Simβ-AD study: Using active neutron detection and Monte-Carlo codes to improve radioactive waste management from cyclotron facilities

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SATIF-16 - Frascati, Italy - 2024

Why Simβ-AD study?

Radioactive waste management during operation and dismantling of cyclotron facilities is a high-demanding process:

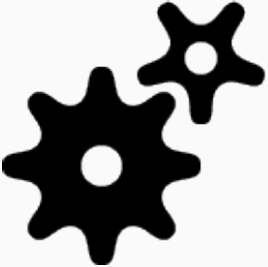
- Safety for temporary disposal
- **Radiological characterization (β-γ spectrocopy)**
- Administrative process
- Financial resources

Current status: Difficulties to provide sufficient radiological characterization, especially for β-only radionuclides (Difficult-To-Measure), prevented radioactive waste to be sent to dedicated disposal

Monte-Carlo used to assess neutron fluences $\Longleftrightarrow$ Results validated by experimental measurements

$\Longrightarrow$ Definition of correlation factors $R_{\frac{DTM}{ETM}}$ $\Longrightarrow$ Improvement of the radioactive waste management

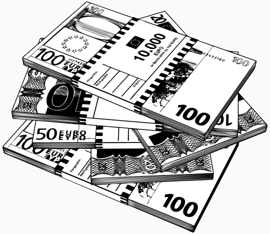
Simβ-AD: Industrial methodology to characterise radioactive waste for cyclotrons



Reliability (Simulation + Detection)

Minimal Impact during the exploitation of the accelerators

Optimization of the Radioactive Waste Management



Cost effective

Simβ-AD Consortium

CNRS associated with the two companies, IBA and TRAD, gathering their expertise and experiences

Project financed by FRANCE2030 Program piloted by BPiFrance and ANDRA

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Liberté
Égalité
Fraternité

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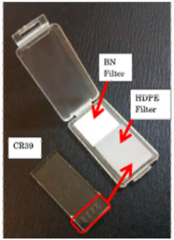
Numerical simulations

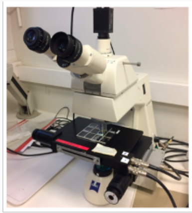
- Benchmarking of Monte-Carlo codes/Cross-Section Library
- Numerical simulations on various cyclotrons facilities
- Irradiation of Passive Detectors
- Radiological characterization of existing radioactive waste

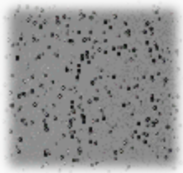
FLUKA MCNP6 GEANT4 A SIMULATION TOOLKIT

PHITS Particle and Heavy Ion Transport code System GATE RayXpert

- Goal is to make a mapping of the irradiation room around particle accelerator
- Reference detectors: Solid Nuclear Track Detectors (SNTD)







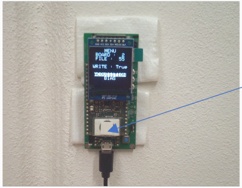
✗ Single use
✗ No real-time
✗ Time consuming

Simβ-AD study: Working Package 2
Real-Time and Compact Active Detectors Development

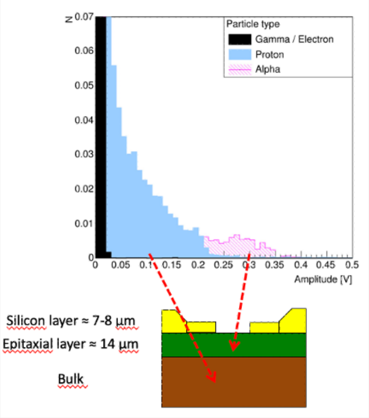
- Development of a 4D neutron monitoring system:

→ CMOS sensor network (3D - space)

→ Real-time monitoring (1D - time)



CMOS sensor + ^{10}B/PE converter

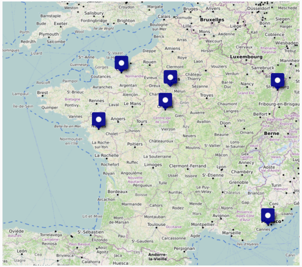


Working Package 3
Simβ-AD Methodology Valorization

- Use of the 4D neutron monitoring system in cyclotron made by IBA
- Simβ-AD methodology +

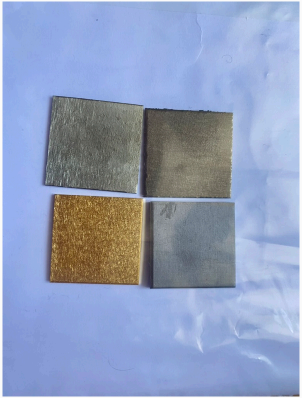
Simβ-AD study: Cyclotrons Panel

Facilities	Beam	E_{max} (MeV)	I_{max} (μA)	Targets
CYRCé	p	25	300	L/S
CYCERON	p/d	18/9	80-50	L/G/S
CEMHTI	p/d/α	38/25/50	40/40/15	Irradiation
ARRONAX	p/d/α	70/30/68	750/80/35	L/S
CPO	p	235	600.10^{-3}	Protontherapy
CAL	p	65/235		Protontherapy
TBD				



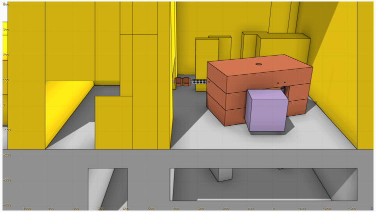
Passive detectors irradiation

- Done for three facilities (CEMHTI-CYRCé-CYCERON)
- Four materials used: Au, Sc, Ta, Tb
- Proton/Deuteron beams for CEMHTI
- Proton beam and ^{18}F yield for CYRCé
- Proton beam and ^{18}F/^{11}C (gas) for CYCERON

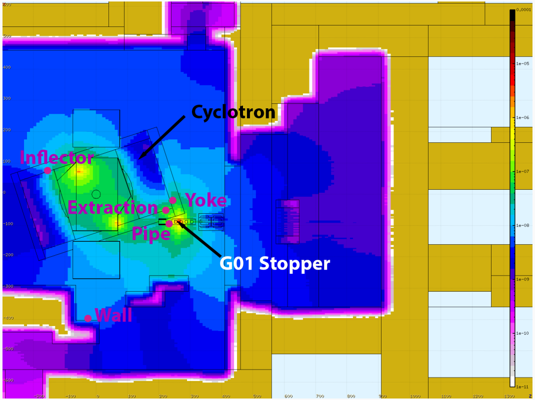


Simβ-AD study: CEMHTI - Proton Beam

- Two loss points: Inflector and G01 Stopper
- 5 Activation Foils matrixes used
- Beam parameters: proton, 25 μSv, 5 h

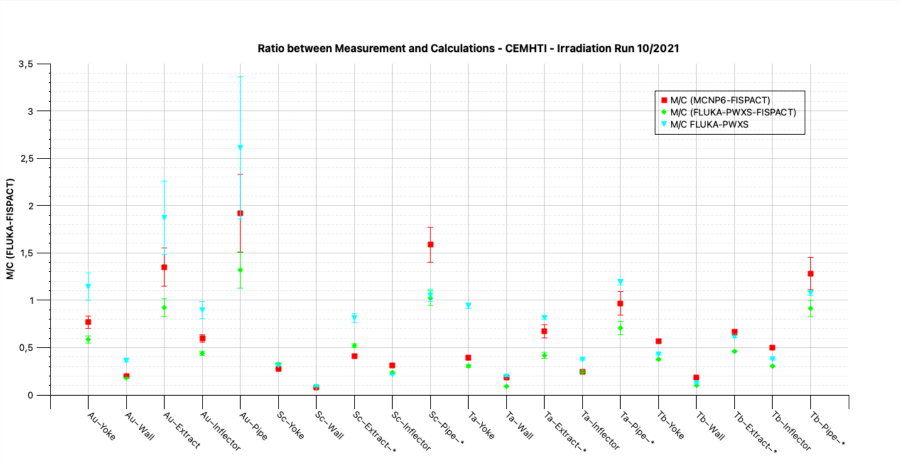


FLUKA Model - View with FLAIR



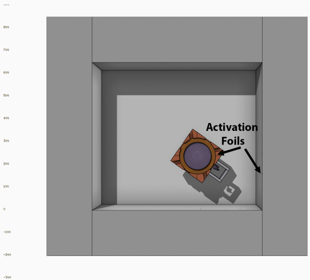
Location of the different activation foils and the beam stopper - Neutron Fluence in $n.cm^{-2}.pp^{-1}$

Simβ-AD study: CEMHTI-Proton Beam



Ratio between activity measured by γ-spectroscopy at the end of irradiation and the activity calculated using neutron fluences produced by Monte-Carlo Codes

- Proton beam: 16.5 MeV -35 μA
- Activation Foils in two locations
  - Wall in front of the target
  - Yoke at the side of the target



Location of the activation foils

Simβ-AD study: CYRCé - Proton Beam

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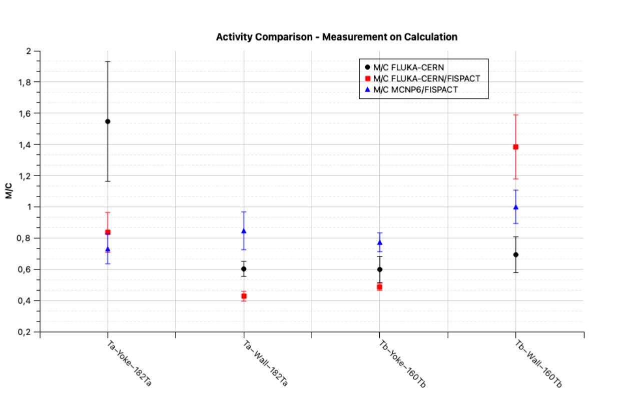
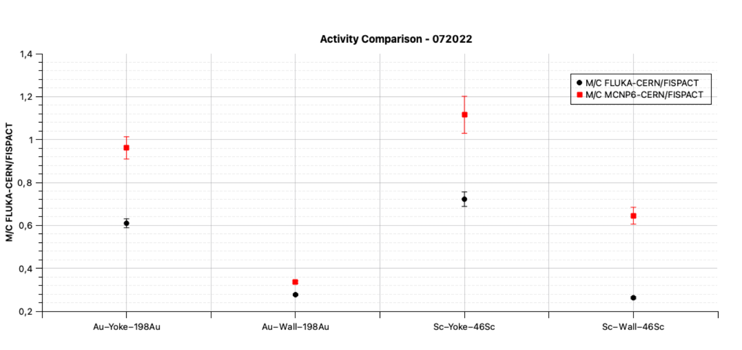
- First irradiation run (04/2021) : 2 groups of two different materials (Ta, Tb).
- Irradiation on ^{18}O target only



Ratio between activity measured by γ-spectroscopy at the end of irradiation and the activity calculated using neutron fluences produced by Monte-Carlo Codes

Simβ-AD study: CYRCé - Proton Beam

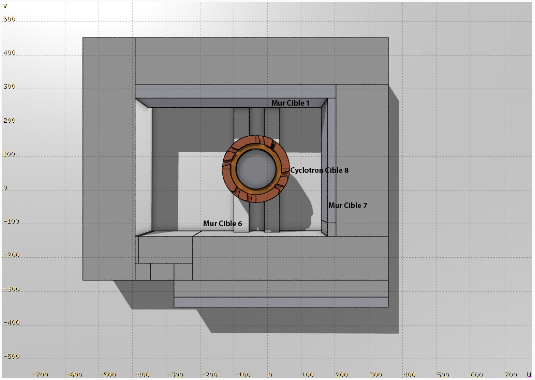
- Second irradiation run (07/2022) : 2 groups of two different materials (Au, Sc).
- Irradiation on ^{18}O or ^{16}O targets



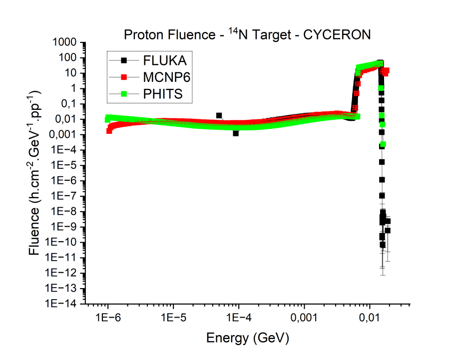
Ratio between activity measured by γ-spectroscopy at the end of irradiation and the activity calculated using neutron fluences produced by Monte-Carlo Codes

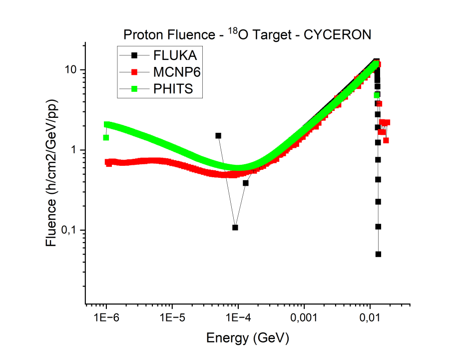
Simβ-AD study: CYCERON
Proton beam for $^{18}F/^{11}C$ yield

- Four Activation Foils matrix during irradiation runs made between June and July of 2023
- Irradiations on $^{14}N_2$ gaseous target or $H_2{}^{18}O$ liquid target
- Proton Beam, 18 MeV (15 – 16 MeV with degrader for ^{14}N)



Simβ-AD study: CYCERON
Proton beam for $^{18}F/^{11}C$ yield





Very similar trends for protons with energy superior to 1 MeV, ROI for nuclear reactions.

Simβ-AD study:CYCERON
Proton beam for $^{18}F/^{11}C$ yield

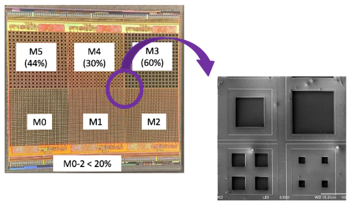
^{18}**F Yield in Liquid Target (GBq EOB)** (2.3 ml,16 μAh)			
FLUKA	MCNP6	PHITS	Theoretical (IBA)
41.6	40.5	39.1	44.7
^{11}**C Yield in Gaseous Target (GBq EOB)**(55 mL, 30 μAh)			
FLUKA	MCNP6	PHITS	Theoretical (IBA)
173	183	181	121

^{18}F Yield at EOB are in good agreement with theoretical values (7-12,5%).

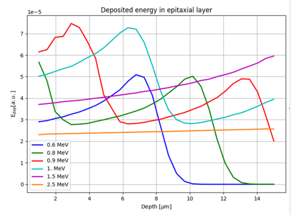
For gaseous target, density uncertainty could lead to some discrepancy between calculated, theoretical and experimental values.

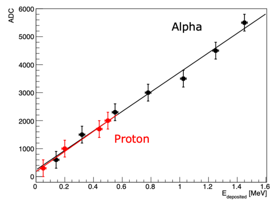
AlphaBeast: New version of the CMOS neutron counting system

- New sensor designed in 2022 (IPHC) with 6 different diodes configurations



- Proton and Alpha detection calibration (based on charge collection modeling)





AlphaBeast: New version of the CMOS neutron counting system

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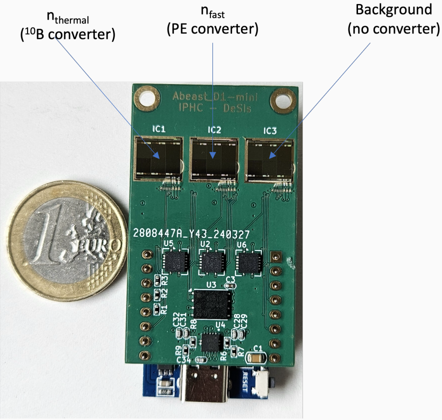
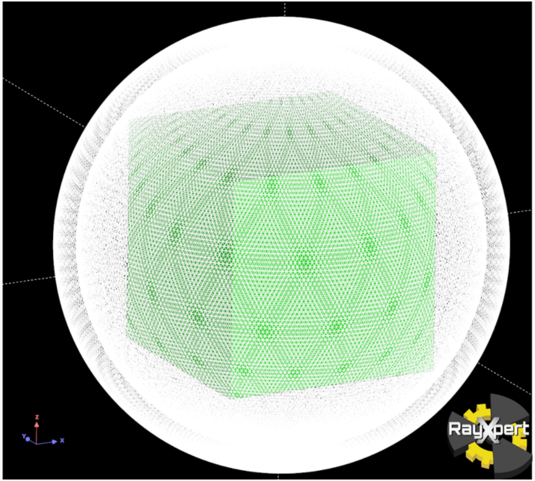
- Autonomous sensor (internal threshold, battery, wireless data communication)



Intercomparisons on simplified models

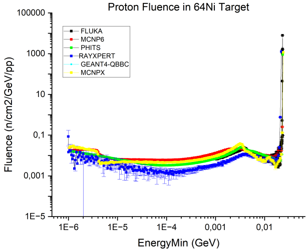
- Intercomparisons of different codes on simplified models of target
- Proton beam
- ^{18}O Liquid Target ($1\,\mathrm{cm}^3$, E_h=18 MeV)
- ^{64}Ni Solid Target ($2.32 \times 10^{-3}\,\mathrm{cm}^3$, E_h=23.4 MeV)
- ^{89}Y Solid Target ($1.38 \times 10^{-2}\,\mathrm{cm}^3$, E_h=24.3 MeV)
- Sphere of air surrounding the target (1 cm radius, 1 mm width)

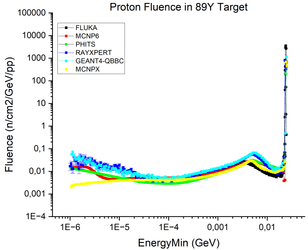


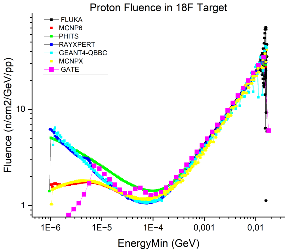
Model made with RayXpert

Intercomparisons on simplified models

- General trends are well reproduced by the different codes, especially for energy interesting for radionuclides yield energies

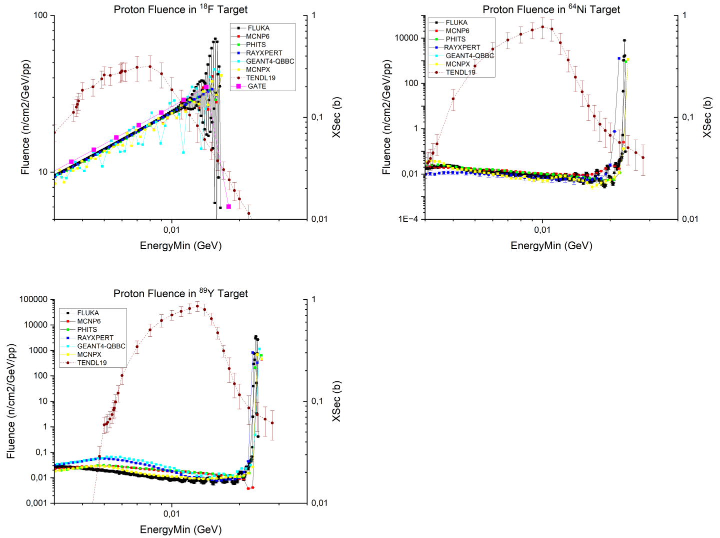






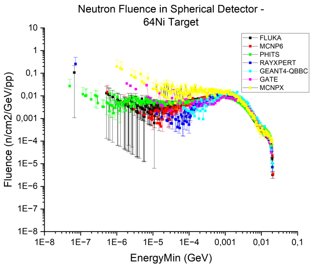
Intercomparisons on simplified models

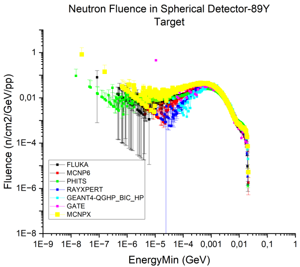
- General trends are well reproduced by the different codes, especially for energy interesting for radionuclides yield energies
- RayXpert development version: Critical physical parameters identified (e^-_{step}, h_{step} and e^-_{cut})

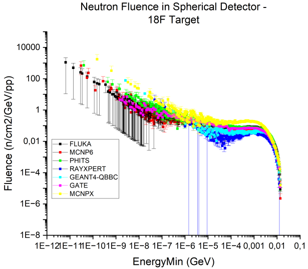


Intercomparisons on simplified models

General trends are well reproduced by the different codes, with some differences in thermal energies.

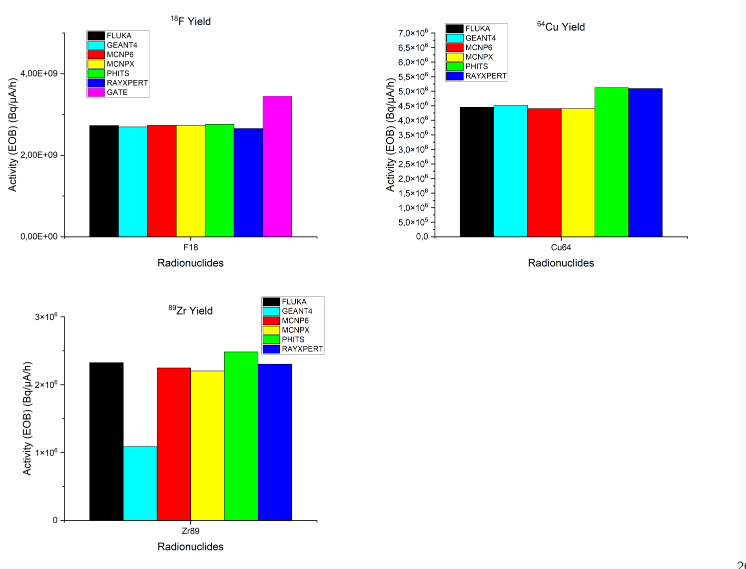






Intercomparisons on simplified models

- Activity of the main radionuclide on each target calculated using FISPACT-II + Proton fluences calculated with the different codes
- RayXpert results in good agreement with other codes



AdA connected to LINAC at Orsay in 1963 (A real adventure to transfer this donut!)

> *But we had one accident and one incident, luckily both with happy endings. Bruno [Touschek] wanted to "personally" test the stability of the truck carrying AdA [...] and he knocked down a street lamp because of his inexperience in driving such a large vehicle. Then, when the truck arrived at the Italian-French border, the driver phoned us very excitedly because the customs officers wanted "to inspect the inside of the donut." Thanks to the Italian Minister of Foreign Affairs, who became alarmed by a call from Felice Ippolito, we convinced the customs officers that the donut contained an unprecedented high vacuum.*

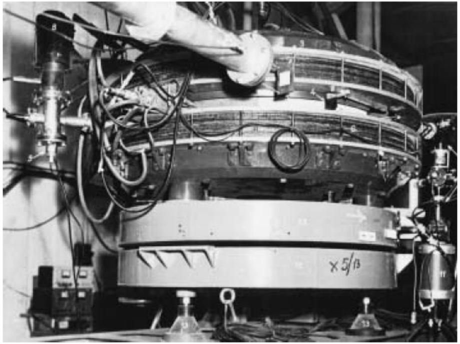


Fig. 11. AdA on the rotating and translating platform at Orsay. The injector beam channel is visible on the left. Courtesy of Jacques Haïssinski.

Intercomparisons on simplified models

- FLUKA (last version)
  - Neutrons Xsec: ENDF VIII-O/JEFF3.3
  - 95% Low Energy neutrons survivability
  - FLUKAFIX for protons (.01%ΔE)
- MCNP6 (MCNP6.3)
  - Neutrons Xsec: TENDL21
  - Protons Xsec: TENDL19
- PHITS (v3.341)
  - Neutrons and Protons XSec: TENDL21
  - Charged particles $\frac{dE}{dx}$: ATIMA
- MCNPX (V2.71)
  - Neutrons XSec: ENDFVII-0 or models
  - Protons XSec: TENDL19

RayXpert	Step Limit		Cut Threshold (keV)		
	e^-/e^+	h	e^-	γ	e^+
h	1 μm	0.01 μm	1	100	100
n	1 mm	1 mm	100	100	100

Physics List: QBBC

	Step Limit		Cut Threshold			
GEANT4	e^-/e^+	h	e^-	γ	e^+	h
h/n	1 μm	0.1 μm	1 mm	1 km	1 km	0

Physics List: QBBC

- GATE
  - Physics List: QGSP_BIC_AIIHP
  - Protons XSec: TENDL19