Development of a new method for the detection of illicit materials based on the active interrogation method and photoneutron spectrometry

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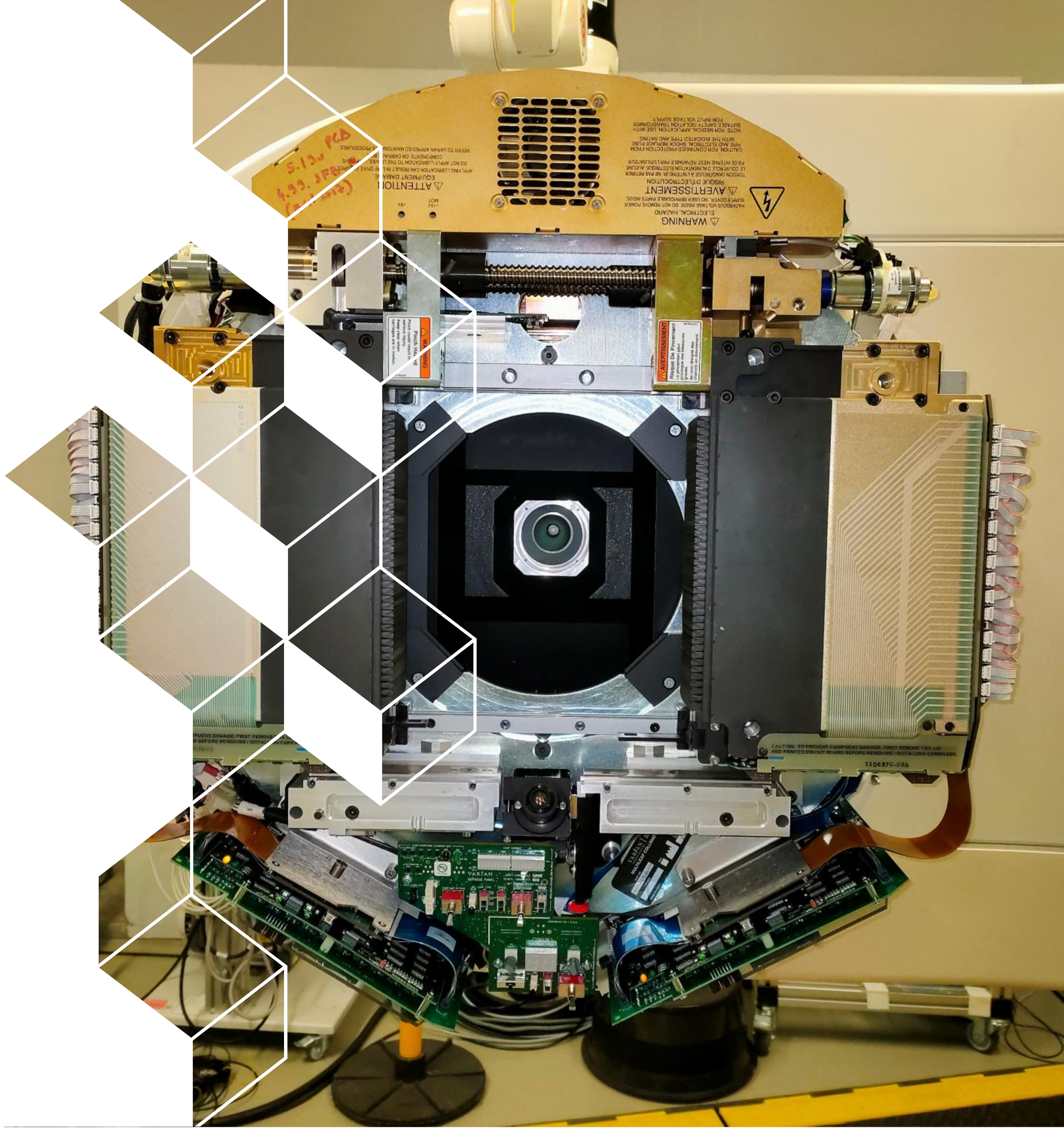
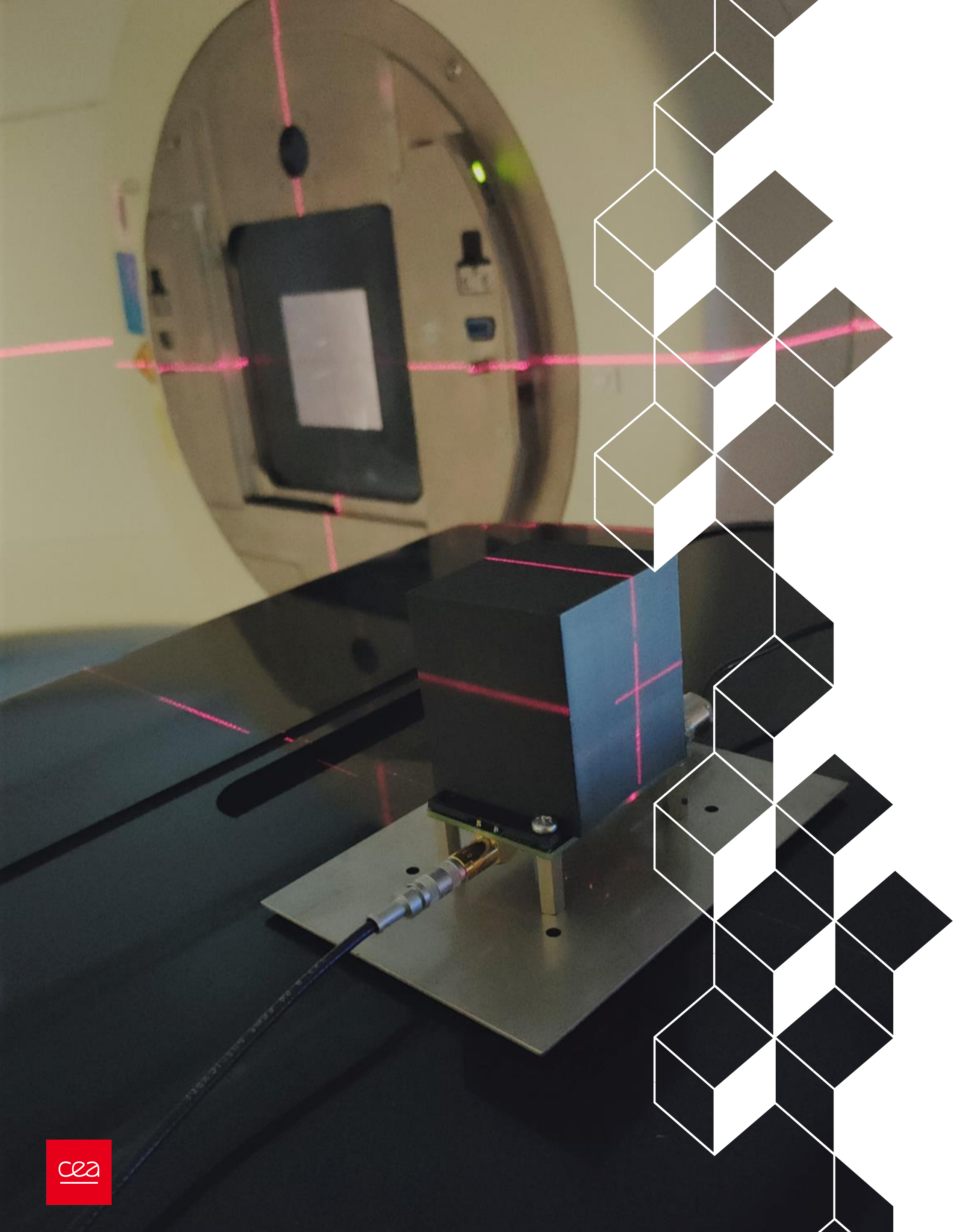




Contents

Introduction

State of the art:

1 - Active Neutron Interrogation (ANI) :

Detection of illicit materials using the associated particle technique (APT) (n,γ).

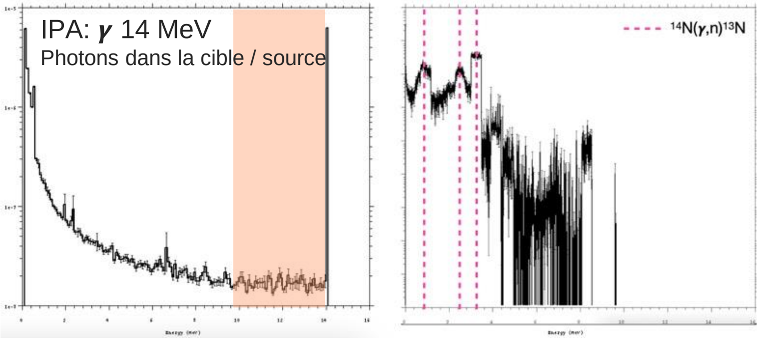
- High background noise (gamma radiation produced by a multitude of mechanisms)
- Attenuation and neutron scattering effects
- High radiation protection constraints

2 - Active Photon Interrogation (API) :

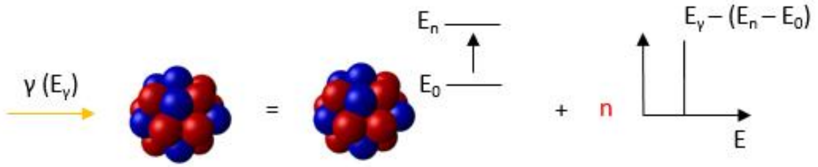
Detection of actinides using photofission reactions (γ,f).

- Limited to actinides

→ **New non-invasive and non-destructive method for detecting light elements based on (γ,n) reactions.**

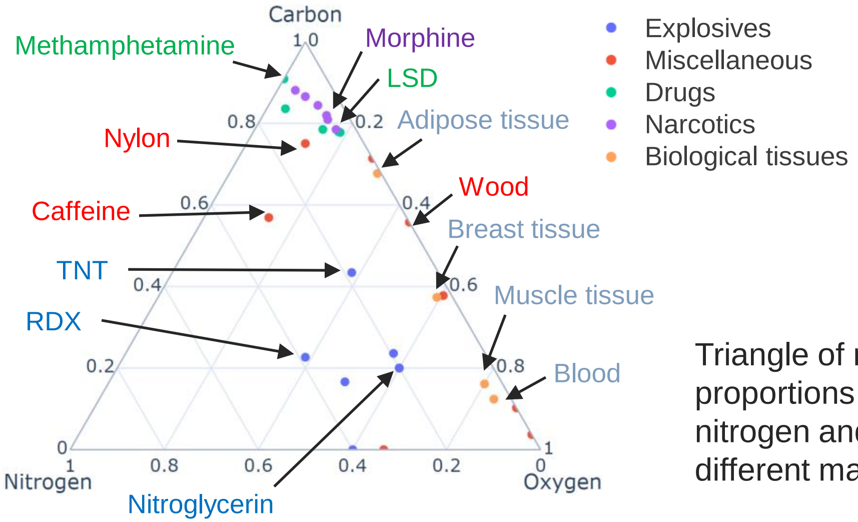


Physics involved and potential application:



Measurement of the radiation emitted by a nucleus when exposed to a high energy photon flux:

→ **Determination of the composition of light elements such as nitrogen, oxygen and carbon.**

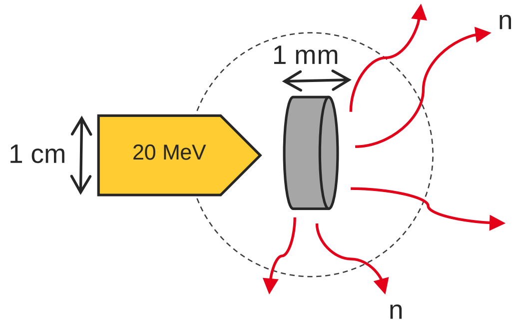


Triangle of normalized proportions of carbon, nitrogen and oxygen of different materials.

Intercomparison of simulated photoneutron energy spectra using several Monte Carlo codes

Methods:

In order to focus the study on the physics of the nuclear reactions involved, a simple set-up has been used with different Monte-Carlo codes :



Intercomparison of simulated photoneutron energy spectra 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, Pb, W).

WG6 – Computational dosimetry

Simulated neutron spectra:

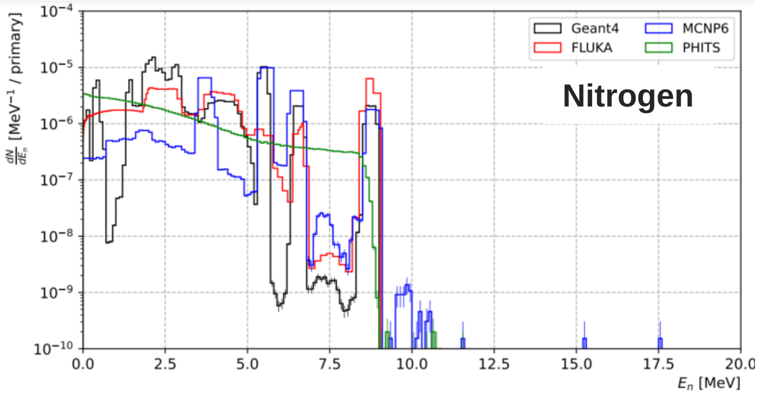
- Natural nitrogen: ρ= 1.00 g.cm^{-3}
N-14 (99.6%), N-15 (0.4%)

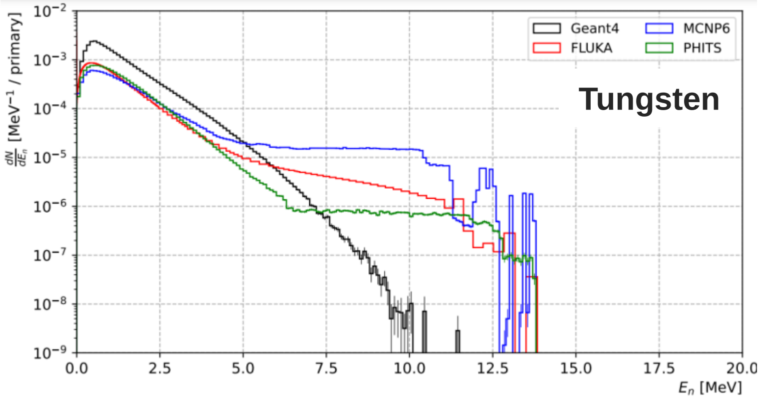
- Natural tungsten: ρ= 19.3 g.cm^{-3}
W-182 (26.5%), W-183 (14.3%), W-184 (30.6%), W-186 (28.4%)

- Nuclear levels effects are smeared out for heavier elements
- The various codes show quite different handling of nuclear levels
- Claims of better results can only be supported after benchmark with data
- Peak structures have been be carefully checked

Energy levels of ^{13}N	Photo-neutron energy (MeV ± keV)
g.s.	8.92
2.3649 ± 0.6	6.58
3.502 ± 2	5.52
3.547 ± 4	5.48
6.364 ± 9	2.87
6.886 ± 8	2.38
7.155 ± 5	2.13

Energy levels of ^{13}N and corresponding photo-neutron energies.





Intercomparison of simulated photoneutron energy spectra using several Monte Carlo codes

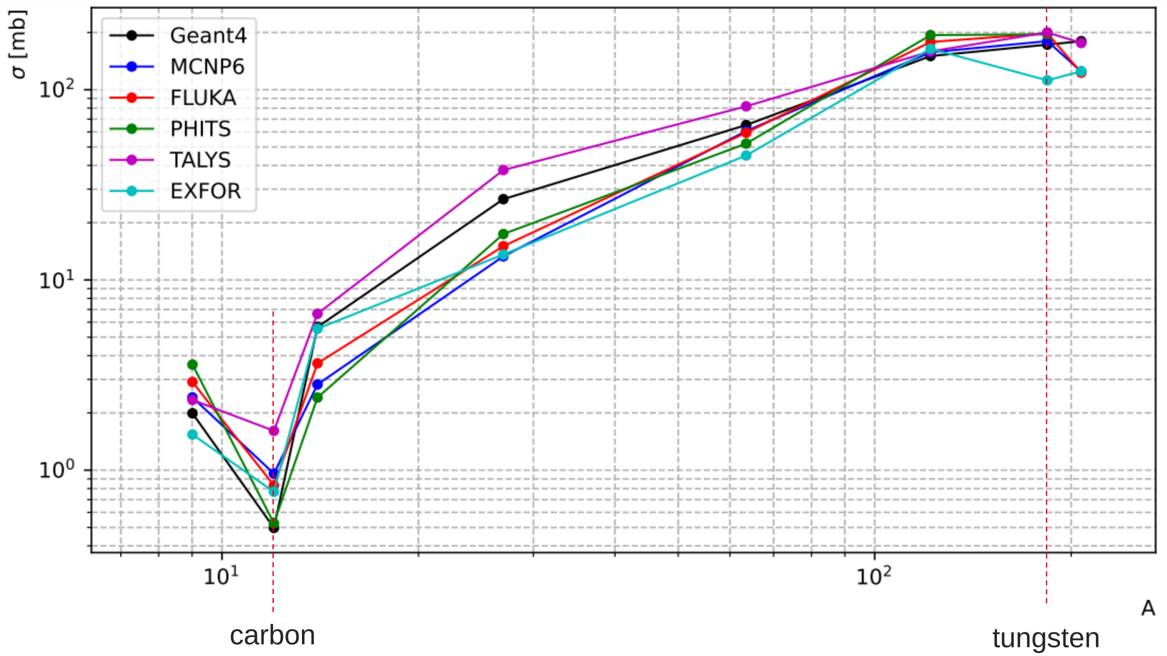
Integrated cross-sections:

No experimental data available in the literature for neutron spectra:
→ one can compare the codes predictions against experiments for the photo-neutron production only in terms of total cross-section (integrated over the energy and angle).

Intercomparison of integrated cross sections of simulated materials as a function of atomic mass (including EXFOR experimental and TALYS calculated integrated cross sections) have been added to the comparison.

- The photo-neutron production cross-section increases with the mass of the target nucleus and reaches a plateau for heavy elements since no significant increase is observed between tungsten and lead.
- MCNP6, FLUKA and PHITS show better general agreement with the data while GEANT4 and TALYS produce higher cross-sections for light and intermediate mass nuclei.
- For tungsten all the calculated cross-sections are overestimated.
- Despite showing an inaccurate simulation of the energy spectra of photo-neutrons, PHITS is able to reproduce the same trend as the other codes for integrated cross-section

Integrated cross sections of the simulated materials, as a function of atomic mass.

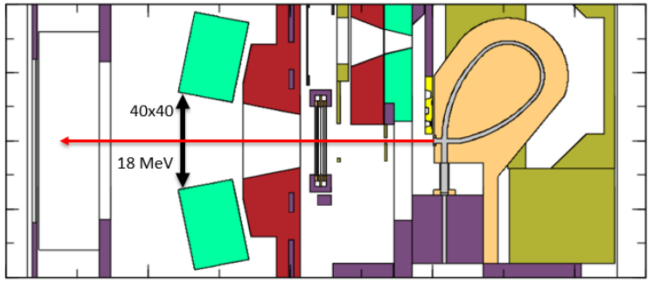


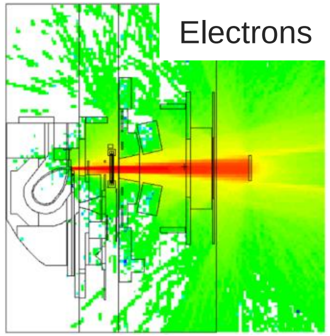
This strengthens the importance of the approach of this study for a more accurate code benchmark based on the comparison in terms of neutron spectra.

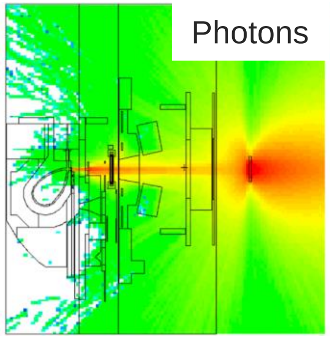
Preliminary feasibility simulations and measurements on a test bench based on a LINAC

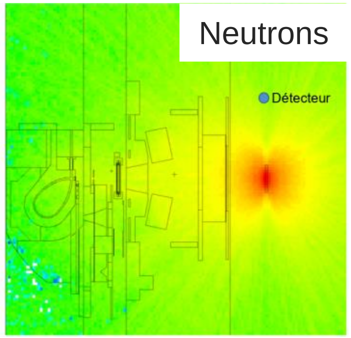
Modeling of the TrueBeam® medical LINAC from VARIAN:

The geometry of the TrueBeam® head and its environment have been fully modelled to allow an accurate description for Monte Carlo simulations.







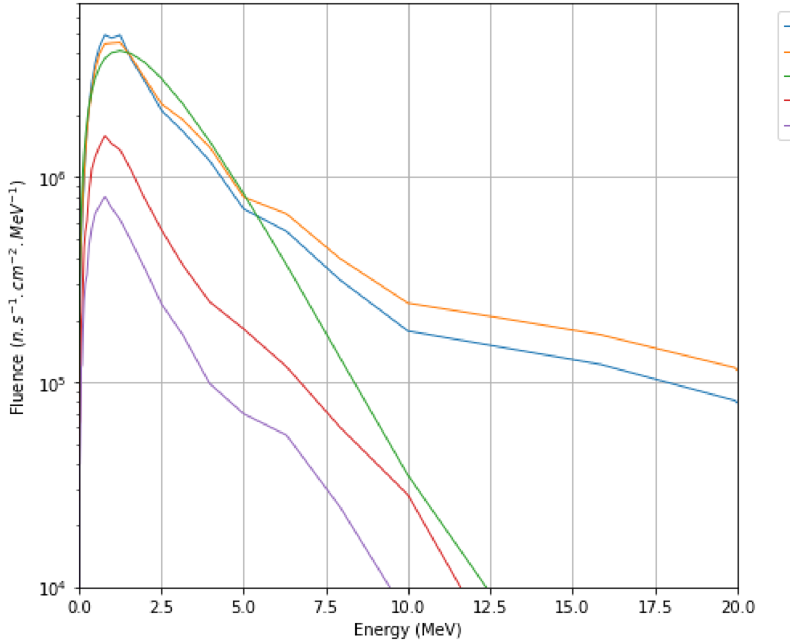


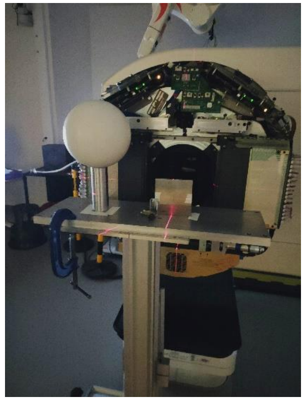
The results allowed us to refine the characterisation of the accelerator, particularly with regard to its gamma and neutron environment, since we pointed out some differences between the measured and simulated results.

Bonner sphere neutron spectrometry:

- Neutron spectrum measurement with a passive Bonner sphere system at 20 MeV and with a 1 cm thick tungsten target.
- Calculation of response matrices with MCNP6.2 and handling of deconvolutions with GRAVEL, MLEM and by Monte-Carlo method using Markov chains.

→ Factor 2 between simulation and measurements: change of accelerator configurations to limit its photon and neutron noise.





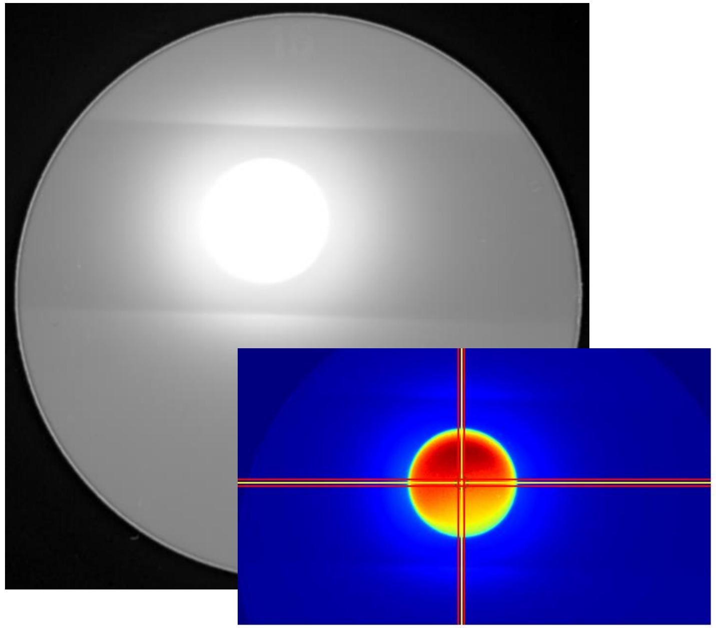
Preliminary feasibility simulations and measurements on a test bench based on a LINAC

Optimization and modifications of the LINAC:

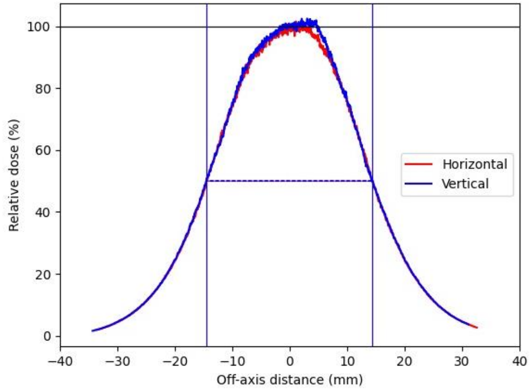
Electron beam size measurements with Gafchromic™ films.

→ Measured beam size larger than expected from literature and manufacturer data

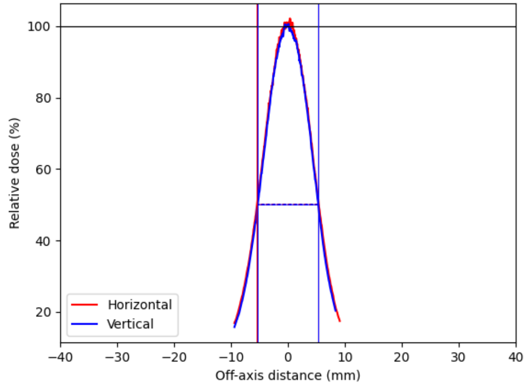
→ Changed in the configuration to get rid of the problem of the steel electron primary collimator irradiated by the beam, source of unwanted photo-neutrons.



Improvement of the beam characteristics for our specific application:



FWHM : 29 mm (at 70 cm)

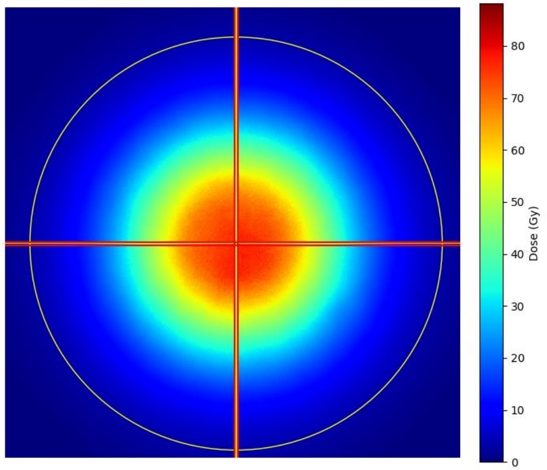


FWHM : 10,8 mm (at 27,5 cm)
soit 21,4 mm à 70 cm

→ The beam size has been reduced.

→ The contamination by unwanted photo-neutrons from the head of the accelerator has been reduced.

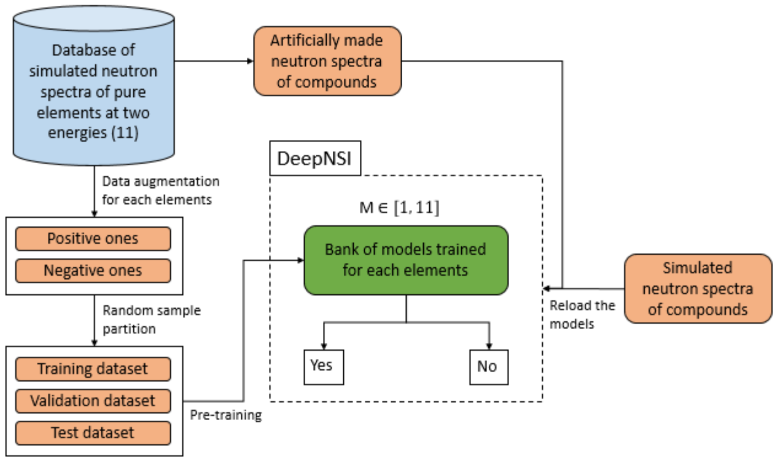
→ The model better describes the actuals experimental setup.



Development of a new method for neutron spectra analysis based on a deep learning algorithm for the detection of illicit materials

Method:

- Database contains the simulated neutron spectra of 11 pure elements established through simulations with MCNP6.2.
- Data augmentation was applied and the augmented dataset of each compound was divided for training, validation and testing.
- Convolutional Neural Network (CNN) extract spectral features and learn to recognize elements even amidst complex interferences.



Database of simulated neutron spectra of pure elements at two energies (11)

Artificially made neutron spectra of compounds

Data augmentation for each elements

Positive ones

Negative ones

Random sample partition

Training dataset

Validation dataset

Test dataset

Pre-training

DeepNSI

M ∈ [1, 11]

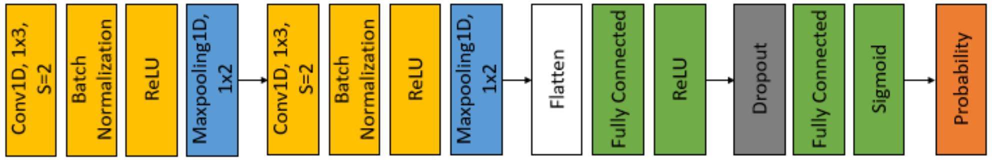
Bank of models trained for each elements

Yes

No

Reload the models

Simulated neutron spectra of compounds



Conv1D, 1x3, S=2

Batch Normalization

ReLU

Maxpooling1D, 1x2

Conv1D, 1x3, S=2

Batch Normalization

ReLU

Maxpooling1D, 1x2

Flatten

Fully Connected

ReLU

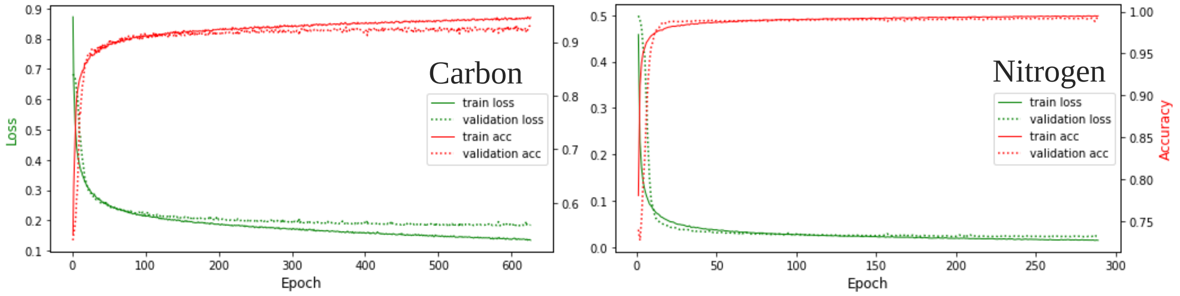
Dropout

Fully Connected

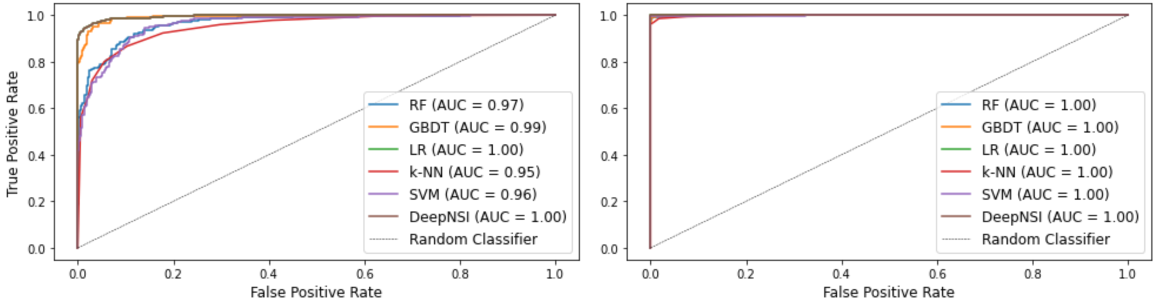
Sigmoid

Probability

Prediction Accuracy for Element Identification:



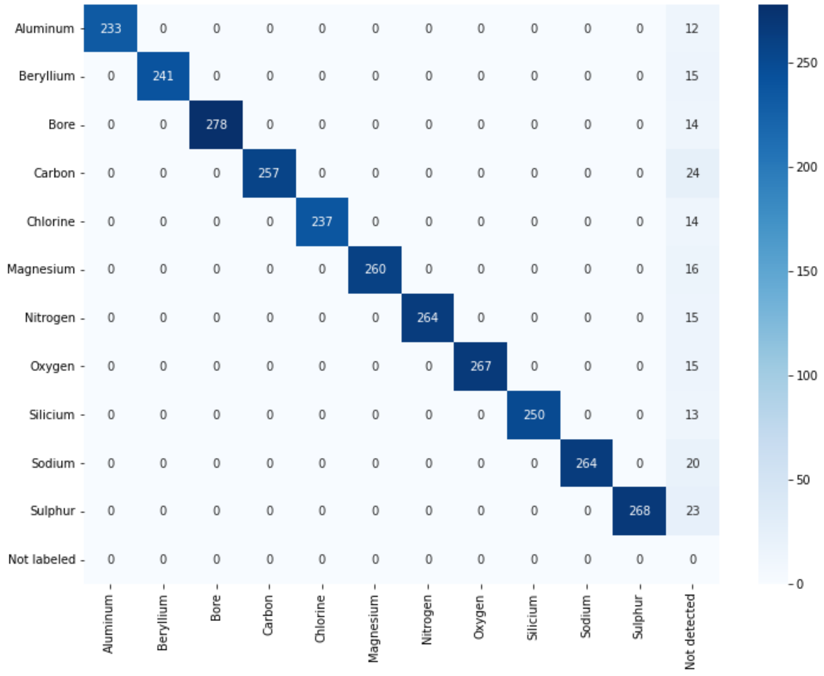
	DeepNSI	RF	GBDT	LR	k-NN	SVM
Carbon	97.9 %	89.8 %	95.4 %	97.5 %	87.9 %	84.7 %
Nitrogen	99.5 %	98.7 %	99.0 %	99.5 %	96.8 %	96.2 %
Oxygen	99.7 %	94.2 %	98.5 %	99.7 %	95.4 %	96.8 %
Chlorine	99.9 %	98.0 %	99.0 %	99.9 %	98.3 %	98.8 %
Sulfur	99.5 %	94.9 %	97.6 %	99.5 %	94.8 %	94.0 %



Development of a new method for neutron spectra analysis based on a deep learning algorithm for the detection of illicit materials

Prediction Result on Artificially Made Compounds:

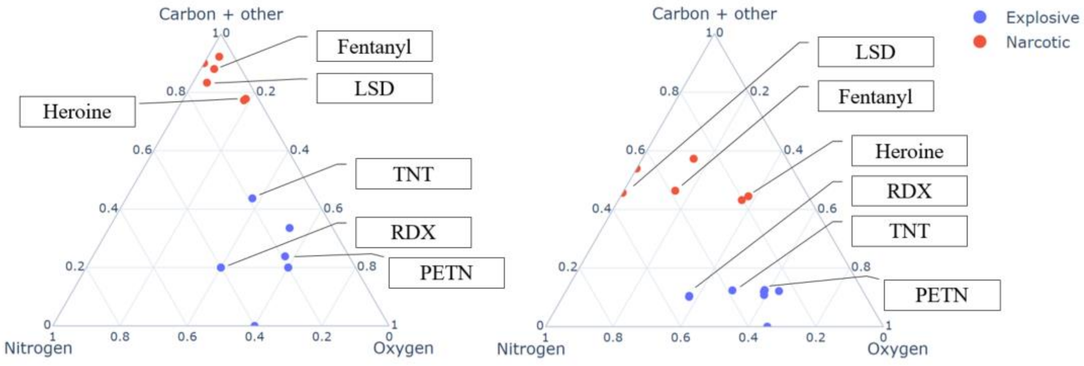
DeepNSI shows good performances using artificially made compounds, which are mixtures of neutron spectra of elements randomly selected from the database and added in random proportions with random noise on each energy bin.



	Aluminum	Beryllium	Bore	Carbon	Chlorine	Magnesium	Nitrogen	Oxygen	Silicium	Sodium	Sulphur	Not detected
Aluminum	233	0	0	0	0	0	0	0	0	0	0	12
Beryllium	0	241	0	0	0	0	0	0	0	0	0	15
Bore	0	0	278	0	0	0	0	0	0	0	0	14
Carbon	0	0	0	257	0	0	0	0	0	0	0	24
Chlorine	0	0	0	0	237	0	0	0	0	0	0	14
Magnesium	0	0	0	0	0	260	0	0	0	0	0	16
Nitrogen	0	0	0	0	0	0	264	0	0	0	0	15
Oxygen	0	0	0	0	0	0	0	267	0	0	0	15
Silicium	0	0	0	0	0	0	0	0	250	0	0	13
Sodium	0	0	0	0	0	0	0	0	0	264	0	20
Sulphur	0	0	0	0	0	0	0	0	0	0	268	23
Not labeled	0	0	0	0	0	0	0	0	0	0	0	0

Prediction Result on a Monte-Carlo Simulated Compound Spectra Dataset:

DeepNSI shows good prediction results on Monte-Carlo simulated neutron spectra from various compounds of interest.
It systematically finds the nitrogen and oxygen in the different molecules but not carbon when it is below 20% in atom fraction as the photonuclear reaction cross section for this element is very low



From atomic fractions

From photoneutron contributions

The ternary plot above represents the neutron contributions estimated using non-negative elastic net and with the reference spectra of the elements in presence predicted by DeepNSI.
It demonstrates the appropriate performance achieved by the method proposed in specifying the nature of compounds and differencing between explosives, chemical weapons, and narcotics.

Conclusion and perspectives

Conclusion:

- As shown by the benchmark, the photo-neutron spectra are heavily influenced by the nuclear levels structure of the nuclei responsible for their emission, especially for light nuclei. The codes evaluated in this study showed significant differences in how this effect is handled. The lack of experimental data for photo-neutron spectra and cross-sections is a major issue in the development and validation of Monte Carlo codes for photo-nuclear reactions.
- A test bench for photoneutrons spectrometry is being developed around a 20 MeV medical LINAC at DOSEO (CEA). Primary experimental studies were performed to optimize the accelerator for this specific application.
- The DeepNSI algorithm is a promising option for element identification based on photo-neutron spectrometry. Its universal and portable structure allows to consider many other applications, such as the detection of light elements for applications other than illicit material detection or for neutron sources identification in the context of radiation protection and decommissioning with mixed neutron spectra.

Perspectives:

ANIMMA 2023 (Italy) – two oral presentations on two topics:

"*Evaluation of neutron-induced activation gamma-rays creation and transport in a LaBr3 inorganic scintillator with PHITS*". (Current trends in development Radiation Detectors)

"*Development of a new method for the detection of illicit materials based on the active interrogation method and photoneutron spectrometry*". (Nuclear Safeguards, Homeland Security and CBRN)

M&C 2023 (Canada) – oral presentation:

“*Development of a New Method for Neutron spectra Analysis based on a Deep Learning Algorithm for the Detection of Illicit Materials*”

Article currently being written:

“*Neutron spectra from photo-nuclear reactions: performance testing of Monte-Carlo codes for specific applications*”

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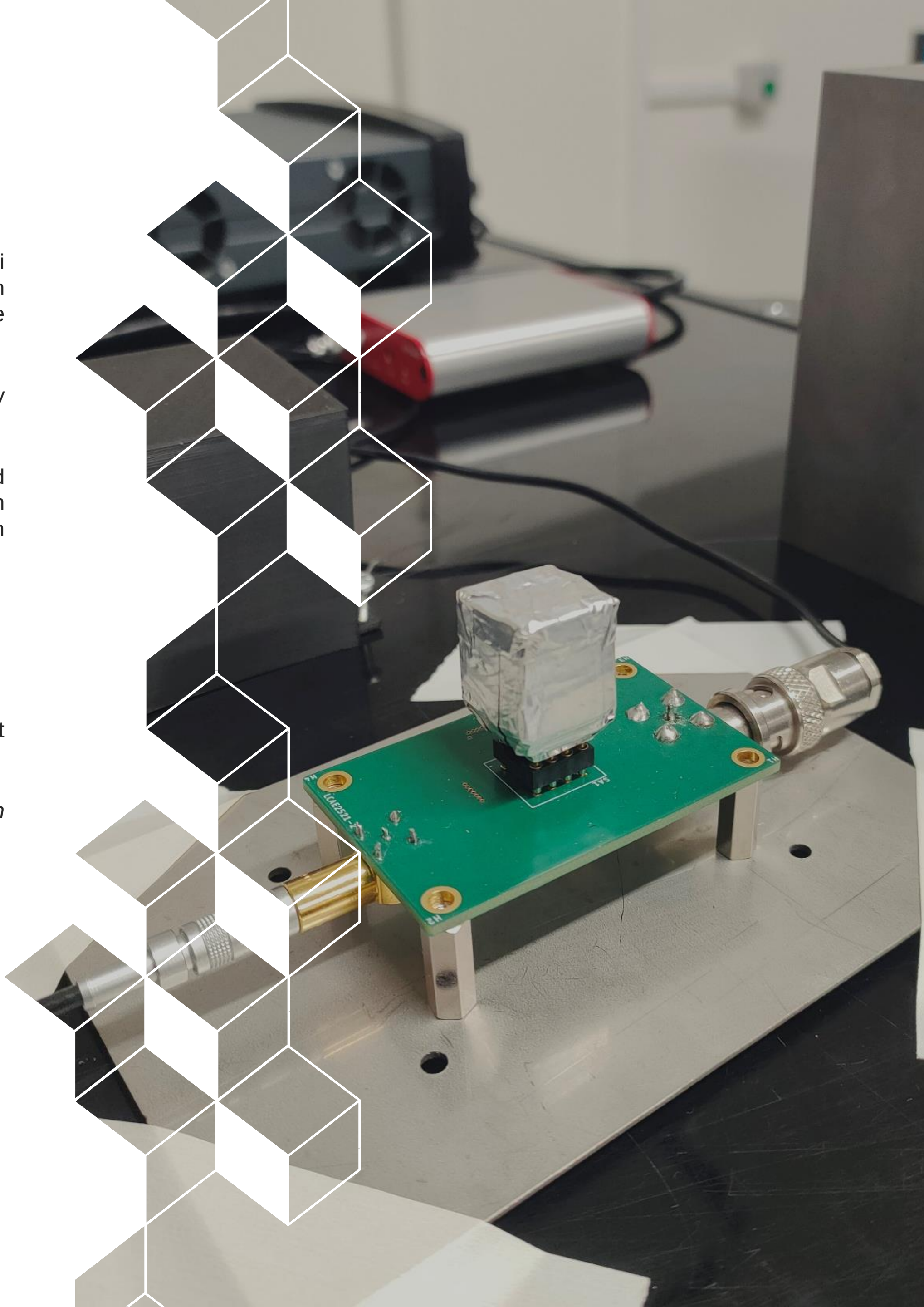

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Thank you for your attention

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