



Enhancements in FLUKA for Radiation Protection at Synchrotron Facilities

12th International Workshop on Radiation Safety
at Synchrotron Radiation Sources — RadSynch25
CNPEM, Campinas, Brazil

June, 24–27, 2025

Ricardo S. Augusto and Konstantin Batkov for the FLUKA collaboration



- 1 Introduction
- 2 Photonuclear interactions
- 3 Synchrotron radiation generation
- 4 X-ray reflectivity
- 5 Pointwise and groupwise neutron transport
- 6 Conclusions



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- The very first version of FLUKA was developed in the early 1970s by **J. Ranft** (East Germany).
- The modern FLUKA began in 1989 in INFN Milan by **A. Fassò, A. Ferrari, J. Ranft, and P.R. Sala**.
- CERN joined the FLUKA Collaboration in 2003.
- The collaboration with CERN ended in 2019.
- At present, **FLUKA continues to be actively developed** by the **FLUKA Collaboration**, which includes two of its original authors, **A. Ferrari** and **P.R. Sala**.
 - **A. Fassò** has retired.
 - **J. Ranft** passed away in 2018.

Recent paper

The FLUKA code: Overview and new developments



EPJ Nuclear Sci. Technol. **10**, 16 (2024)
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<https://doi.org/10.1051/epjn/2024015>



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Status and advances of Monte Carlo codes for particle transport simulation,
edited by Andrea Zoia, Cheikh Diop and Cyrille de Saint Jean

REGULAR ARTICLE

OPEN ACCESS

The FLUKA code: Overview and new developments

The FLUKA Collaboration: Francesca Ballarini^{1,2}, Konstantin Batkov³, Giuseppe Battistoni⁴, Maria Giuseppina Bisogni^{5,6}, Till T. Böhlen⁷, Mauro Campanella⁴, Mario P. Carante^{1,2}, Daiyuan Chen⁸, Angelica De Gregorio⁹, Pavel V. Degtiarenko¹⁰, Pedro De la Torre Luque¹¹, Ricardo dos Santos Augusto¹², Ralph Engel¹³, Alberto Fassò¹⁵, Anatoli Fedynitch¹⁶, Alfredo Ferrari^{13,14}, Anna Ferrari¹⁷, Gaia Franciosini¹⁸, Aafke Christine Kraan⁶, Julie Lascaud¹⁹, Wenxin Li²⁰, Juntao Liu²⁰, Zhiyi Liu²⁰, Giuseppe Magro²¹, Andrea Mairani^{22,21}, Ilaria Mattei⁴, Mario N. Mazziotta²³, Maria C. Morone^{24,25}, Stefan E. Müller¹⁷, Silvia Muraro⁴, Pablo G. Ortega²⁶, Katia Parodi¹⁹, Vincenzo Patera^{18,27}, Lawrence S. Pinsky²⁸, Ricardo L. Ramos², Johannes Ranft^{29,†}, Valeria Rosso^{5,6}, Paola R. Sala^{30,*,*}, Mario Santana Leitner³¹, Giancarlo Sportelli^{5,6}, Thomas Tessonnier²², Kristian S. Ytre-Hauge³², and Lorenzo Zana¹⁰

■ The FLUKA Collaboration

- representing 32 institutes
across 10 countries

■ 63 pages of documented physics improvements since 2019

- many benchmarked against measurements
- only a small subset relevant to **synchrotron radiation facilities** is highlighted in this presentation

Recent paper

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■ The FLUKA Collaboration

- representing 32 institutes across 10 countries
- 3 collaborators attending this conference

■ 63 pages of documented physics improvements since 2019

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6th FLUKA Advanced Course

May 25–31, 2025, Lanzhou, China



■ **Next course:** Dresden, Germany, in early 2026



- **Important:** Within a few weeks, we will launch a new, modern website and change its address from fluka.org to fluka.eu

The screenshot shows the FLUKA website homepage with a green header. The FLUKA logo is on the left, and the INFN logo is on the right. A navigation bar contains links: Fluka >>, Documentation >>, Download, My Account, Tools >>, Discuss >>, and Team >>. Below the navigation bar, there are three main sections: 'Quick launch:' with links for Download, Mailing list, Manual Online, Courses, Flair, and Contact us; 'Last version:' with text 'FLUKA 2025.1.1, June 17th 2025 (last respin 2025.1.1) flair-2.3-0f 05-May-2025'; and 'News:' with a release announcement for FLUKA 2025.1.1 dated 17.06.2025. To the right of these sections is a large text block describing FLUKA as a MonteCarlo simulation package, accompanied by two images: a particle detector cross-section and a heatmap. At the bottom, there is a copyright notice '© FLUKA Team 2000–2025' and a link for 'Informativa cookies'. A date stamp 'Last updated: 21st of May, 2010' is visible on the right side of the main content area.



- Advanced Fermi break-up
- Anomalous form-factors in coherent scattering
- Deuterium pre-formation
- Deuterium-tritium fusion neutron source
- Electromagnetic dissociation and electro-nuclear interaction
- Event-by-event correlations
- Extended bremsstrahlung database
- Fission
- Fluence-to-dose conversion coefficients
- Hadronic interaction models
- Hadron-nucleus cross sections
- Hadron-nucleus resonance model
- In-flight nuclei de-excitation
- New hadronization model
- New photon cross-section database
- Nuclear coherent elastic scattering
- Ortho- and para-hydrogen competition for positron annihilation at rest
- Photonuclear interactions and photo-fission
- Pointwise, fully correlated neutron cross sections
- Pointwise thermal neutron scattering kernels
- Pre-equilibrium stage in rQMD and BME
- Synchrotron radiation
- Transport in electric and magnetic fields
- Updated groupwise neutron transport
- X-ray reflectivity



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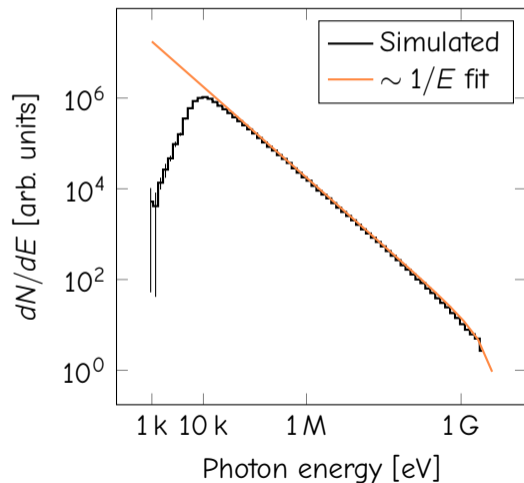
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- At synchrotron facilities, most of photonuclear interactions are generated by **Gas Bremsstrahlung**
- Although relatively low energy, it's **often one of the main sources of radiation**
- High-energy tail above (γ, n) threshold in many materials
- Radiological impact highly dependent on beamline design





Primary Gas Bremsstrahlung

Primary Gas Bremsstrahlung

How to stop it?



- Fully stopping the primary Gas Bremsstrahlung is usually achieved with **bulky and heavy shielding**
 - e.g. Steel or Lead

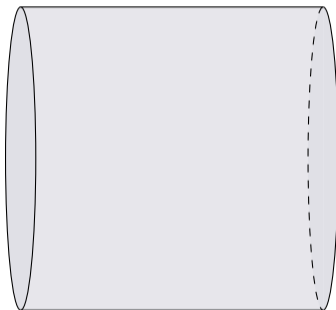
Example: Lead cylinder

Diameter: 20 cm

Length: 20 cm

GB
→

GB stop (Lead cylinder)



Primary Gas Bremsstrahlung

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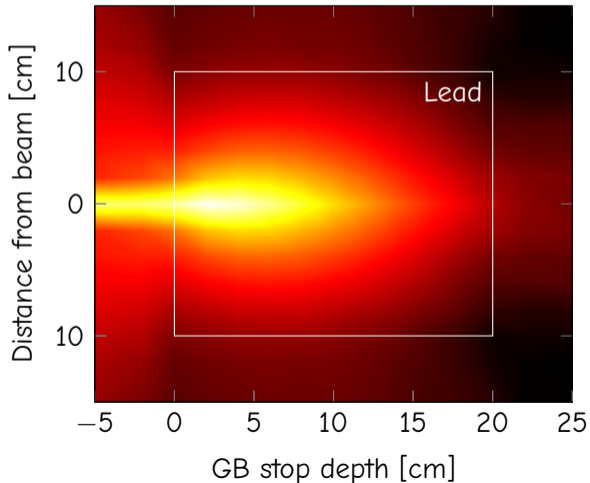
Example: Lead cylinder

Diameter: 20 cm

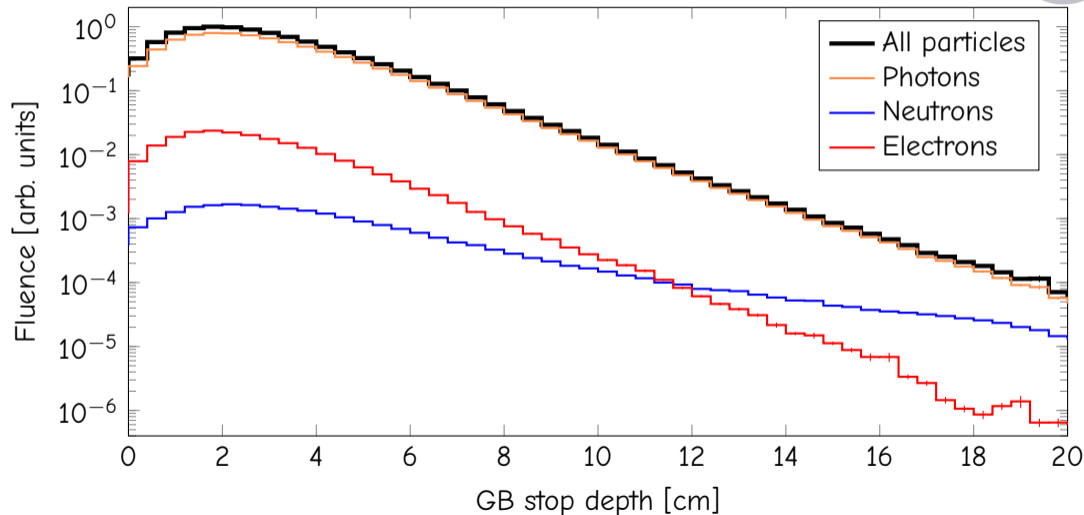
Length: 20 cm

- A few mm wall is never enough

All particle fluence map

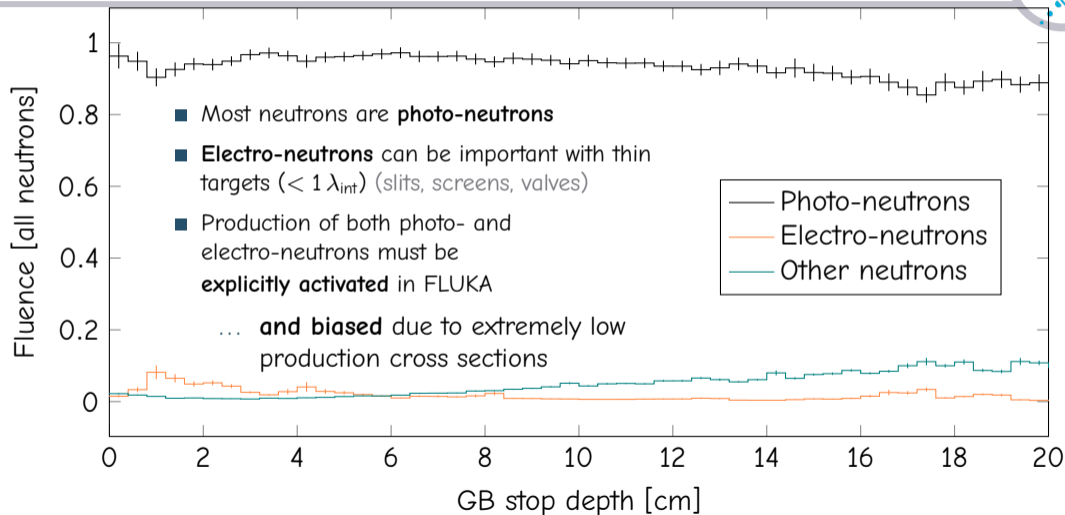
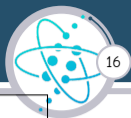


Dominant processes vs shield depth



Dominant processes vs shield depth

Neutrons





Secondary Gas Bremsstrahlung

Secondary Gas Bremsstrahlung

The simplest Optics Hutch geometry



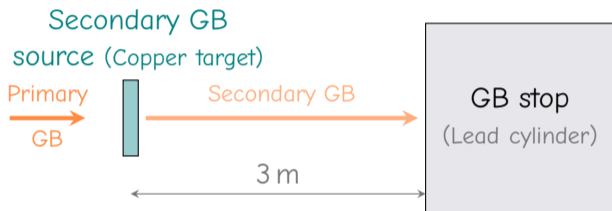
Primary
→
GB

GB stop
(Lead cylinder)

- Axially symmetric geometry
- Primary GB is stopped by the **Lead cylinder**

Secondary Gas Bremsstrahlung

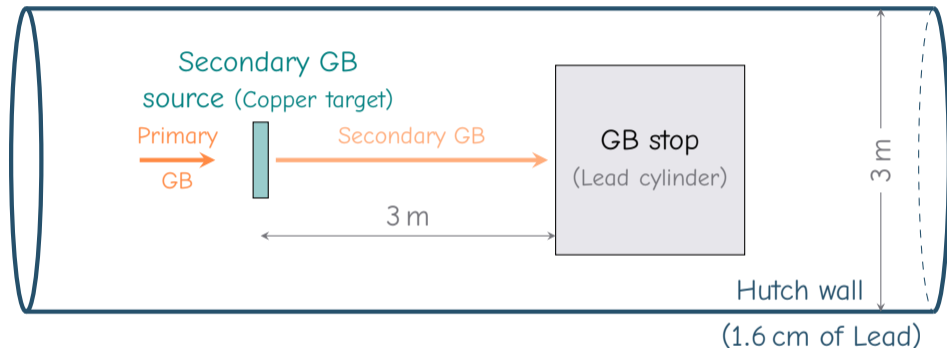
The simplest Optics Hutch geometry



- Axially symmetric geometry
- The **Copper target** scatters the primary GB (mask, slit, valve, pipe etc)

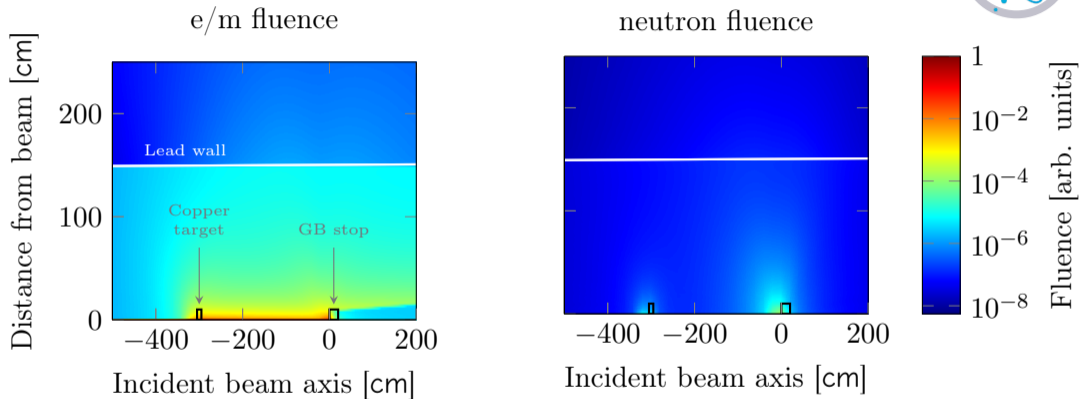
Secondary Gas Bremsstrahlung

The simplest Optics Hutch geometry



- Axially symmetric geometry
- The **Copper target** scatters the primary GB (mask, slit, valve, pipe etc)
- The setup is surrounded by a typical **optics hutch wall**
 - 1.6 cm thick Lead cylinder

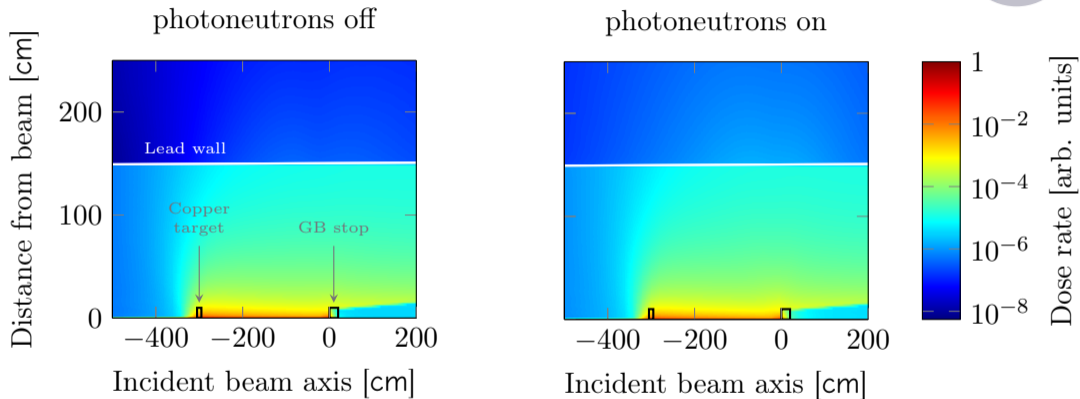
Secondary Gas Bremsstrahlung Fluence maps



- Outside of the hutch wall, **most of the fluence is due to e/m component**, but not due to the neutrons
- The **Lead wall** absorbs part of the e/m component, but it is **almost transparent to neutrons**

Secondary Gas Bremsstrahlung

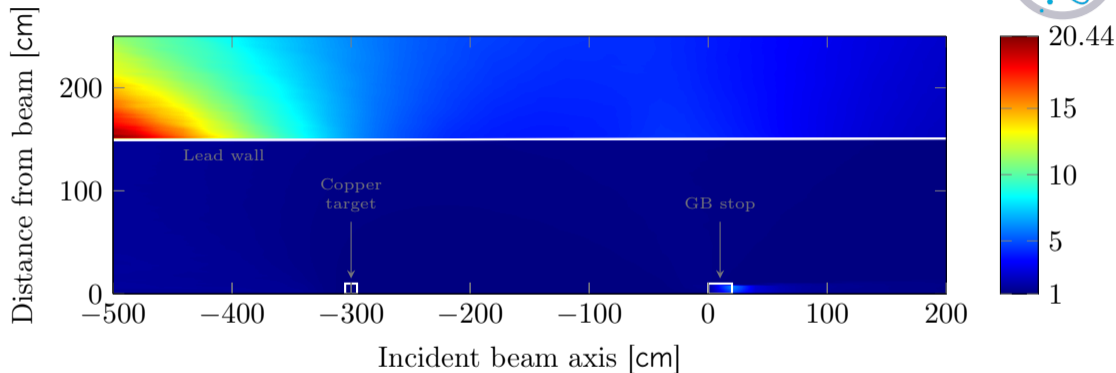
Dose rate maps



- **Photoneutrons** give significant contribution into the **dose rates** outside the hutch walls

Secondary Gas Bremsstrahlung

Ratio photoneutrons on/off

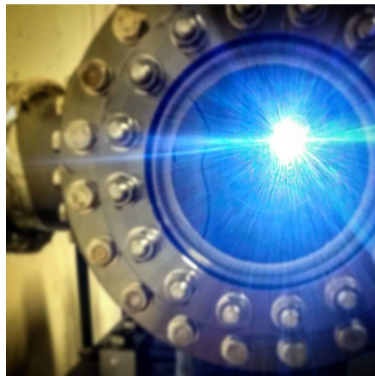


- **Factor-of-few difference** outside the hutch wall
 - ⇒ **accurate photoneutron production and sampling** are essential for shielding design
- **FLUKA's photonuclear cross-sections and models have been thoroughly revised in recent versions**



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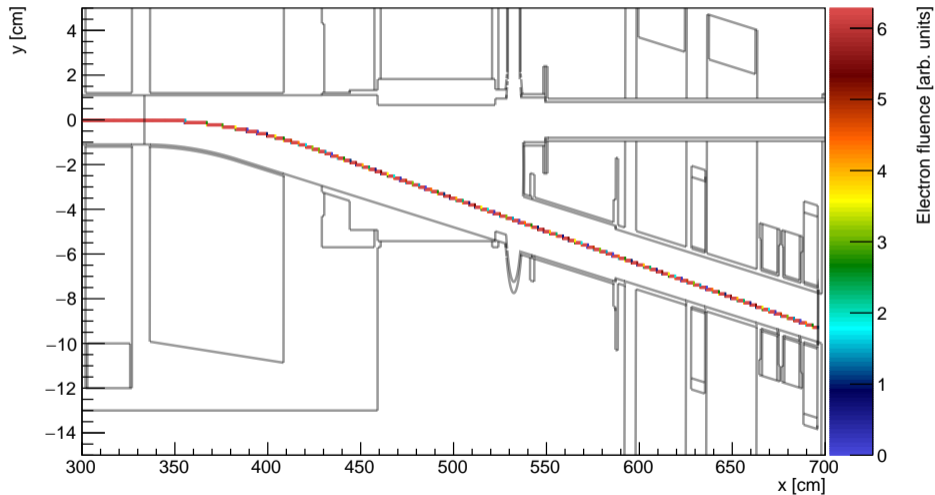
- **Synchrotron radiation emission along particle trajectories** can be explicitly enabled for:
 - Any charged particles
 - Any magnetic field
- New model overcomes limitations of the original model:
 - Previously limited to ultra-relativistic particles
 - Required pitch angles close to 90°
- New model supports:
 - **Moderately relativistic particles** (in transverse plane to the field)
 - **Arbitrary pitch angles**
- See details in Mario's presentation later today



[Foto: Johanna Paulsson]

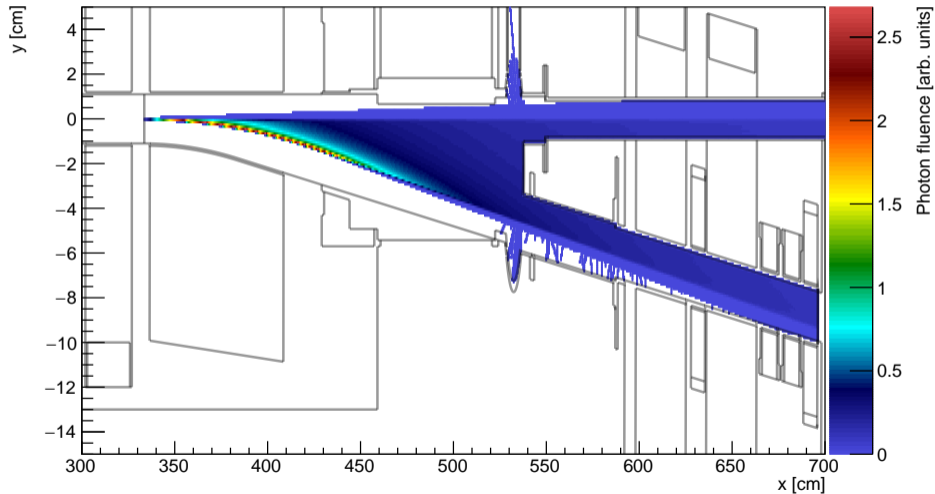
Synchrotron radiation generation

Incident electrons



Synchrotron radiation generation

Synchrotron photons





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FLUKA \geq 2024.1 can handle **X-ray reflectivity** at interfaces between materials.

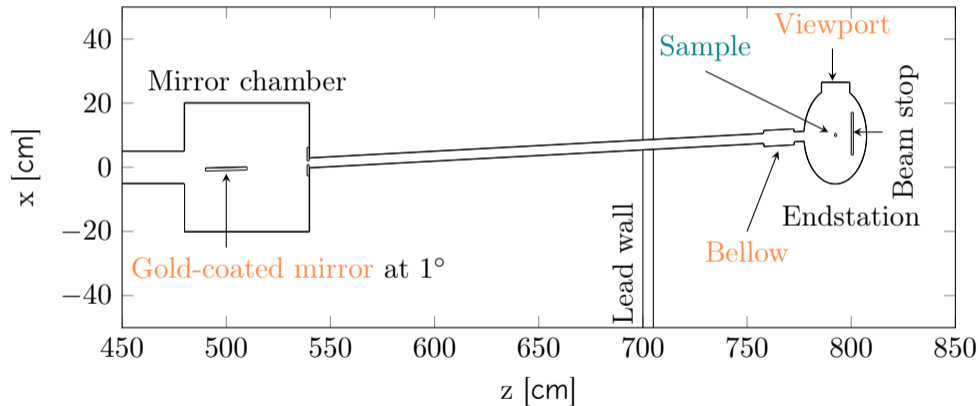
This feature allows the user to:

- Reproduce the transport of photons **within a Monte Carlo framework**, taking advantage of the FLUKA geometry, in-built estimators, etc.
- Although much **slower than analytical codes** it can be helpful, for instance, to visualise selected radiological scenarios in light sources with conservative optical assumptions.
- Multiple single-layer mirror reflective materials can be defined in this manner and multilayer mirror reflections can also be performed, but using a dedicated user routine.

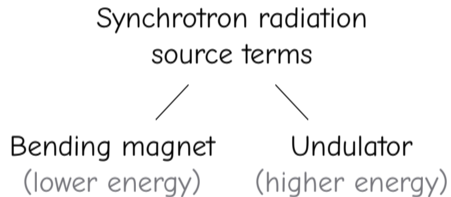


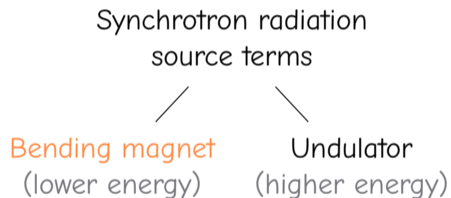
Toy Geometry

Geometry



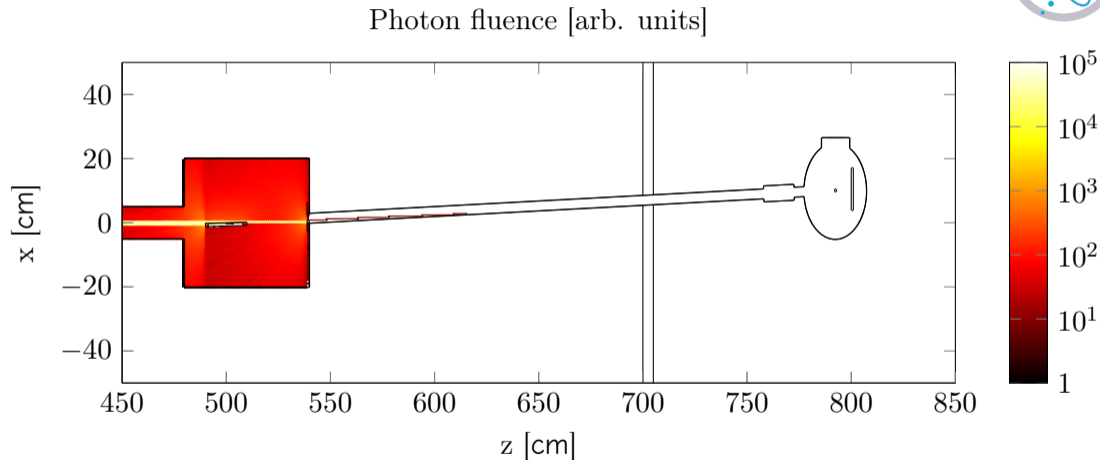
- 2 mm steel except thinner bellow and viewport







Standard FLUKA run
(without x-ray reflectivity)



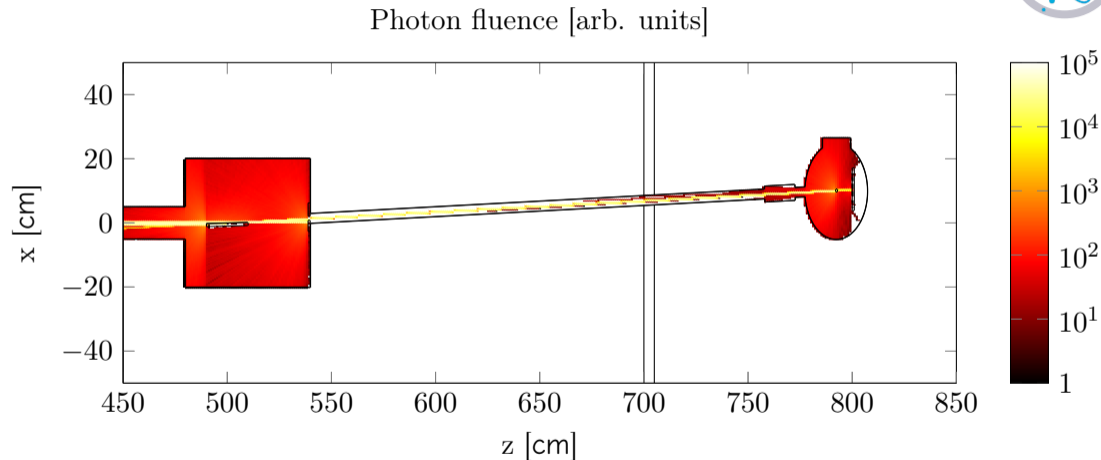
- Almost **no photons** beyond the mirror chamber (despite huge statistics)
- Standard approach: three-step calculation



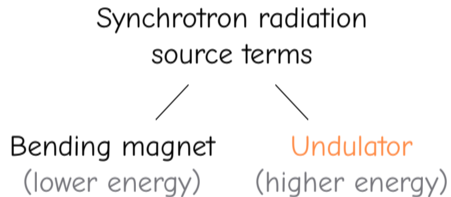
Fiat Lux!

X-ray reflectivity

With reflection



- Plenty of reflected photons inside endstation (same statistics)



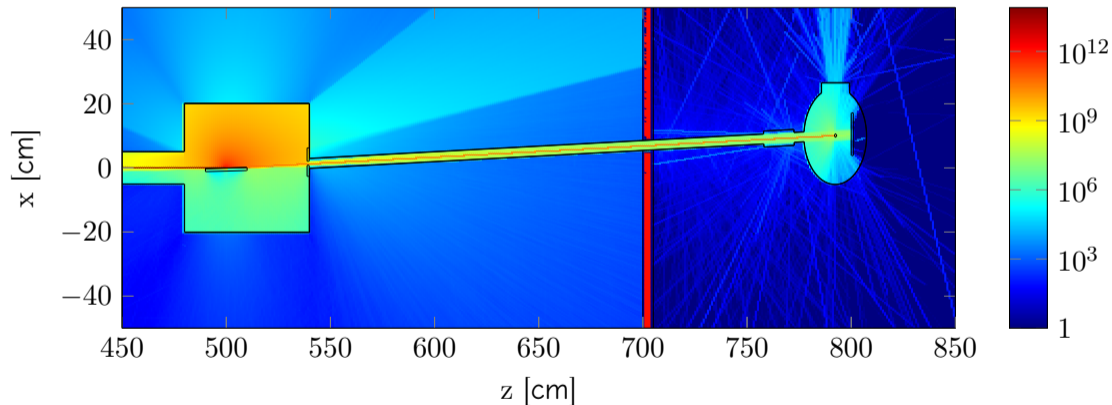
X-ray reflectivity

Undulator source with reflection



39

Dose rate [arb. units]



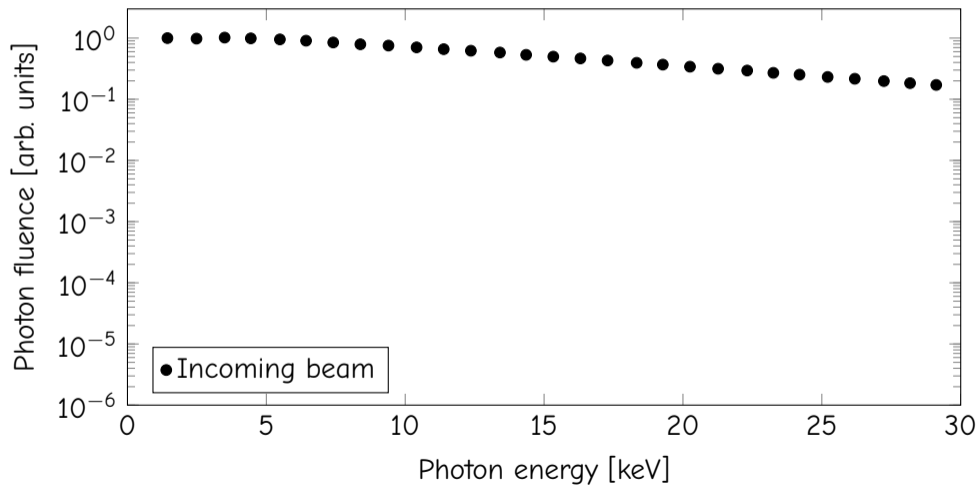
- Radiation leaks from components with underspecified shielding



Benchmarks

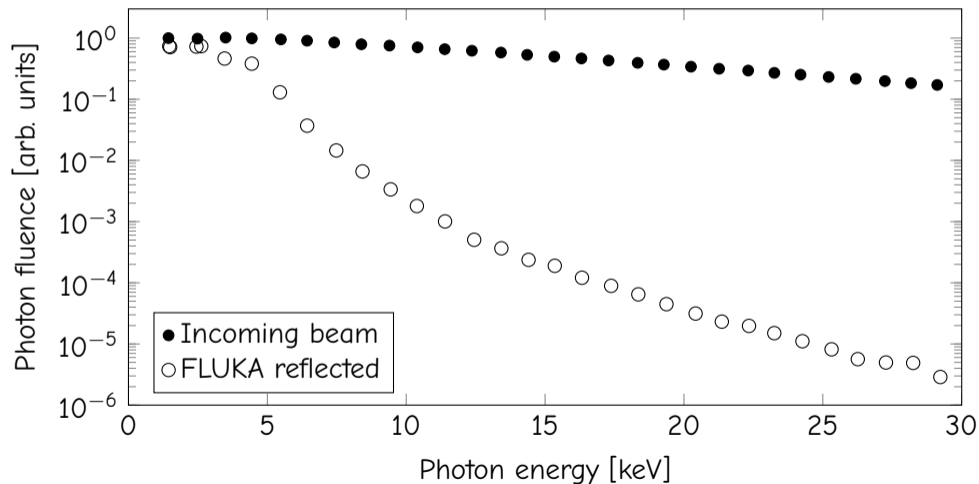
X-ray reflectivity

Benchmarks: photon spectra before and after reflection



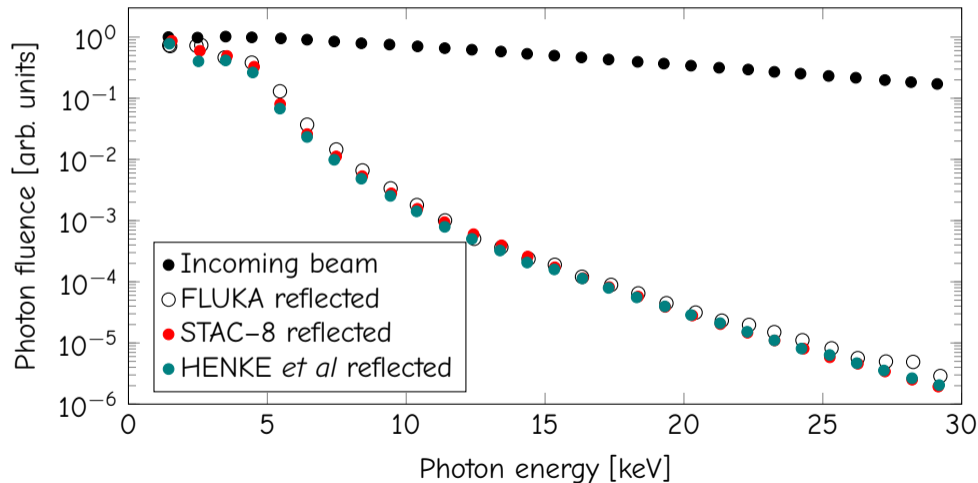
X-ray reflectivity

Benchmarks: photon spectra before and after reflection





X-ray reflectivity

Benchmarks: photon spectra before and after reflection





References for the analytic tools:

-  Yoshihiro Asano and Nobuo Sasamoto
Development of shielding design code for synchrotron radiation beam line
Radiation Physics and Chemistry, **44**(1–2), 133–137 (1994)
[https://doi.org/10.1016/0969-806X\(94\)90119-8](https://doi.org/10.1016/0969-806X(94)90119-8)
-  B. L. Henke, E. M. Gullikson, J. C. Davis
X-Ray Interactions: Photoabsorption, Scattering, Transmission, and Reflection at
 $E=50-30\,000$ eV, $Z=1-92$
Atomic Data and Nuclear Data Tables **54**(2), 181–342 (1993)
<https://doi.org/10.1006/adnd.1993.1013>



By the way: Neutron reflectivity



FLUKA \geq 2025.1 can **reflect neutrons** from supermirror surfaces

- The user must input the supermirror reflection curve
 - and use the appropriate $S(\alpha, \beta)$ scattering kernels
- Similar functionality as e.g. [McStas](#) or [VITESS](#)
 - significantly slower — don't attempt using it for neutron guide optimisation
 - but simulates interactions with matter
- Application:
 - shielding calculations for instruments at neutron sources



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FLUKA is one of the few codes that offer **fully correlated pointwise neutron transport**. This is a highly powerful and precise capability. However:

- It is rarely required at synchrotron light sources.
 - Avoid overusing it unless not truly necessary, as it reduces the computational efficiency ($\delta\sqrt{T}$) – typically by $\sim 30\%$ and potentially up to a factor of few.
- For most problems, using groupwise cross sections with self-shielding correction is enough

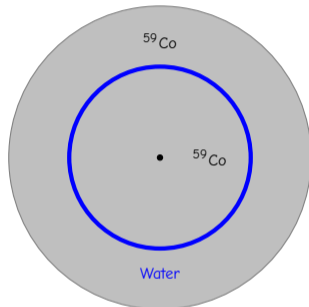


Example: A comparison between pointwise
and groupwise transport



Thick ^{59}Co target:

- Inner layer: $R=40$ cm
- Mid layer: 2 cm water
 - to populate thermal neutron region
- Outer layer: $R=60$ cm



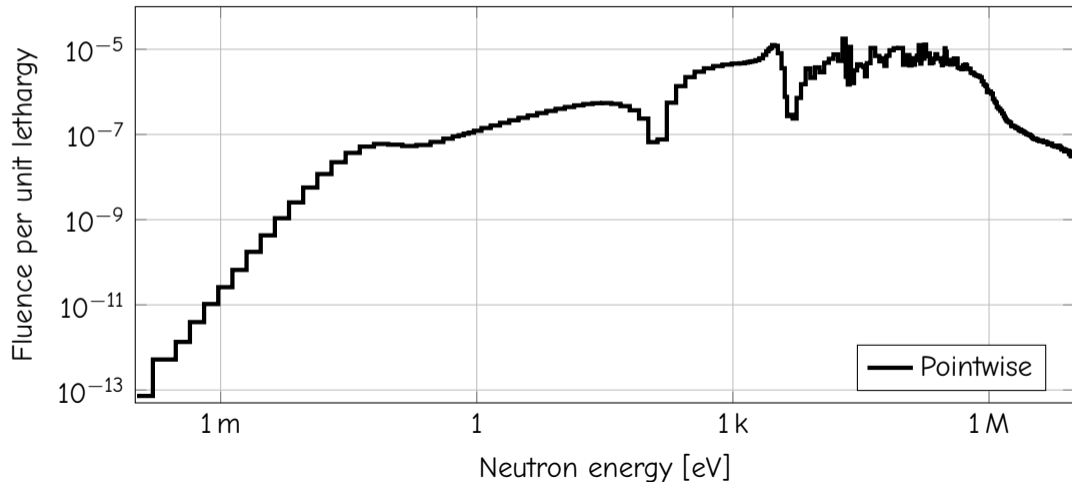
- Source: isotropic 20 MeV neutrons injected at the centre of the sphere
- Scoring: neutron track-length fluence spectra inside the outer Co layer
 - estimator: USRTRACK

Pointwise and groupwise neutron transport

Example: Neutron spectrum



20 MeV neutrons on ^{59}Co

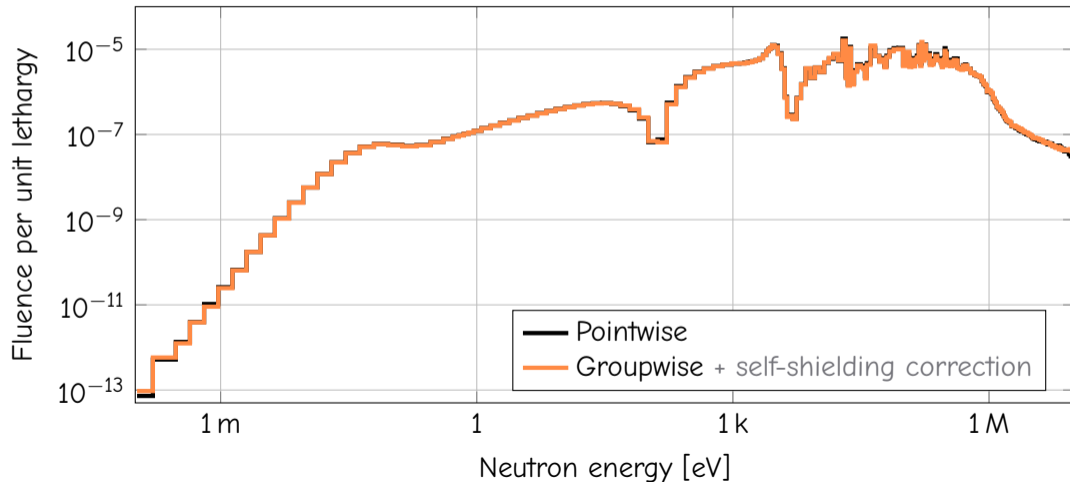


Pointwise and groupwise neutron transport

Example: Neutron spectrum



20 MeV neutrons on ^{59}Co

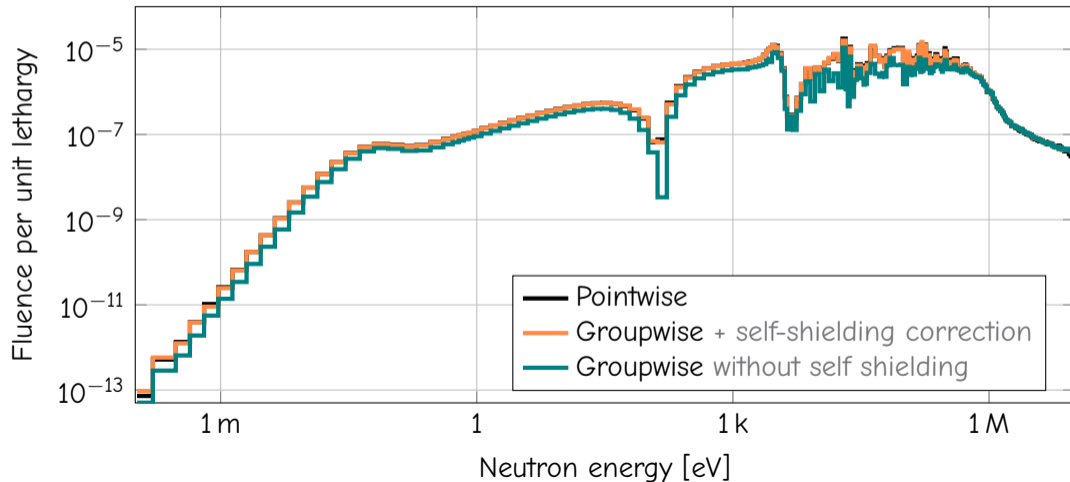


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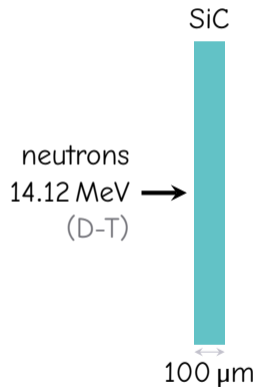




Fully correlated pointwise cross sections

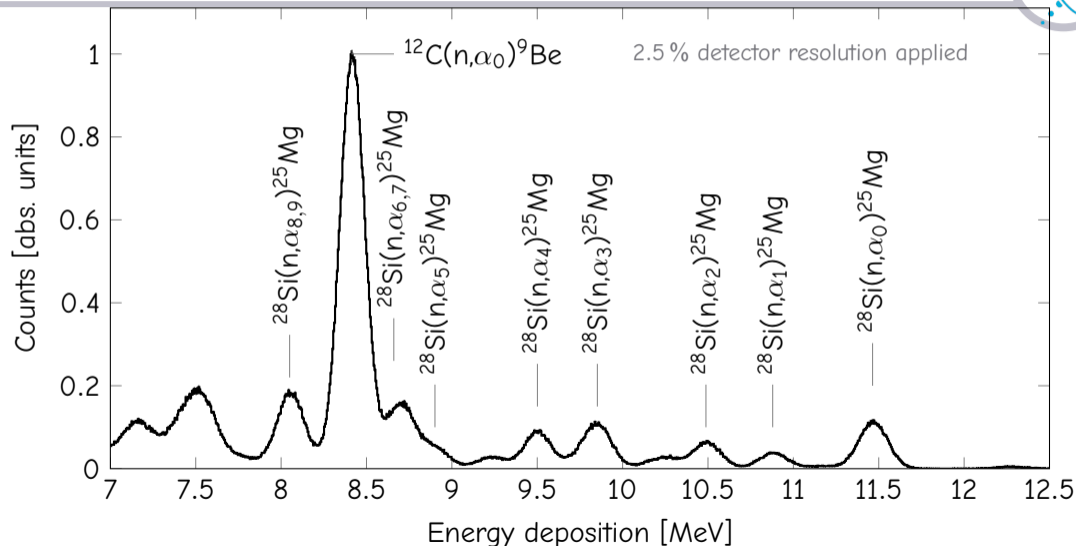
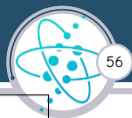
Fully correlated pointwise cross sections

Example: Silicon Carbide neutron detector



Pointwise and groupwise neutron transport

14.12 MeV neutrons on a SiC neutron detector

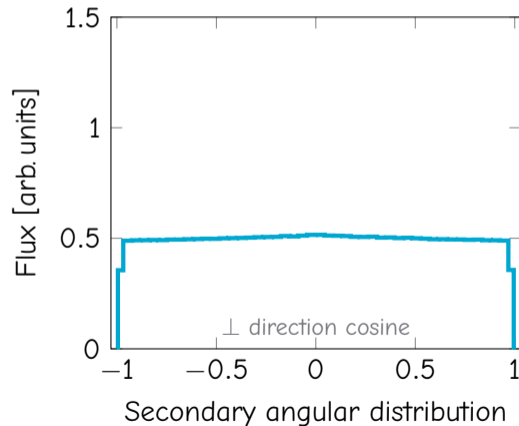
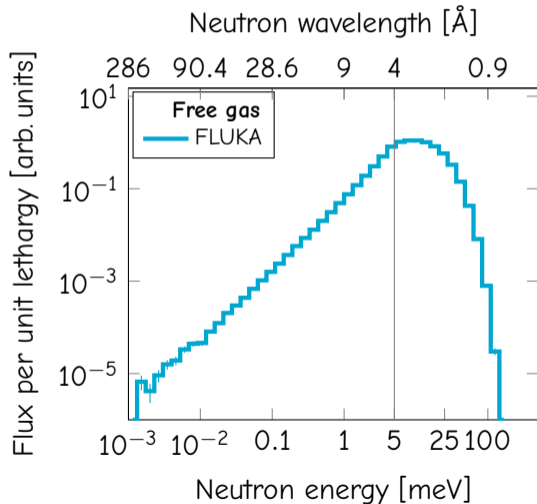




Thermal scattering kernels

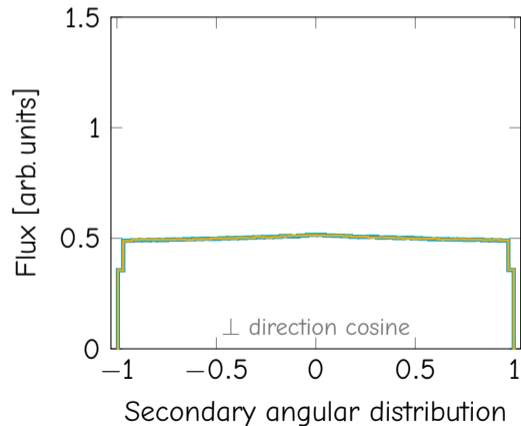
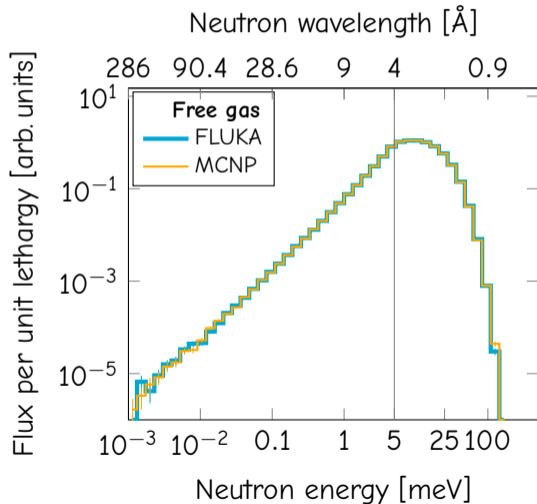
Thermal scattering kernels

5 meV neutrons on reactor graphite at room temperature



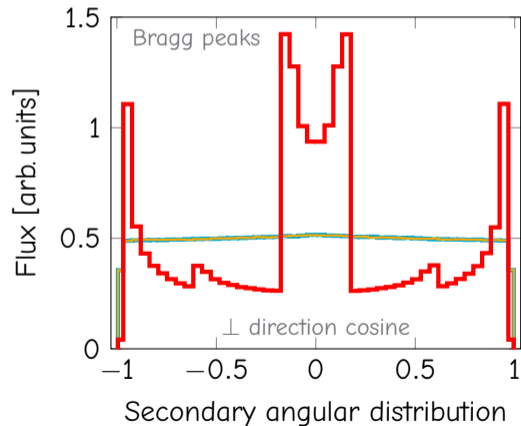
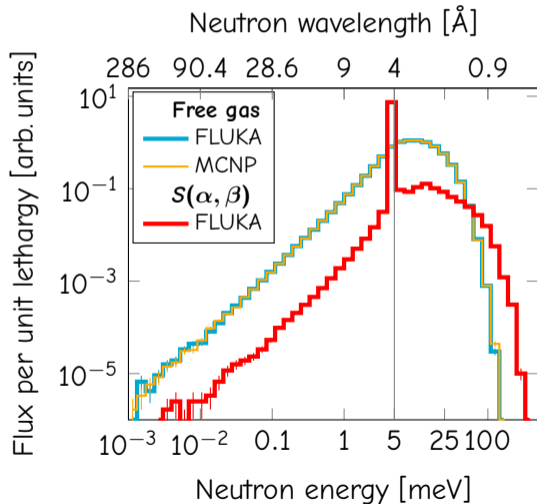
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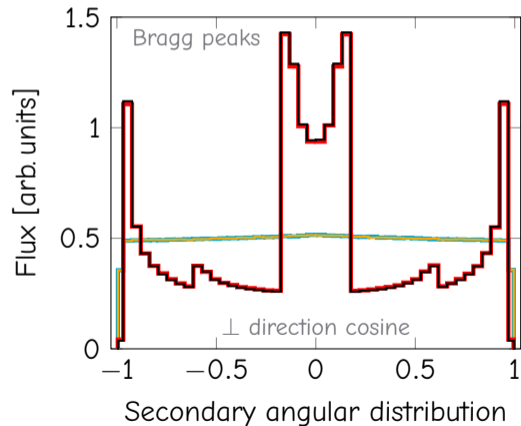
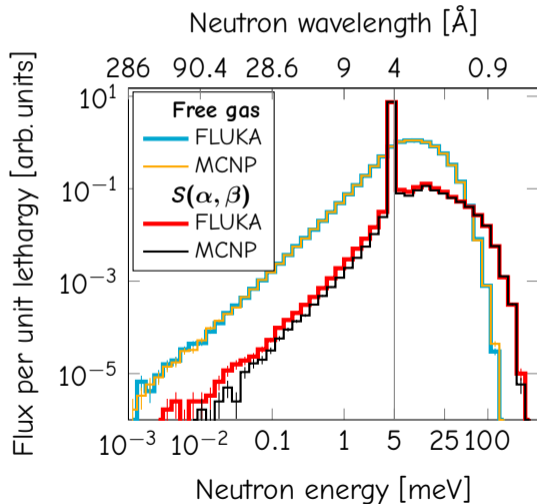
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- Monte Carlo codes are a very helpful tool for radiation physicists in synchrotron light sources.
- FLUKA, in particular, continues to evolve, keeping up-to-date with new data while improving the accuracy of its models, always aiming to provide users with advanced physics features.



We provided here some examples of changes in the code that could have disproportionate repercussions in synchrotron light sources:

- **photonuclear interactions models** — governing the production of neutrons which can dominate the radiation fields outside of shielding due to secondary GB.
- **synchrotron radiation emission** along particle trajectories, allowing accurate estimation of radiological consequences.
- **inclusion of X-ray reflectivity** — enabling users to perform radiation transport calculations in FLUKA accounting for X-ray reflection at elemental interfaces.
- **updated neutron cross sections** — enabling users to transport low energy neutrons efficiently and perform pointwise correlated transport when needed.



-  The FLUKA code: Overview and new developments
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-  FLUKA: a multi-particle transport code
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