

A Monte Carlo and Experimental Tool for Activation Calculations in High-Energy X-Rays Irradiation Process

Nicolas ARBOR¹, Abdel-Mjid NOURREDDINE¹, Jonathan RIFFAUD¹

Florent KUNTZ², Abbas NASREDDINE², Alain STRASSER²

.....

1. IPHC, CNRS – University of Strasbourg

2. Aerial-CRT

.....

(nicolas.arbor@iphc.cnrs.fr)



INTERNATIONAL CONFERENCE ON

ACCELERATORS FOR RESEARCH AND SUSTAINABLE DEVELOPMENT

From good practices towards socioeconomic impact

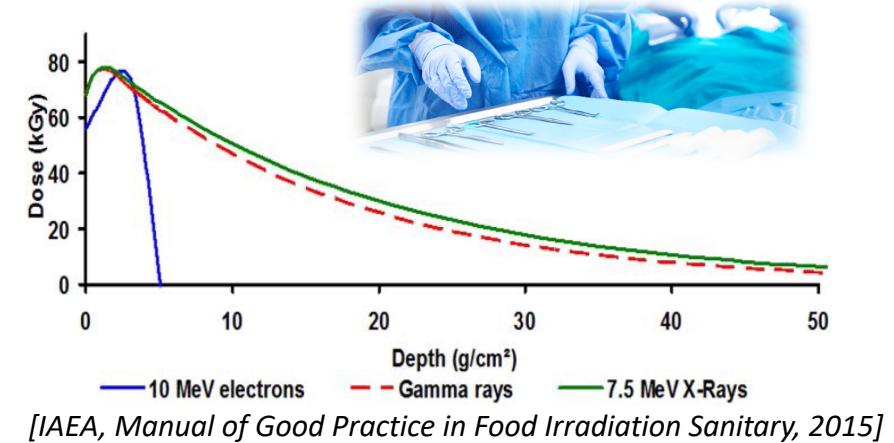


23–27 May 2022

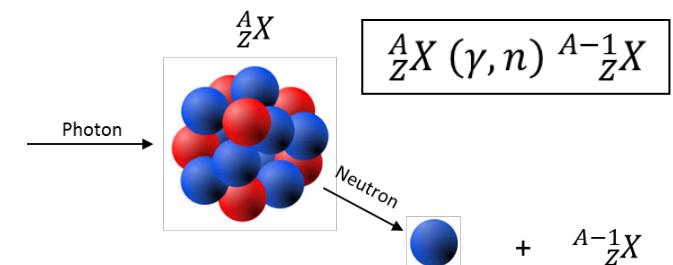
IAEA Headquarters, Vienna, Austria

X-Rays and photo-nuclear processes

- Linear accelerators are increasingly used for industrial irradiation:
 - more penetrating than electrons
 - easier to manage than radioactive sources (^{60}Co , ^{137}Cs)



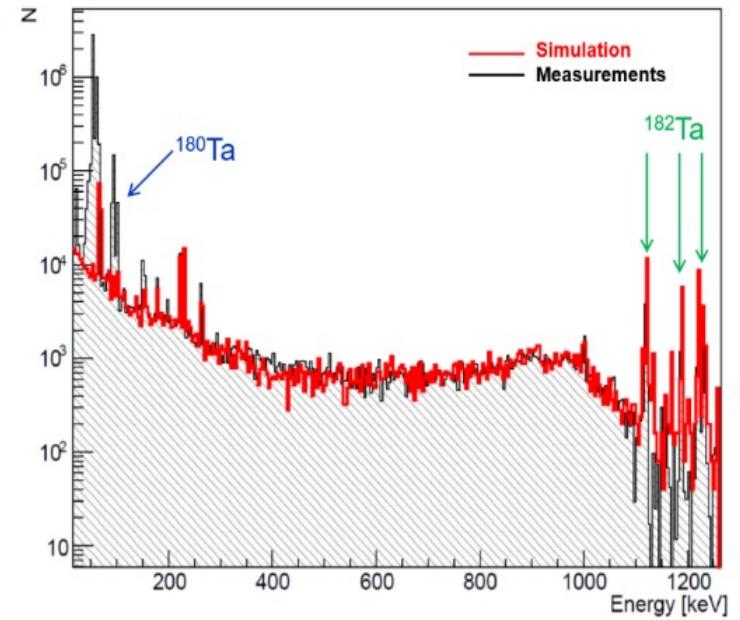
- X-Rays with energy higher than ≈ 2 MeV \Leftrightarrow risk of photo-nuclear activation (neutron production):
 - direct activation (radionuclide produced by photon interaction)
example: $^{204}\text{Pb} (\gamma, n) ^{203}\text{Pb}$
 - indirect activation (radionuclide produced by neutron capture)
example: $^{13}\text{C} (n, \gamma) ^{14}\text{C}$



Activation control

- Gamma spectrometry is the most common control method:

- ✓ radionuclide identification
- ✓ activity quantification (Bq/kg)
- ✗ counting time
- ✗ detection limits (low intensity, self-attenuation, ...)



Gamma spectrum of ¹⁸¹Ta irradiated
with 15 MV X-rays

- Beta and alpha pur emitters are much more complex to characterize

⇒ Need to complete measurements with numerical tool (calculations)

Activation calculations

- Two types of codes are used to estimate radionuclides produced by direct (gamma) and indirect (neutron) activation:
 - Monte Carlo radiation transport codes (GEANT4, MCNPX, FLUKA, ...)
 - Analytical codes (ActiWiz, FISPACT-II, CINDER-90, ...) (using neutron spectrum as input parameter)
- Activation calculations are very sensitive to various parameters:
 - nuclear data and models (cross-sections, photo-neutron production, neutron activation)
 - accelerator modeling (geometry, materials, X-rays spectrum, ..)
 - irradiated sample modeling (geometry, composition, ...)

⇒ **Development of a hybrid numerical and instrumental tool
for a step-by-step validation of activation calculations**

GATE Monte Carlo software @ Aerial/feerix®

- GATE is an open-source MC software based on Geant4
- Simplified interface (macros, actors) for modeling an irradiation facility



<https://www.opengatecollaboration.org/>



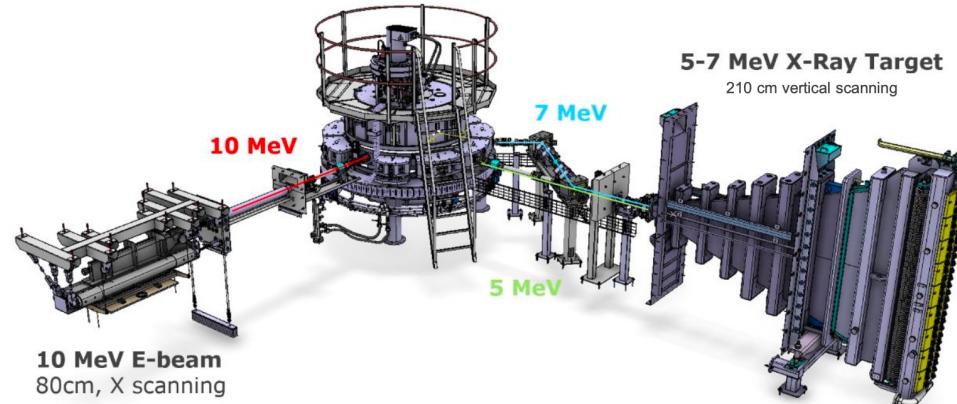
- Work in collaboration between:

- IPHC (CNRS-University of Strasbourg research laboratory)
- Aerial (technological ressource center, IAEA Collaborating Center)



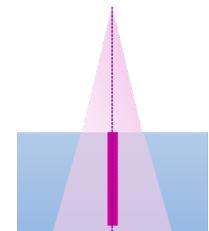
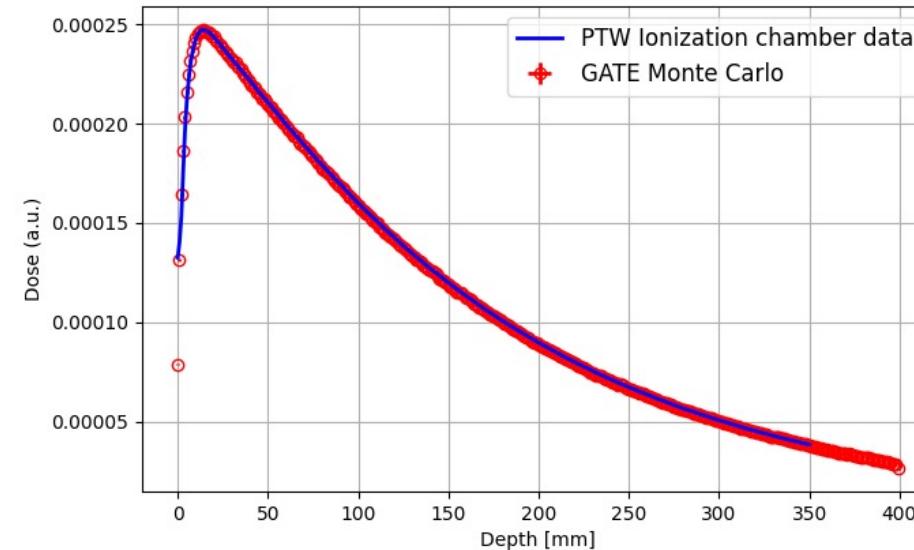
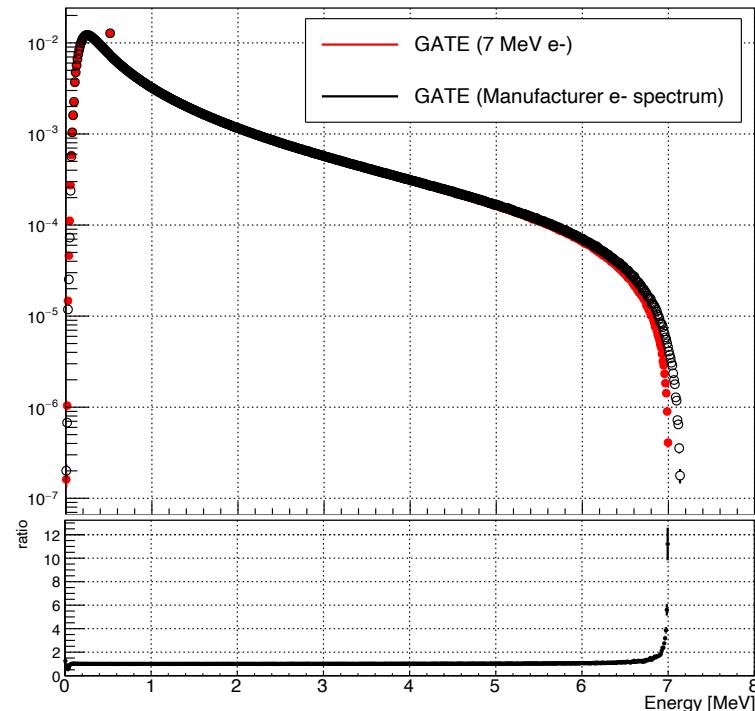
- feerix irradiation facility:

- IBA Rhodotron
- 10 MeV e^- beam, 5-7 MV X-rays
- 100 kW (maximum)



X-Ray energy spectrum

- Compute 7 MV X-ray spectrum from electron beam (spot, energy) and target (geometry, materials)
- Accuracy from 5 MeV is very important for photo-nuclear calculations
- « Classical » depth dose measurements (as in radiotherapy) enable only partial validation



X-Ray energy spectrum

- Compute 7 MV X-ray spectrum from electron beam (spot, energy) and target (geometry, materials)
- Accuracy from 5 MeV is very important for photo-nuclear calculations
- « Classical » depth dose measurements (as in radiotherapy) enable only partial validation
- Possible complementary experimental validation of maximal X-ray energy: photo-activation foil

Some interesting (γ, n) reactions for 7 MV X-ray beam:

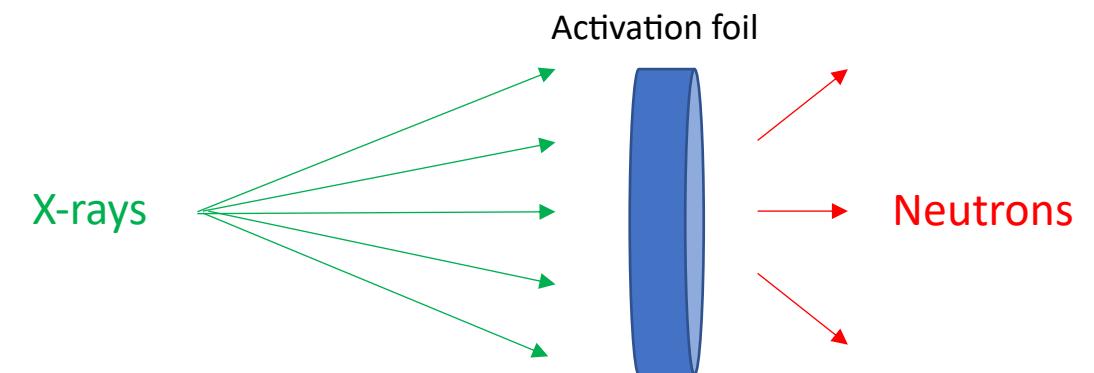
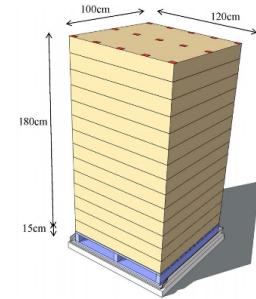


Photo-neutron fields

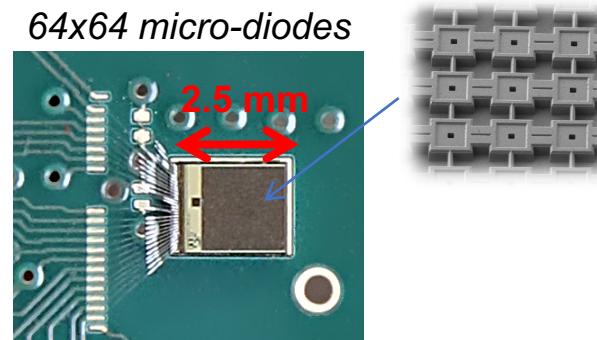
- Compute energy and spatial photo-neutron distributions for a given irradiation setup (beam energy/current, sample geometry and composition, ...)
- Precise neutron fields modeling:
 - global validation of MC simulations (photo-nuclear models, X-ray energy, geometry, material composition)
 - most important input for activation calculations
- Complex and time-consuming experimental validations:
 - solid nuclear track detector (CR-39)
 - activation foils (Au, In, ...)
 - bonner sphere system
 - ...



⇒ Online neutron monitoring system?

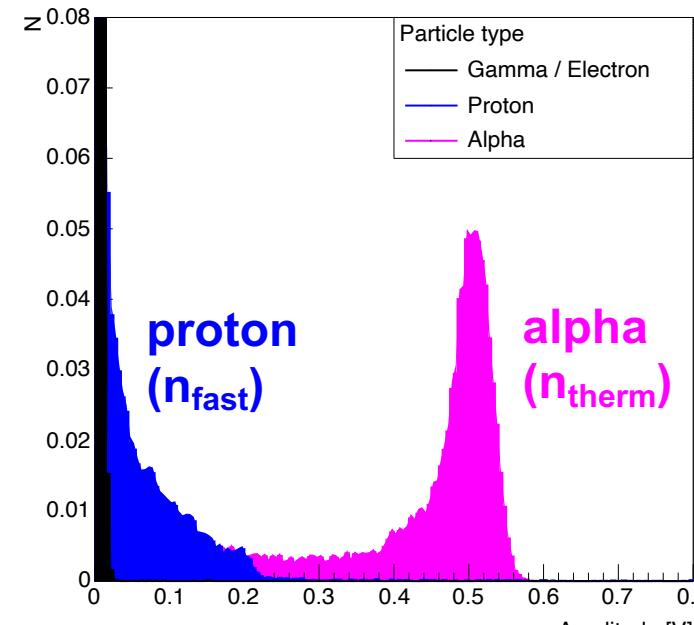
Online Neutrons Monitoring System

- Specially designed CMOS sensor for parallel detection of thermal and fast neutrons (IPHC)
- High gamma transparency for measurements in mix gamma/neutron fields
- Compact (out/in-box measurements) and easy to use (real-time, low power, autonomous)

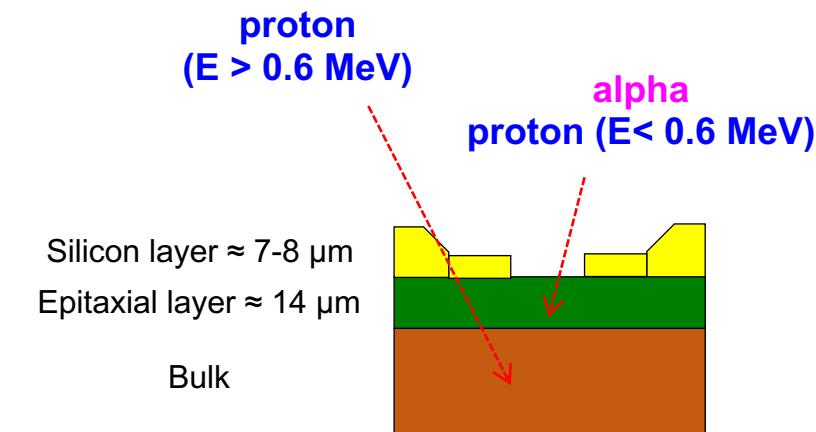


Neutrons are converted into:

- protons (n_{fast} , PE)
- 1.4 MeV alpha particles (n_{therm} , ^{10}B)

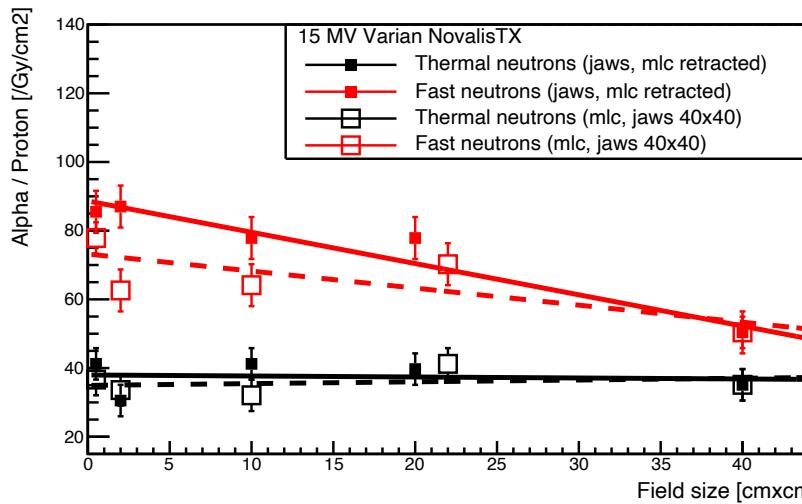


[N. Arbor et al., NIM A 888 (2018)]

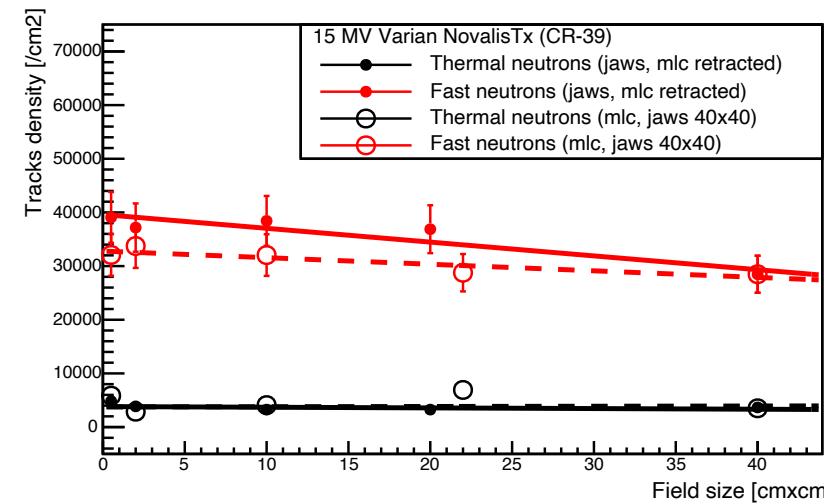


Online Neutrons Monitoring System

- 1st tests in radiotherapy room (photo-neutrons from 15 MV Varian NovalisTx)
- Similar relative variations registered with CMOS sensors and CR-39



Neutron production vs field size
(CMOS data – 15 MV NovalisTx)



Neutron production vs field size
(CR-39 data – 15 MV NovalisTx)

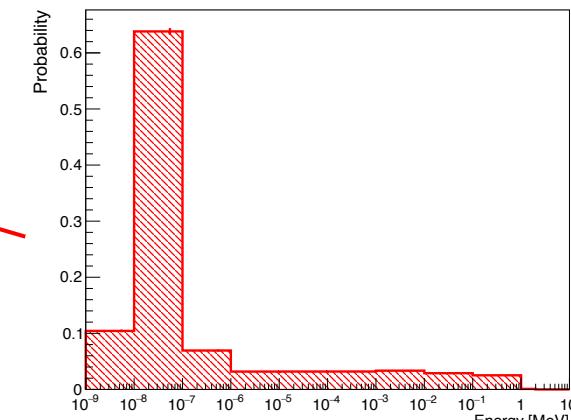
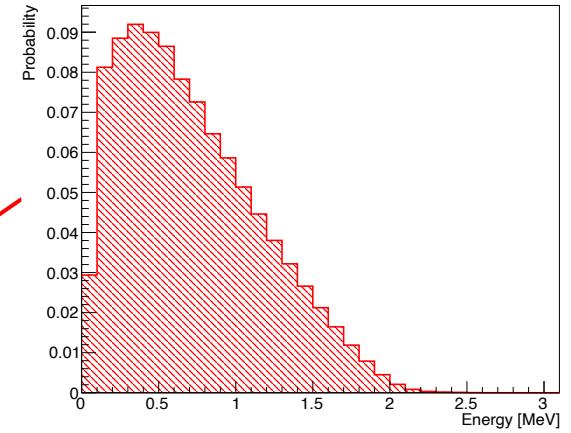
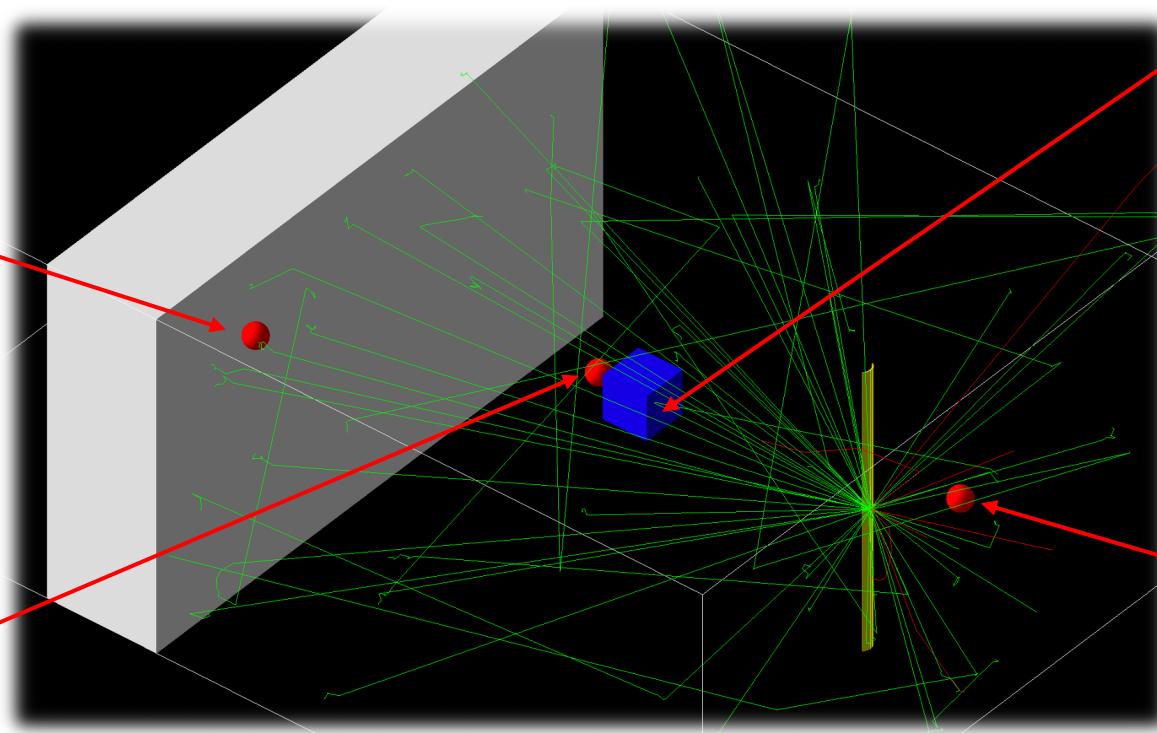
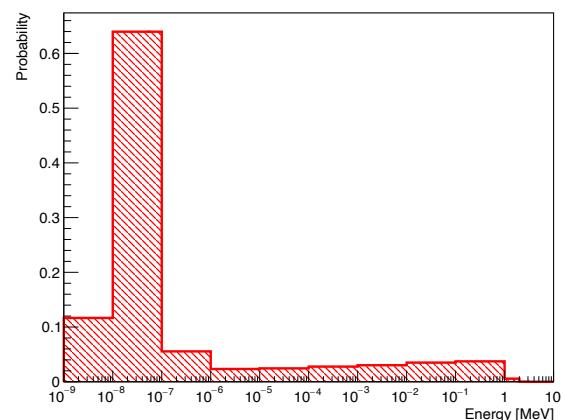
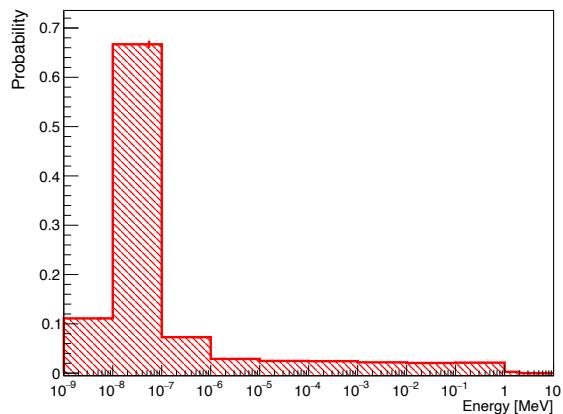
[N. Arbor et al., Phys. Med. Biol. 62 (2017)]

⇒ On-going tests at Aerial/feerix® irradiation facility



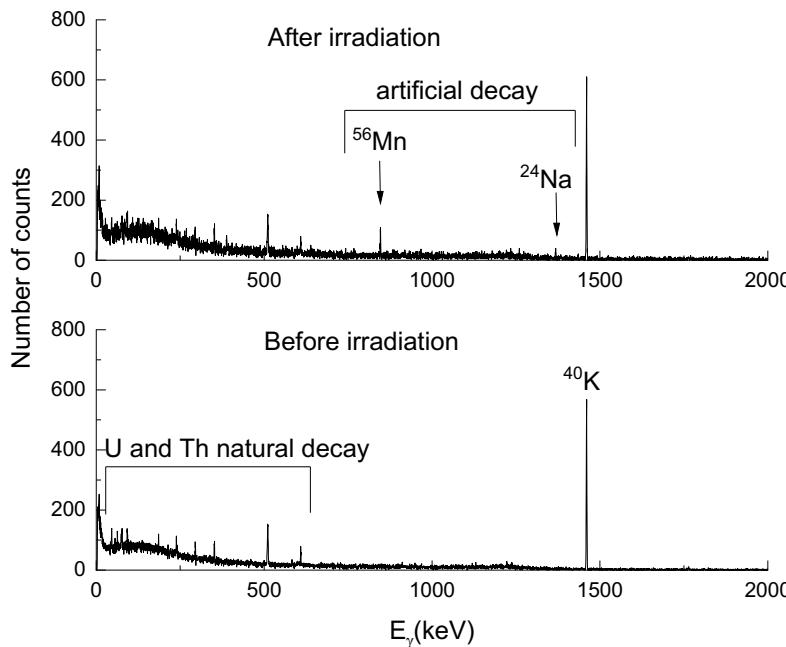
Online Neutrons Monitoring System

- Compute 3D neutron maps using GATE Monte Carlo software
- Define interesting experimental control points (fast / thermal neutrons)



Activations calculations

- Radionuclides calculated from GATE photo-neutron distributions and sample geometry/composition
- Two methods: pre-computed MC database (GATE) or analytical calculations (FISPACT-II)
- Partial validation using gamma spectrometry, estimation of all radionuclides (α, β, γ) using calculations



Radionuclide	Period	Emission	γ -spectrometry	Simulation
$^{87\text{m}}\text{Sr}$	2.8 h	γ	Yes	No
$^{135\text{m}}\text{Ba}$	1.2 d	γ	Yes	No
^{24}Na	15.0 h	β, γ	Yes	Yes
^{42}K	12.4 h	β, γ	Yes	No
^{56}Mn	2.6 h	β, γ	Yes	Yes
^{14}C	5 700 y	β	No	Yes
^{32}P	14.3 d	β	No	Yes
^{31}Si	2.6 h	β	No	Yes

7 MV X-ray irradiation, 14 kGy, Rabbit food

Conclusion

- Reference publications conclude that radioactivity induced by X-rays irradiation processes is most likely well below natural radioactivity (*IAEA-TECDOC-1287 (2002)*), but:

" [...] as the neutron flux depends on many design parameters that may not have been anticipated in these estimates, the above calculations, estimates and recommendations should only serve as rough guide." (IAEA-TECDOC-1287)

- Lack of industrial solutions to fully estimate/control the potentially induced radioactivity

⇒ **developement of a hybrid tool combining Monte Carlo calculations and photo-neutrons monitoring**

- GATE Monte Carlo calculations are validated/normalized in two steps:
 - thermal and fast photo-neutron fields using CMOS sensors for monitoring around and inside samples
 - activation using gamma spectrometry (low-level performance with anti-Compton device)

⇒ **On-going tests at Aerial/feerix® facility to validate a full protocol
compliant with industrial constraints**



Thank you



INTERNATIONAL CONFERENCE ON
**ACCELERATORS FOR RESEARCH
AND SUSTAINABLE DEVELOPMENT**
From good practices towards socioeconomic impact

