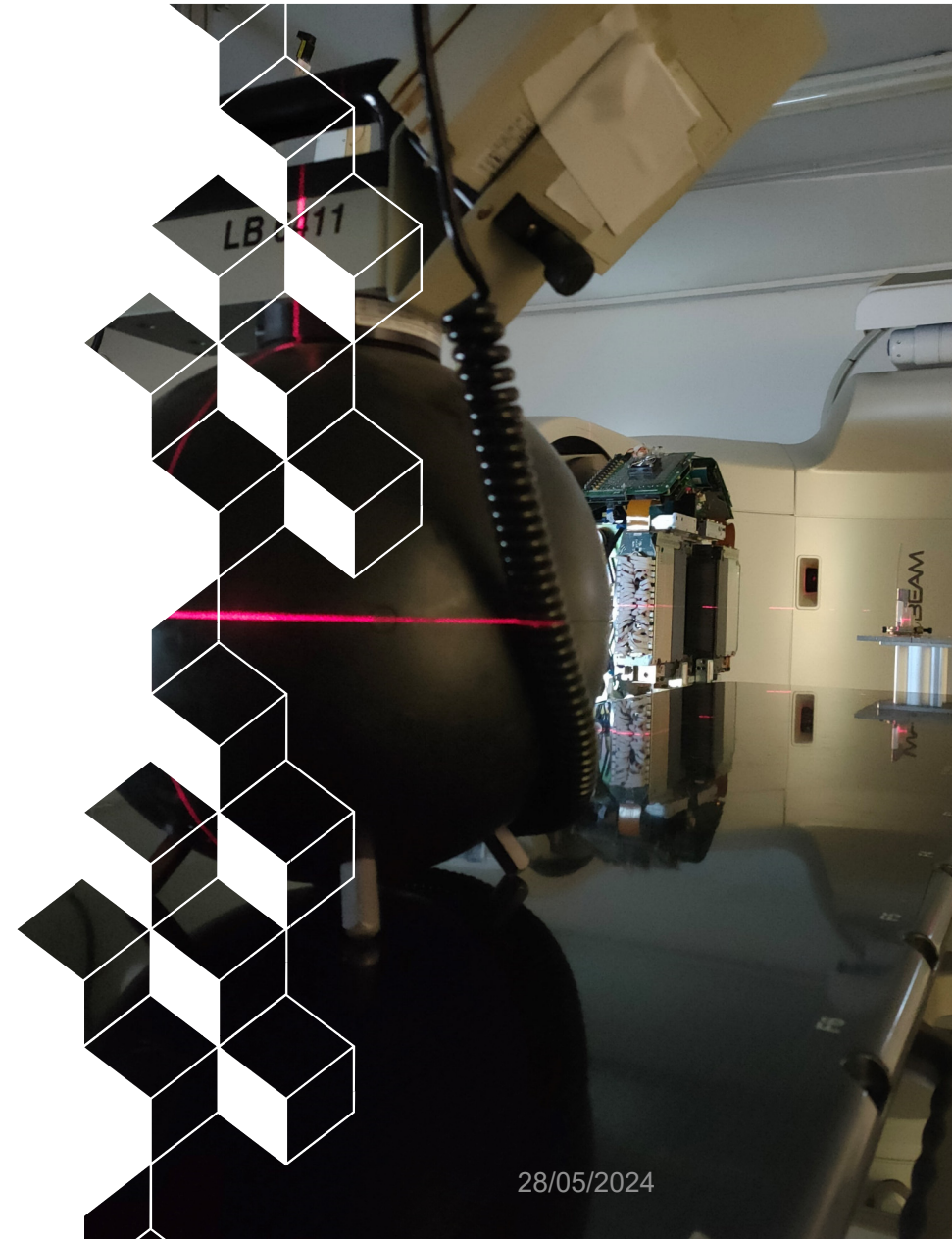
Photon-induced nuclear reactions are showing growing interest through recent needs related to several widely-spread applications using electron accelerators

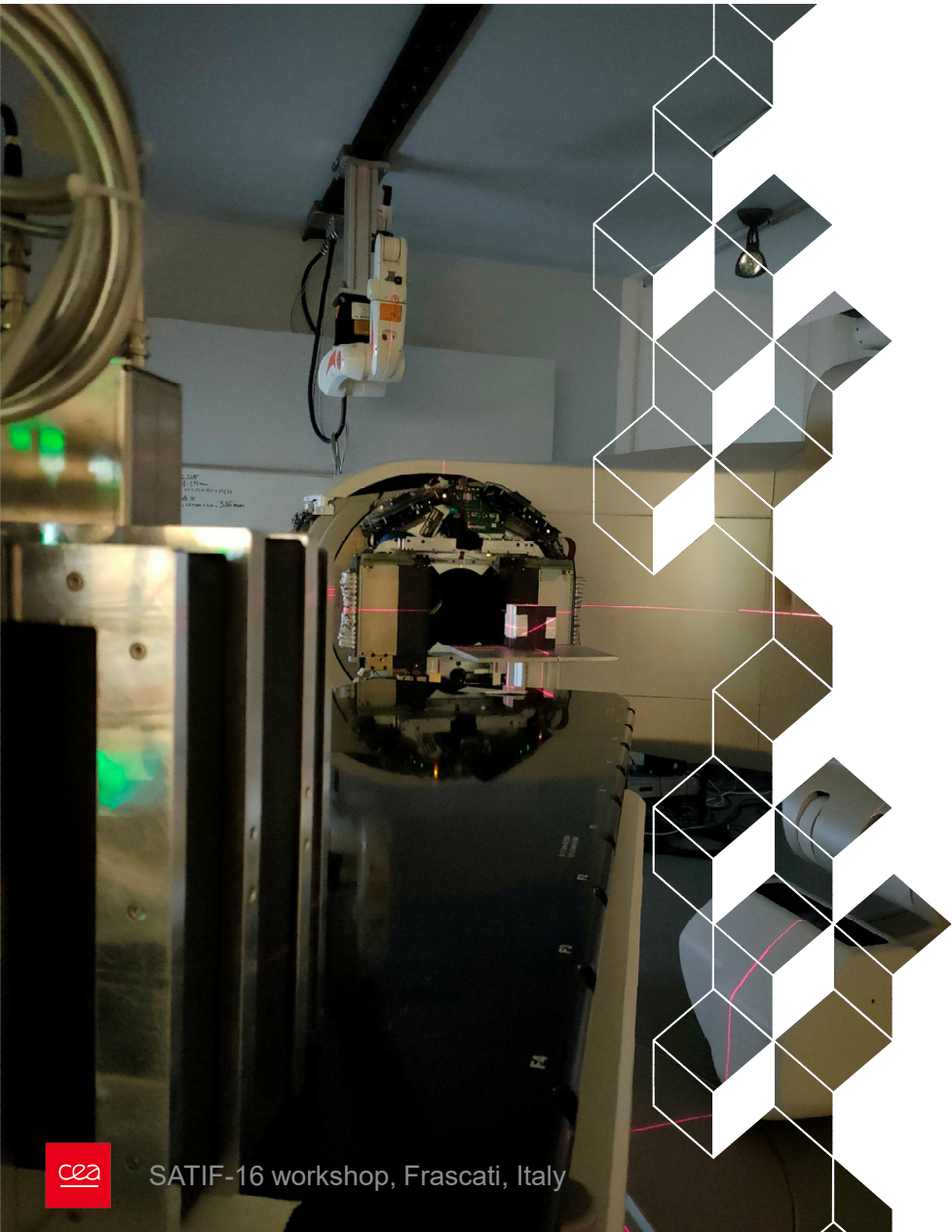
- **Radiotherapy treatments:** Photonuclear reactions contribute to additional neutron doses and impact nearby accelerator components.
- **Decommissioning of electron accelerators:** need for appropriate waste management based on good knowledge of induced activity in components.

Recent Interest:

- **Homeland security:** Spectrometry of neutron produced in photo-nuclear reactions are at the basis of a new active photon interrogation technique for detection of illicit materials (explosives, narcotics, toxic gases)

Presentation Focus: Simulation and measurement of photo-neutron production and differential distributions at electron LINACs.





01
Benchmark of Monte-Carlo codes:
Neutron spectra from
photonuclear reactions

02
Measurements of
photoneutron
production using a
medical LINAC



Benchmark of Monte-Carlo codes: Neutron spectra from photonuclear reactions

Benchmark exercise organized in 2022 within EURADOS WG6 “Computational Dosimetry”

V. Blideanu¹, C. Besnard-Vauterin¹, D. Horvath²,
B. Lefebvre², F. Salvat-Pujol³, R. Versaci²



MCNP (6.2)
PHITS (3.27)



Geant4 (11.1.1)
FLUKA (4-3.0)
PHITS (3.27)

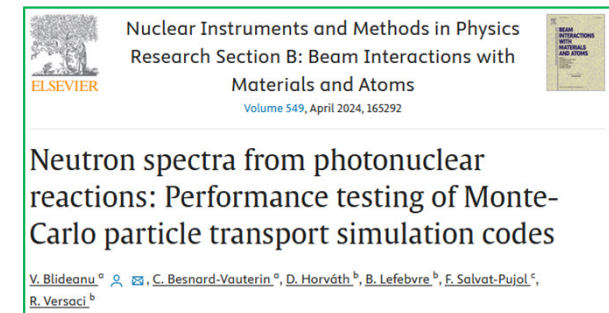
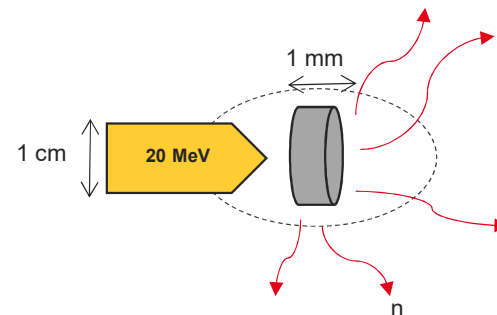


Theoretical
insights

- Lack in the present literature of measured photoneutron differential distributions
× **experimental validation of the simulations is not straightforward**
- **Benchmarking of Monte-Carlo codes** appears as the only option to assess their capabilities in accurately simulating photo-neutron production

Methods:

- Intercomparison of simulated photoneutron energy distributions was done with Geant4 (11.1.1), MCNP (6.2), PHITS (3.27) and FLUKA (4-3.0) for different materials of interest (Be, N, C, Al, Cu, Sb, W, Pb) :





Benchmark of Monte-Carlo codes: Neutron spectra from photonuclear reactions

How the codes handle photonuclear reactions when using [default physics options](#):

MCNP (6.2)

- Developed by the Los Alamos National Laboratory.
- Photonuclear reactions are introduced through **tabular data sampling**. **The tabular data used here is known as the LA150 library (default)**.
- The lack of a needed table is normally handled by using physics models but this was not the case for the materials used in this study.

Geant4 (11.1.1)

- Developed by the Geant4 collaboration.
- Use of FTFP_BERT physics list (*considered as a default by the official guide for physics lists*).
- Photonuclear reactions below 6 GeV are handled by the **Bertini model** whereby the final state is determined by an **intranuclear cascade**.

PHITS (3.27)

- Developed by a collaboration among JAEA, RIST, and KEK.
- PHITS uses the evaluated photonuclear reaction cross-sections data contained in **JENDL/PD-2004**, with an **evaporation model**.
- *Since version 3.27 allows to use external photonuclear data libraries in the ACE format (for example MCNP's LA150) but it is not the default.*

FLUKA (4-3.0)

- Developed by the FLUKA/CERN collaboration.
- **Pre-equilibrium stage** followed by an **evaporation stage** (Fermi break-up model for $A < 18$), and a final gamma de-excitation stage.
- Photonuclear interaction rate driven by a **reaction cross section library derived from experimental and evaluated compilations**.

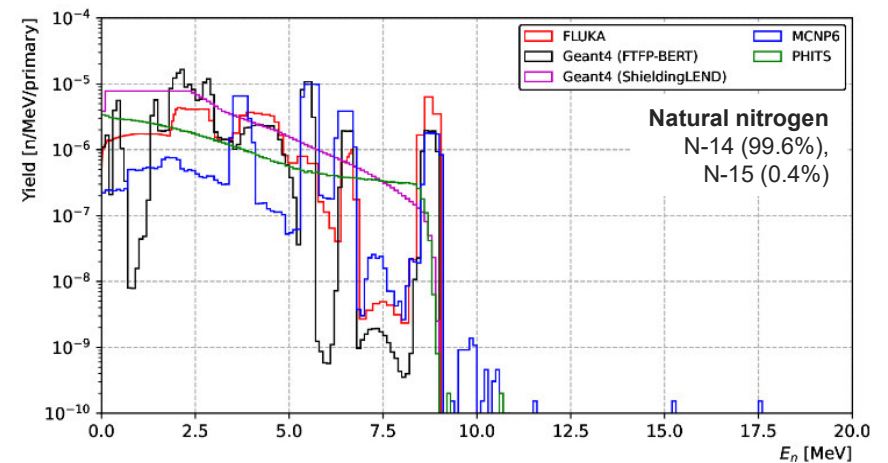
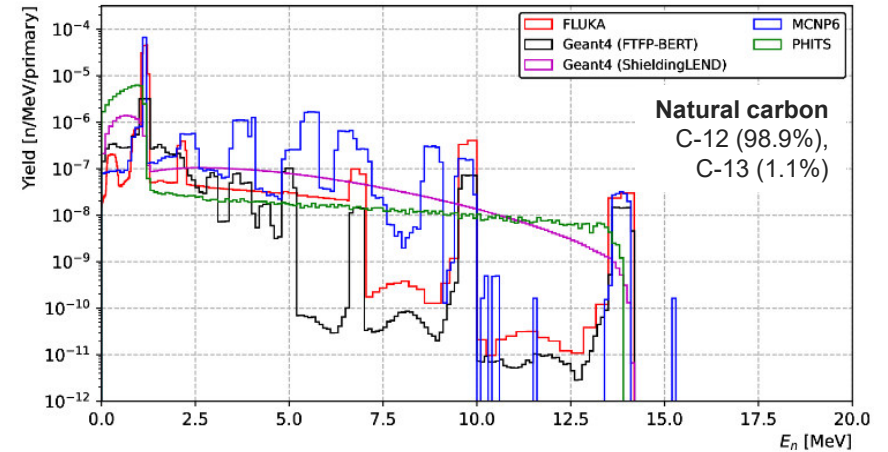


Intercomparison of photoneutron energy distributions for (γ, Xn) reactions on light nuclei

- Geant4, MCNP6, and FLUKA agree on the ground state and the first three excited states photoneutron peaks from (γ, n) reactions
- PHITS exhibits a completely different behavior: integrated cross-sections of JENDL/PD-2004 are taken into account and comparable with other codes but not for energy distributions

$$E_n = \frac{E_\gamma - Q - E_{state}}{1 + A_{residual}^{-1}}$$

Carbon		Nitrogen	
Energy levels of ^{11}C (MeV \pm keV)	Photo-neutron energy	Energy levels of ^{13}N (MeV \pm keV)	Photo-neutron energy
g.s.	1.24 MeV	g.s.	8.92 MeV
Energy levels of ^{12}C (MeV \pm keV)	Photo-neutron energy	2.3649 \pm 0.6	6.58 MeV
g.s.	14.06 MeV	3.502 \pm 2	5.52 MeV
4.439 \pm 0.21	9.79 MeV	3.547 \pm 4	5.48 MeV
7.654 \pm 0.19	6.83 MeV	6.364 \pm 9	2.87 MeV
9.641 \pm 5	4.99 MeV	6.886 \pm 8	2.38 MeV
10.847 \pm 4	3.88 MeV	7.155 \pm 5	2.13 MeV



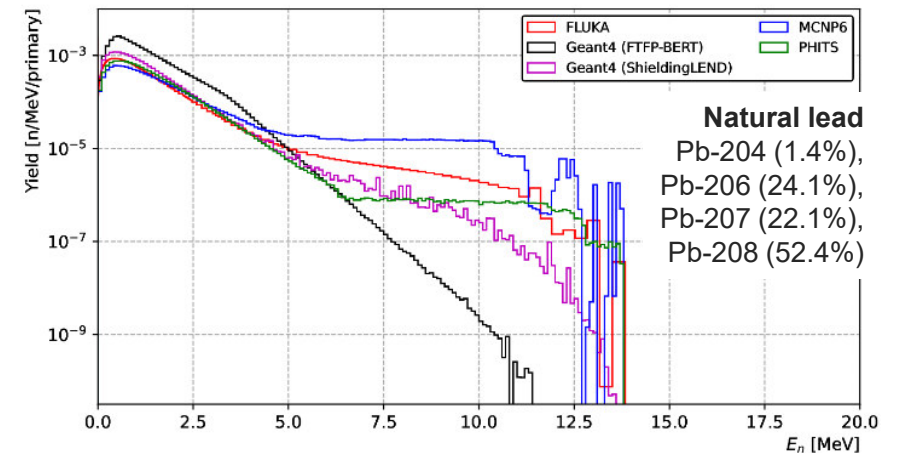
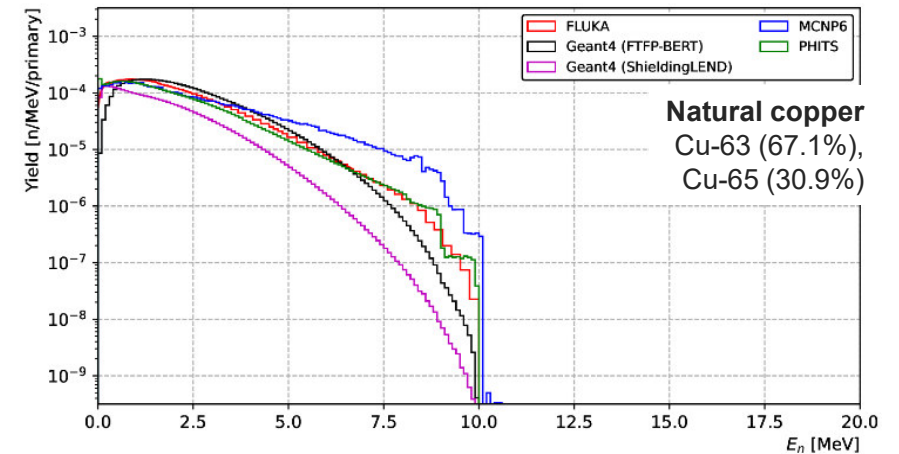


Intercomparison of photoneutron energy distributions for (γ, Xn) reactions on intermediate and heavy nuclei

- Geant4 is underestimating the neutron contribution above 3 MeV while MCNP6, PHITS and FLUKA are sharing similar trends
- For heavy targets the Geant4 spectrum does not present a change of slope as other codes, therefore resulting in a maximum energy way below the expected value according to the energy conservation

$$E_n = \frac{E_\gamma - Q - E_{state}}{1 + A_{residual}^{-1}}$$

Copper			Lead		
Energy levels)	Reaction threshold	Photo-neutron energy	Energy levels	Reaction threshold	Photo-neutron energy
Cu-62 (g.s.)	10.85 MeV	9.06 MeV	Pb-206 (g.s.)	8.09 MeV	11.87 MeV
Cu-64 (g.s.)	9.97 MeV	9.91 MeV	Pb-207 (g.s.)	6.74 MeV	13.21 MeV
			Pb-208 (g.s.)	7.37 MeV	12.58 MeV

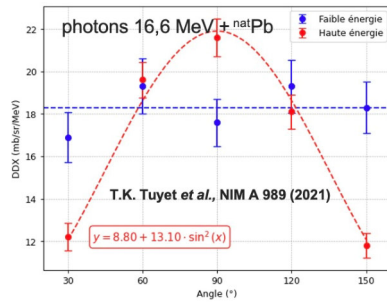
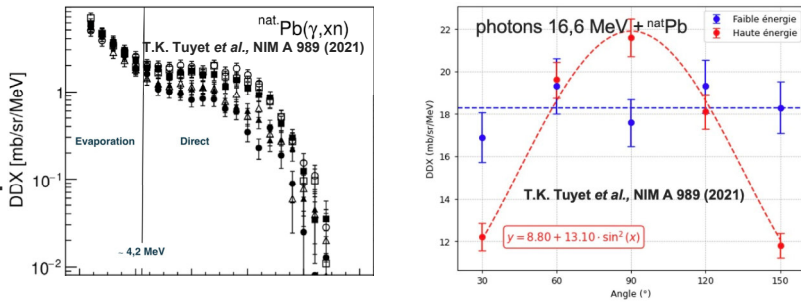




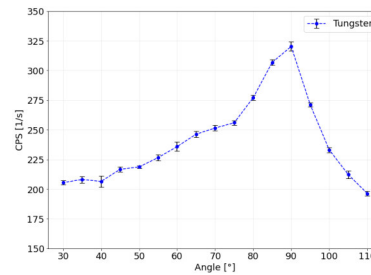
Intercomparison of photoneutrons angular distributions

Photoneutrons emitted by irradiation with Bremsstrahlung photons in 20 MV range

Experiment

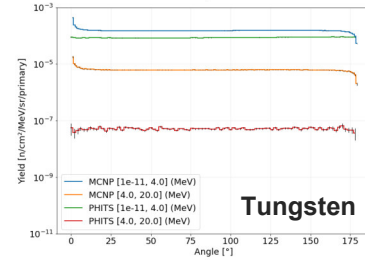
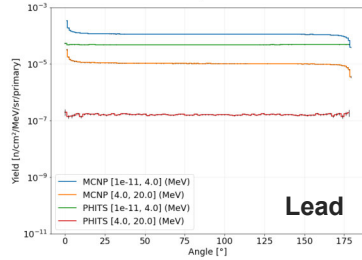
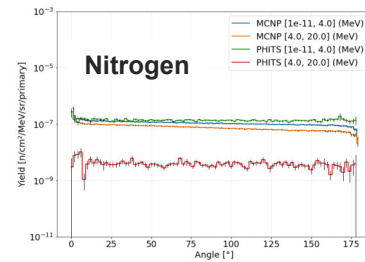
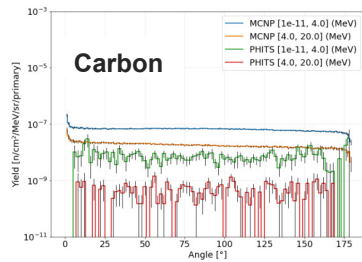


Consequences for dosimetry around a medical electron accelerator:



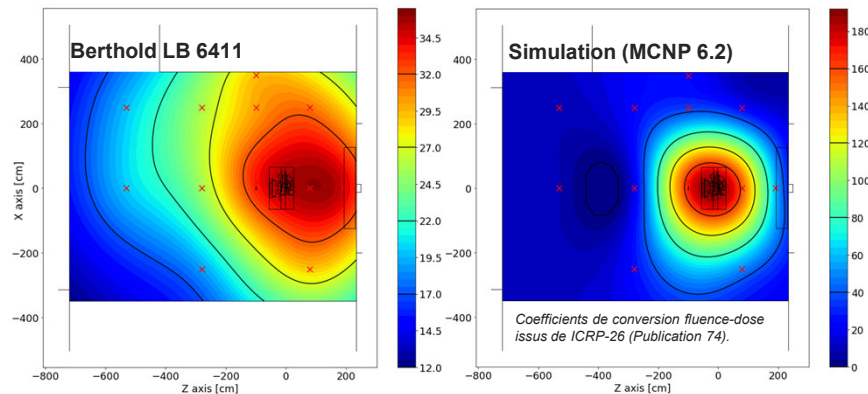
- Expected shape of the angular distribution of photo-neutrons emitted during irradiation of tungsten

Simulations



- The Monte-Carlo codes tested do not correctly reproduce the anisotropic angular distribution of photoneutrons emitted through the direct mechanism in (γ, Xn) reactions

Measurement of the ambient dose equivalent rate $H^*(10)$ around the Varian TrueBeam accelerator:



- MCNP 6.2 generally agree with measurements for the 10 positions in the forward hemisphere
- MCNP 6.2 globally appropriate for dimensioning radiation protection shielding



Intercomparison of integrated (γ, Xn) cross-sections

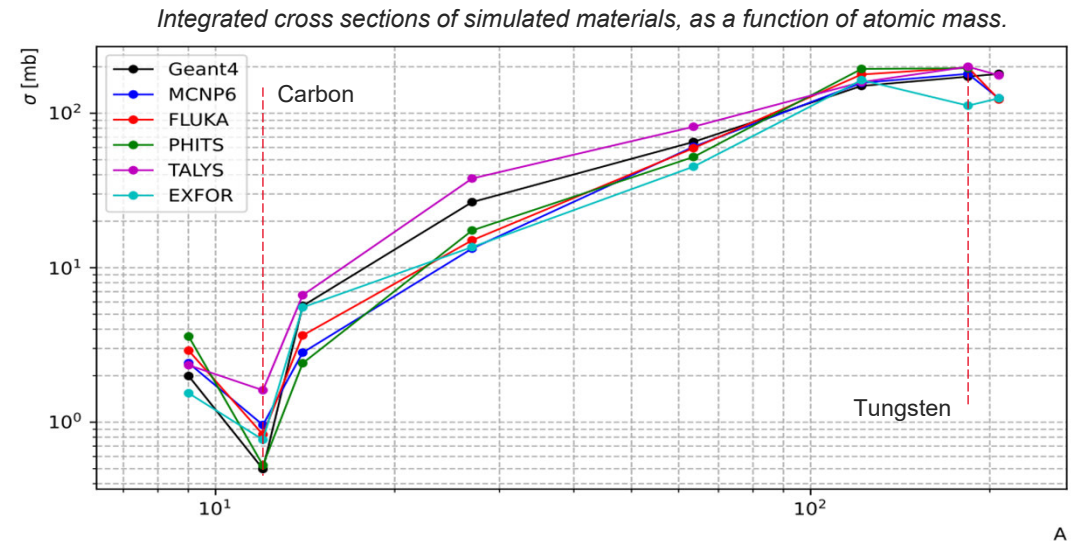
Integrated cross sections vs. atomic mass

- Monte-Carlo codes
- EXFOR (experimental)
- Nuclear reactions model calculations with TALYS code (source of TENDL evaluated cross sections library)

- The photo-neutron production cross-section increases with the mass of the target nucleus, except a decrease observed in the case of carbon ($E_{\text{threshold}}=18,72$ MeV), and reaches a plateau for heavy elements since no significant increase is observed between W and Pb

- For tungsten all the calculated cross-sections are overestimated

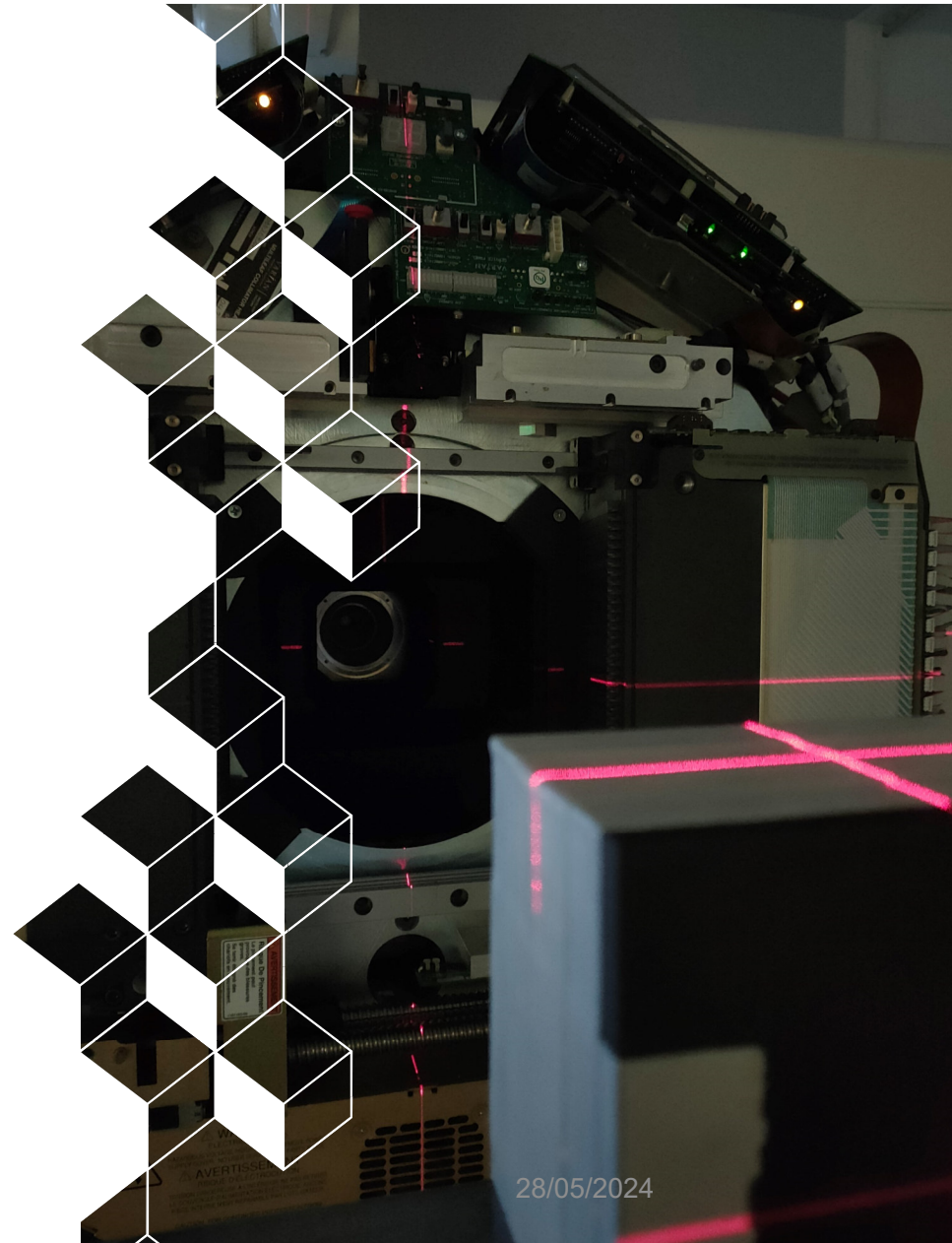
- MCNP6, FLUKA and PHITS better general agreement with the data from EXFOR while GEANT4 and TALYS predict higher cross-sections for light and intermediate mass nuclei



- Integrated cross sections alone does not allow deep physics study
 - Energy and angular distributions must also be considered
- **Need for new measurements since presently there is practically no data in the literature for differential distributions**

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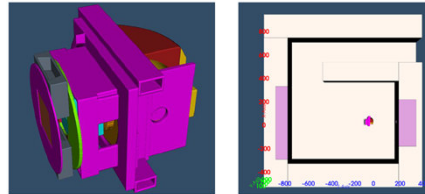




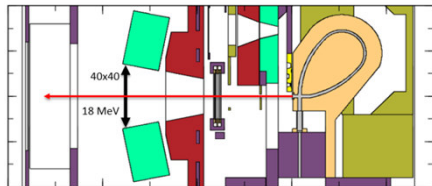
Modelling, modifications and characterization of CEA's TrueBeam VARIAN accelerator

Development of a complete geometry model of the Varian TrueBeam® accelerator head and its environment

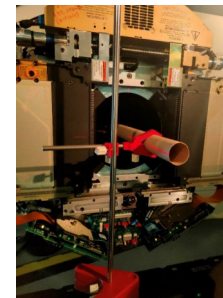
3D modelling of the TrueBeam® medical accelerator head (left) and its installation in the bunker (right)



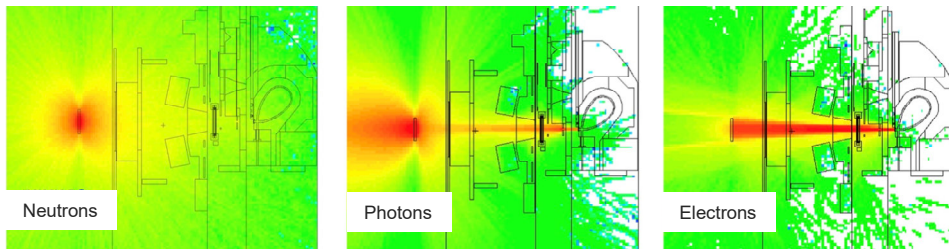
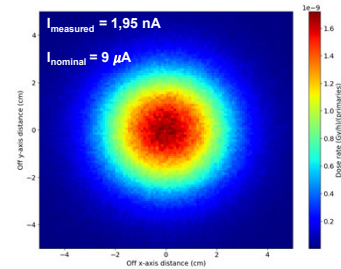
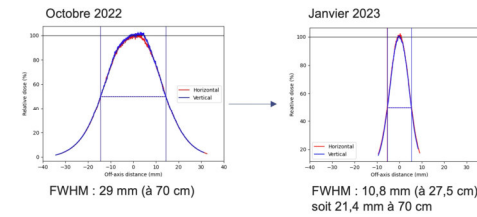
- Medical accelerator (6, 10, 15, 20 MeV)
- Pulsed electron beam (3,5 μ sec, 120 Hz)
- Mixed radiation field with ratio neutron/photon \ll 1



View of the modelled geometry of the accelerator head. The red arrow indicates the direction of the beam

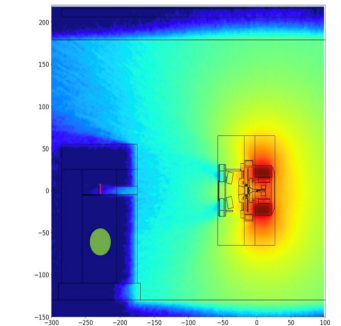
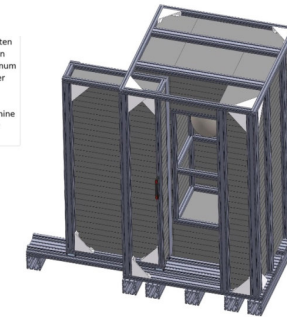
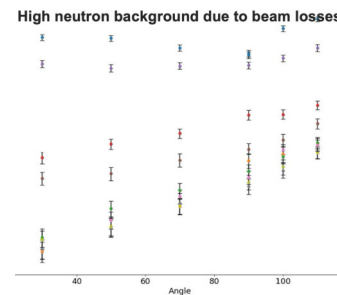


Improvement of beam focusing



Monte Carlo simulations faithfully reproducing experimental conditions

Development of a shielded detection cell for neutron spectrometry

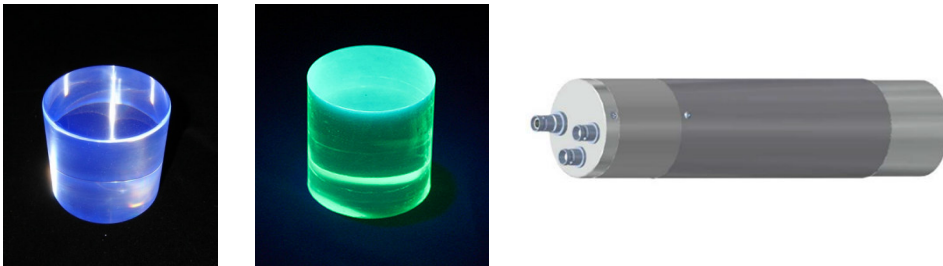


Active neutron spectrometry in mixed short-pulsed fields with intense photon flashes



Detection capabilities

- Use of an ELJEN plastic scintillator (EJ-276):

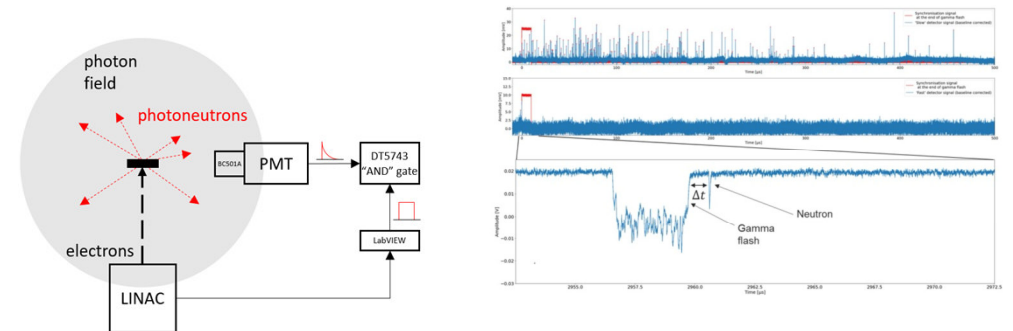


- Use of a SAINT GOBAIN liquid scintillator (BC-501-A):



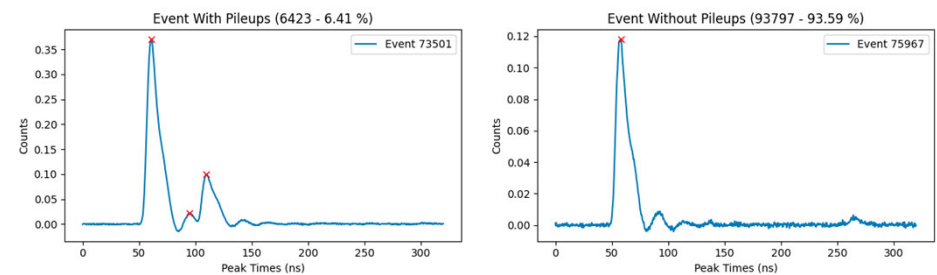
✓ Fast response time (few nanoseconds).

Neutron detection and electronics installation



Synchronized data acquisition with beam pulses

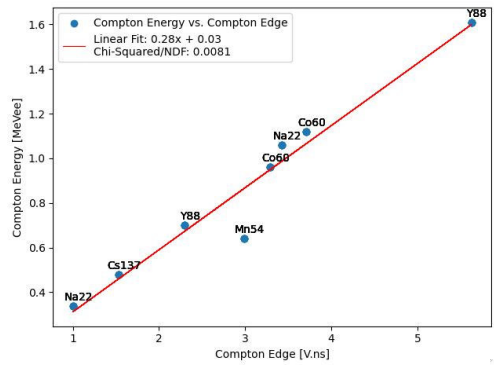
Post-processing and rejection of pile-ups





Measurement of neutron energy distributions

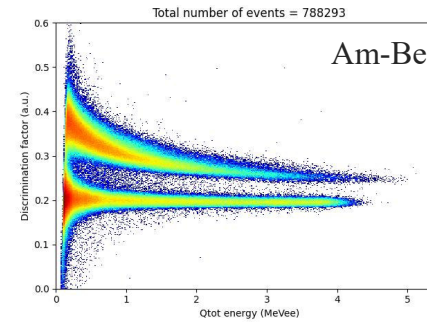
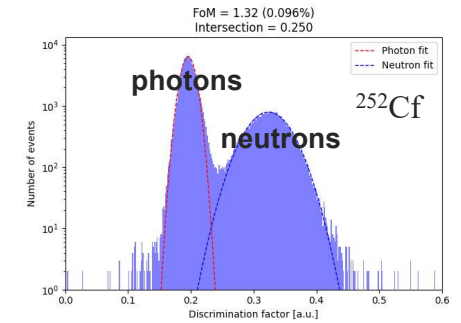
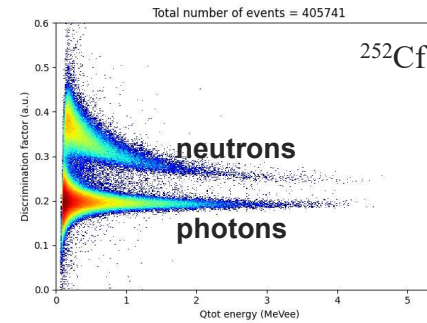
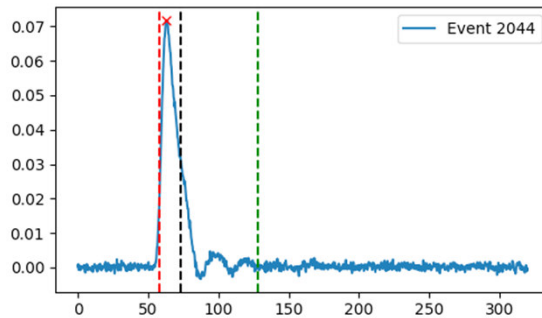
Energy calibration of detectors



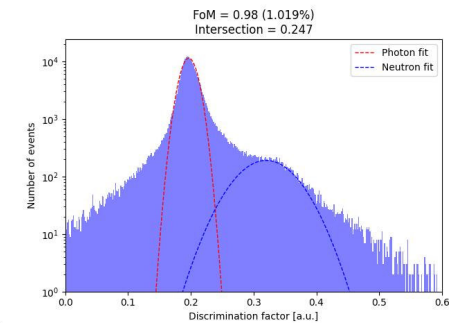
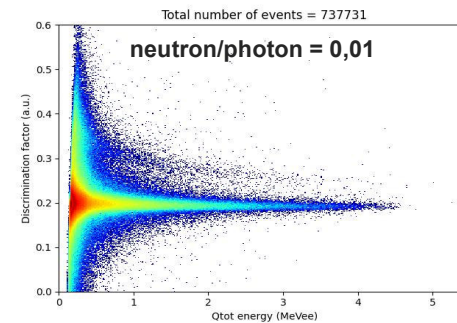
Two-dimensional pulse shape discrimination figures

A unique event with red-green doors for Q_{tot} and black-green doors for Q_{tail}

$$R = Q_{tail}/Q_{tot}$$



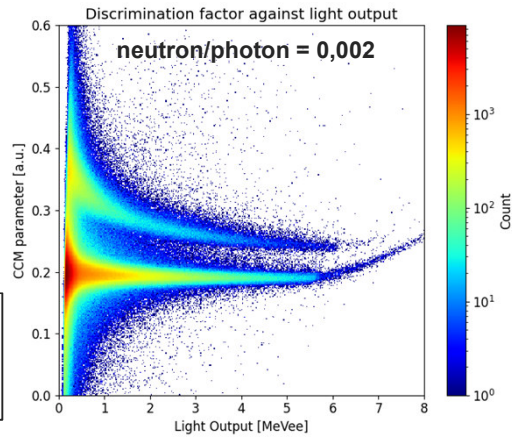
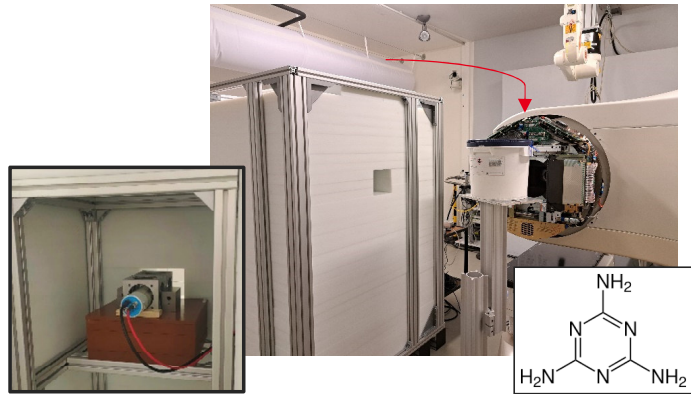
Tungsten irradiation with 22 MV Bremsstrahlung photons



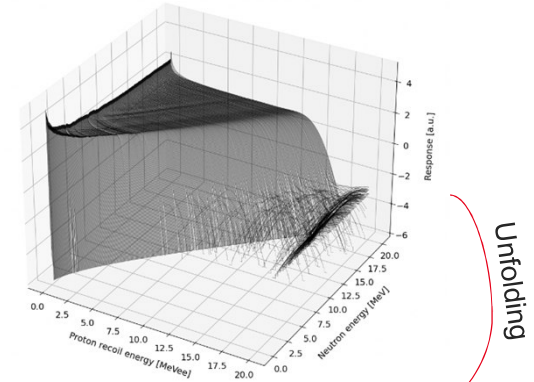


Measurement of neutron energy distributions

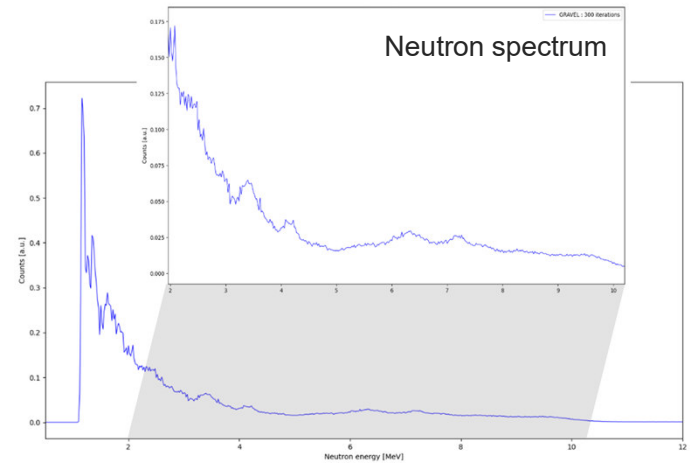
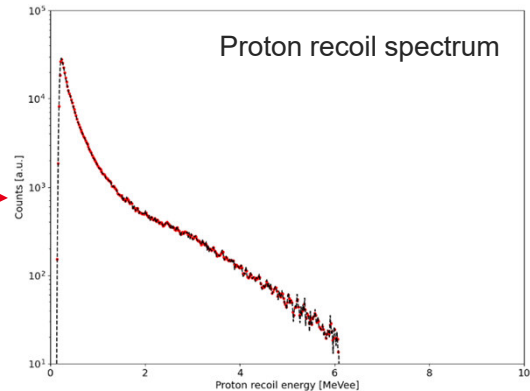
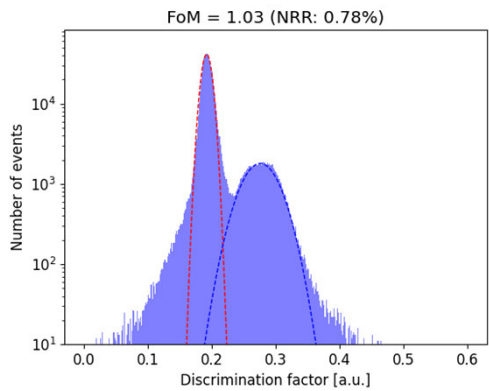
Melamine ($C_3H_6N_6$) irradiation with 22 MV Bremsstrahlung photons



Response functions matrix



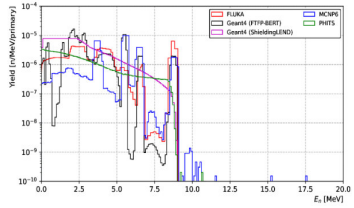
Neutron/gamma discrimination





Neutron energy distribution from melamine irradiation with Bremsstrahlung 22 MV photon spectrum

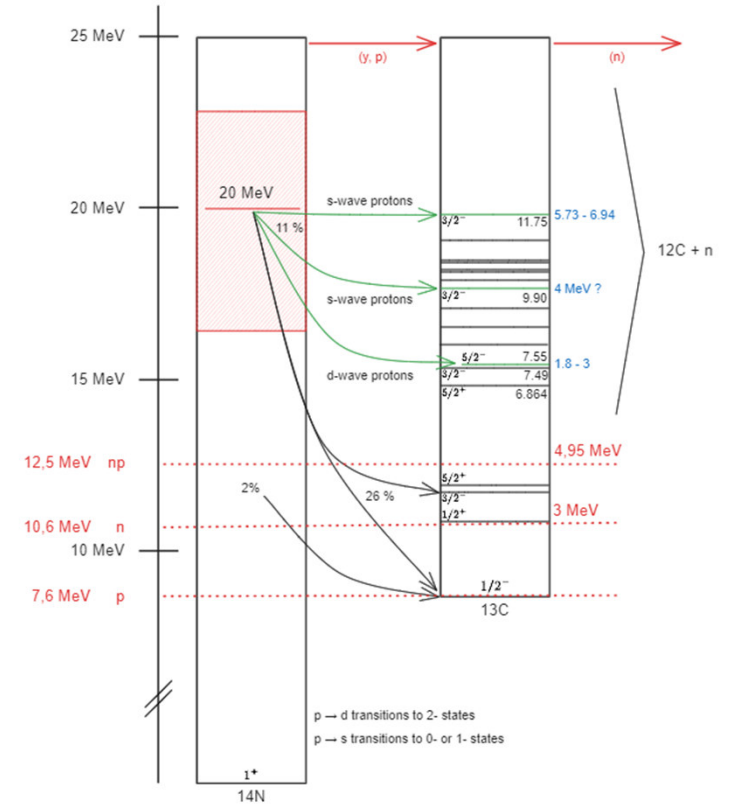
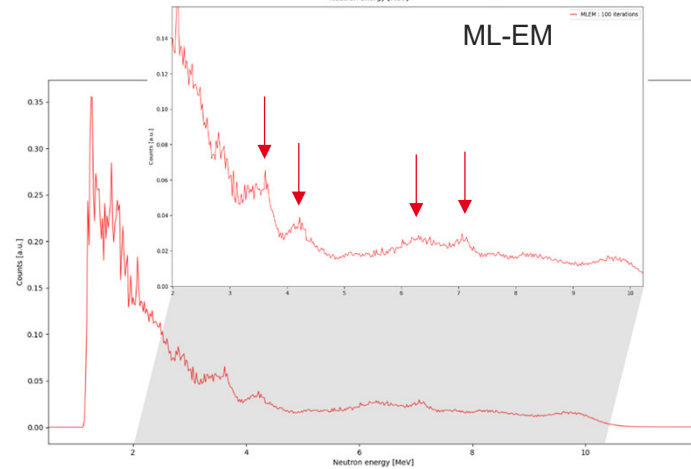
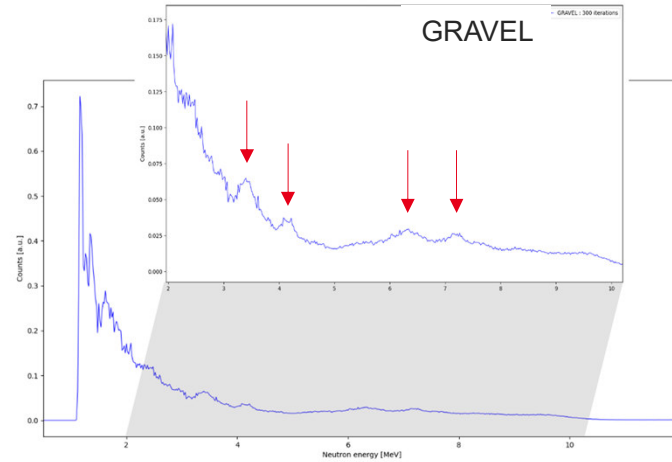
20 MeV mono-energetic photons



- Peaks from (γ, n) reactions are washed out because of the continuous energy spectra of Bremsstrahlung photons

- Structures still observed for 3,5 MeV, 4,2 MeV, 6,5 MeV and 7,2 MeV neutrons

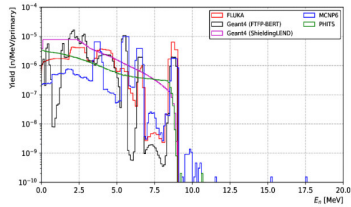
Possible interpretation
 2-step (γ, pn) reaction
 photonucleon cascade
 $\gamma + {}^{14}\text{N} \rightarrow p + {}^{13}\text{C}^* \rightarrow n + {}^{12}\text{C}$





Back to Monte-Carlo simulations ...

20 MeV mono-energetic photons



- Peaks from (γ, n) reactions are washed out because of the continuous energy spectra of Bremsstrahlung photons

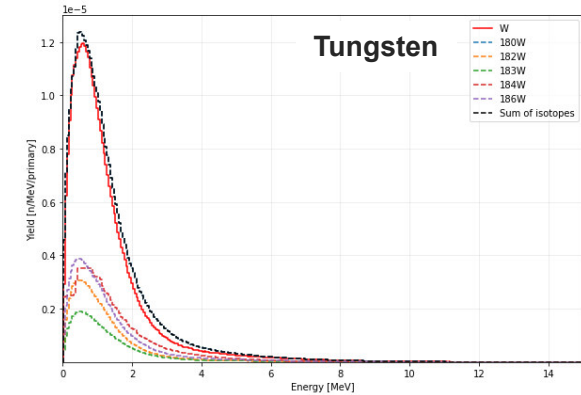
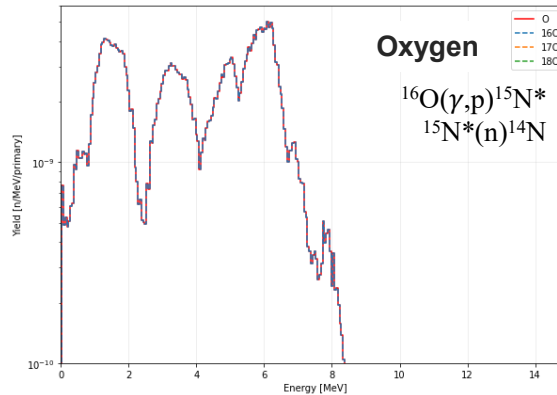
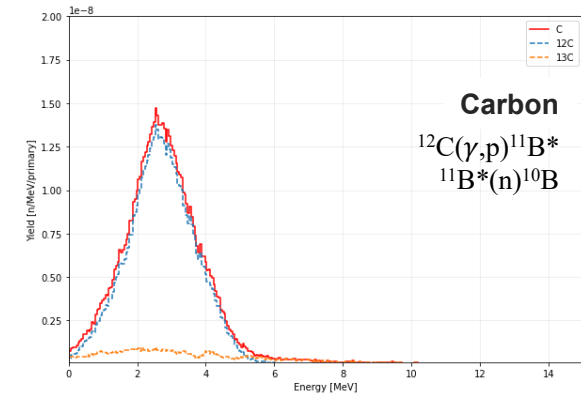
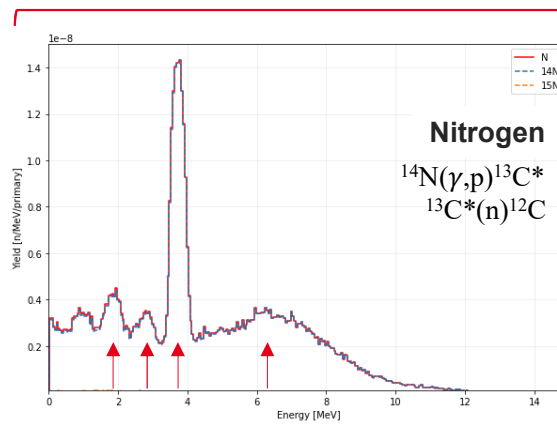
- Structures potentially from (γ, pn) reactions present for light targets but further deep analysis is needed to confirm

For nitrogen :

Peaks at 1.9 MeV, 2.9 and MeV 3.8 MeV. Large bump around 6.5 MeV not exactly matching the experimental findings

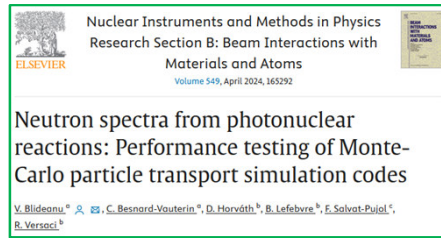
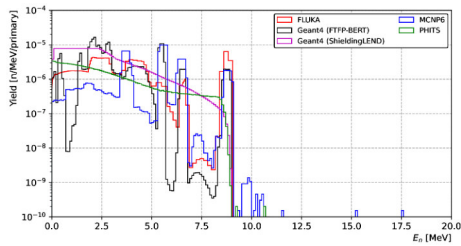
Need for a new code intercomparison on photoneutron energy distributions (this time with Bremsstrahlung photons)

MCNP6.2

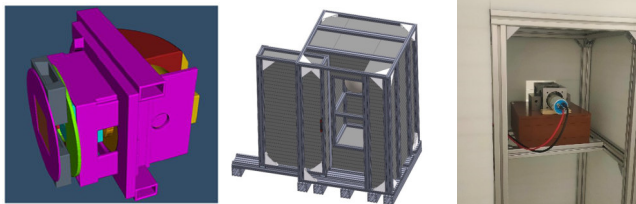


Summary

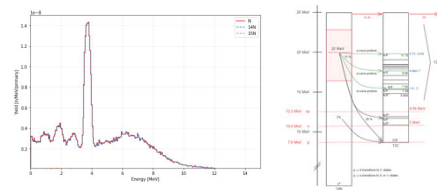
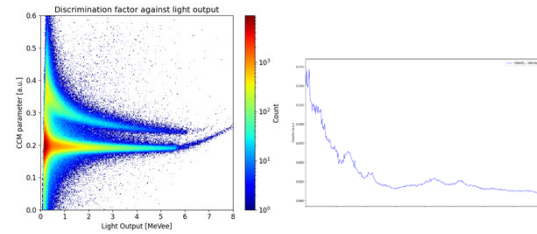
1 - Benchmark of Monte-Carlo codes for 20 MeV photon beam



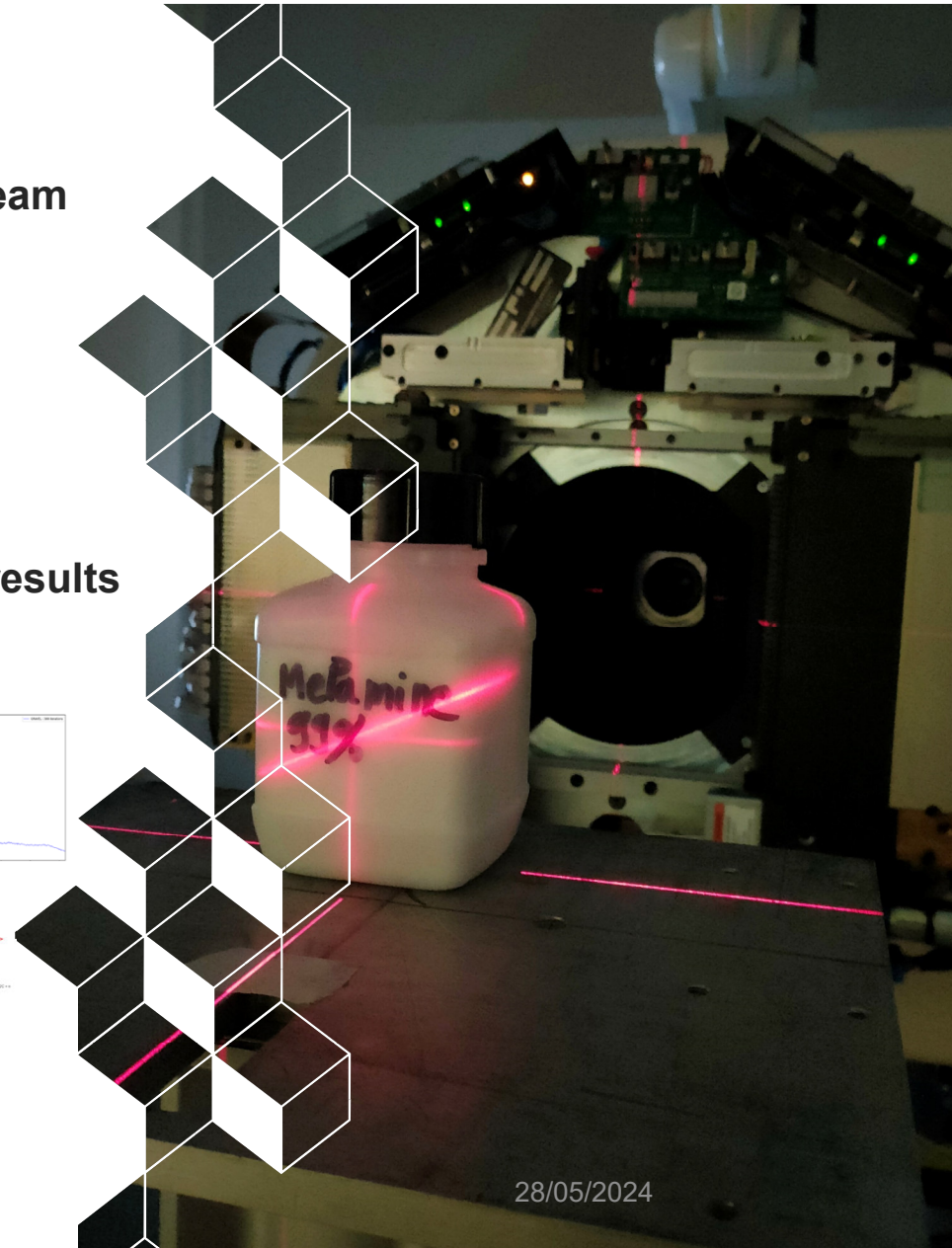
2 - Photoneutron detection facility available at CEA-Saclay



3 - First experimental results

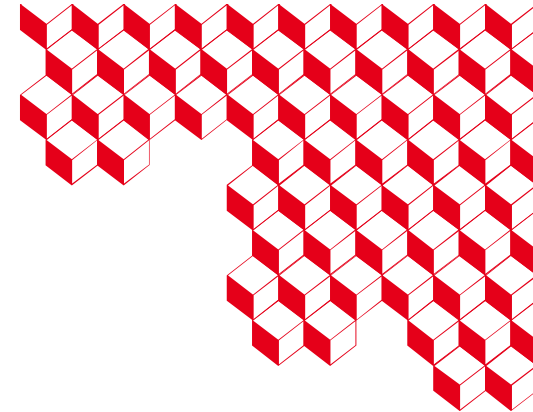


4 - Need for new code benchmark with Bremsstrahlung photon beam





list



Thank you for your attention



WG6 – Computational dosimetry

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