Recent radiological studies at NSLS-II using the Monte Carlo code FLUKA

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NSLS-II U radiological impact:
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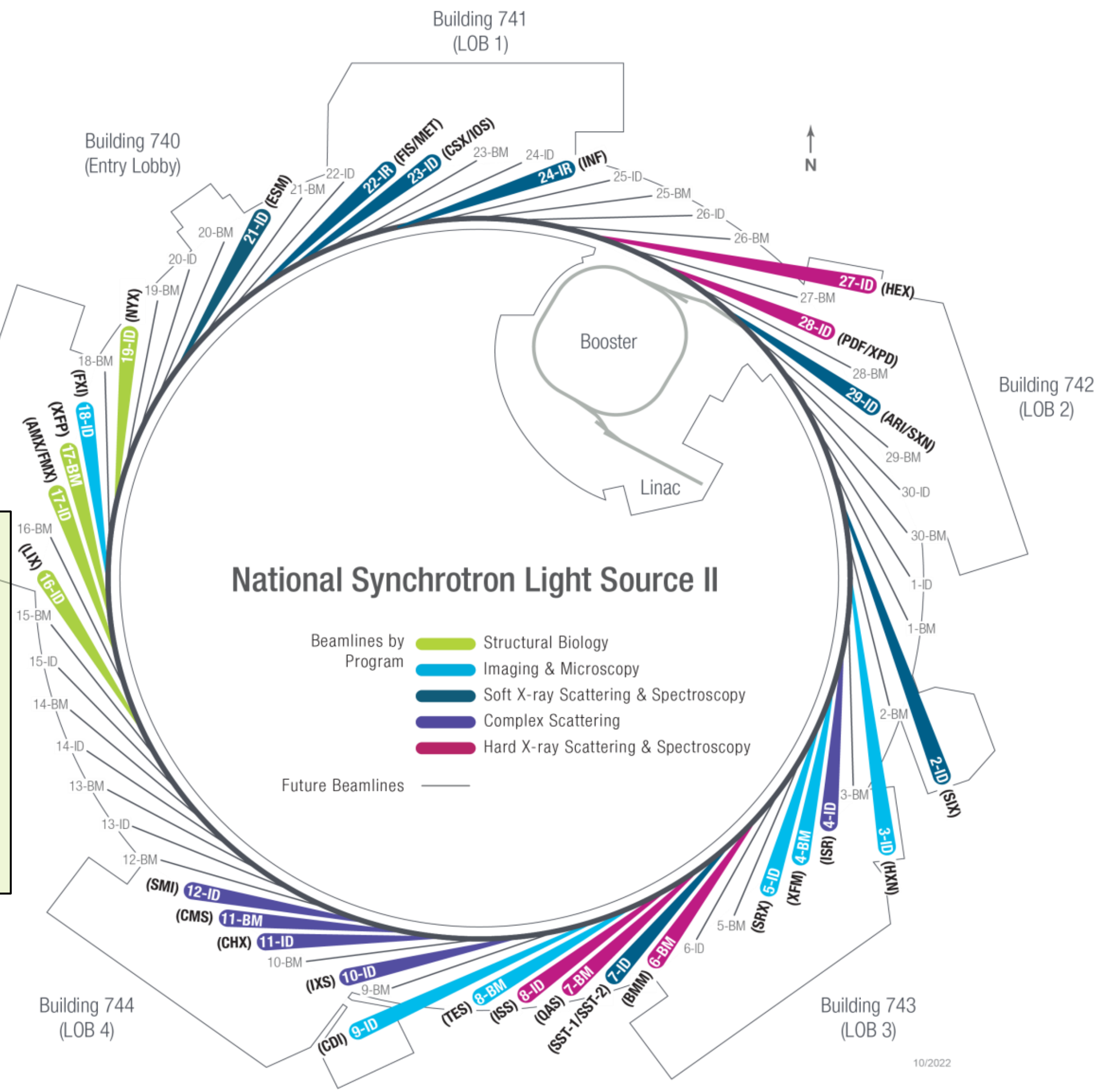
NSLS-II The National Synchrotron Light Source II @ Brookhaven National Laboratory.

- Operating since **2014**
- **3 GeV & 500 mA**
- **3rd generation** synchrotron radiation light source
- **29 beamlines** operating in the top-off mode
- Capacity for **~60 beamlines**

NEXT-III Project

In 2022, DOE granted CD-0 approval to build 8-12 new beamlines and supporting infrastructure over the next 10-12 years.
To be executed in phases: 2-3 beamlines launched every 1-2 years.



- *Sponsored by the U.S. Department of Energy Office of Science*
- *1700+ international researchers/year from a wide range of research fields*

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NSLS-II U*

*Selected cases only

Most upgrades currently under consideration aim at increasing the light source brightness by up to ~100× with a focus on X-ray energies up to 10 keV

To achieve this, a new storage ring based on a low emittance lattice is required, envisaging a beam energy up to 4 GeV and operating with a beam current as high as 600 mA.

- This is a very complex endeavor involving enhancement of geometry beam parameters, beam intensity and upgrades in insertion devices with minimal disruption to existing infrastructure **and to NEXT III plans**.

Upgrade	Energy [GeV]	Intensity [mA]
NSLS-IIU 3	*3*	*600*
NSLS-IIU 3.5	*3.5*	*500*
NSLS-IIU 4	*4*	*400*

Beam energy: *increases zero-intensity emittance proportionally to* $\mathbf{E^2}$
Intra-beam scattering: *increases the beam emittance with bunch intensity, approximately* $\propto \mathbf{1/E^3}$

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The DIM beam line

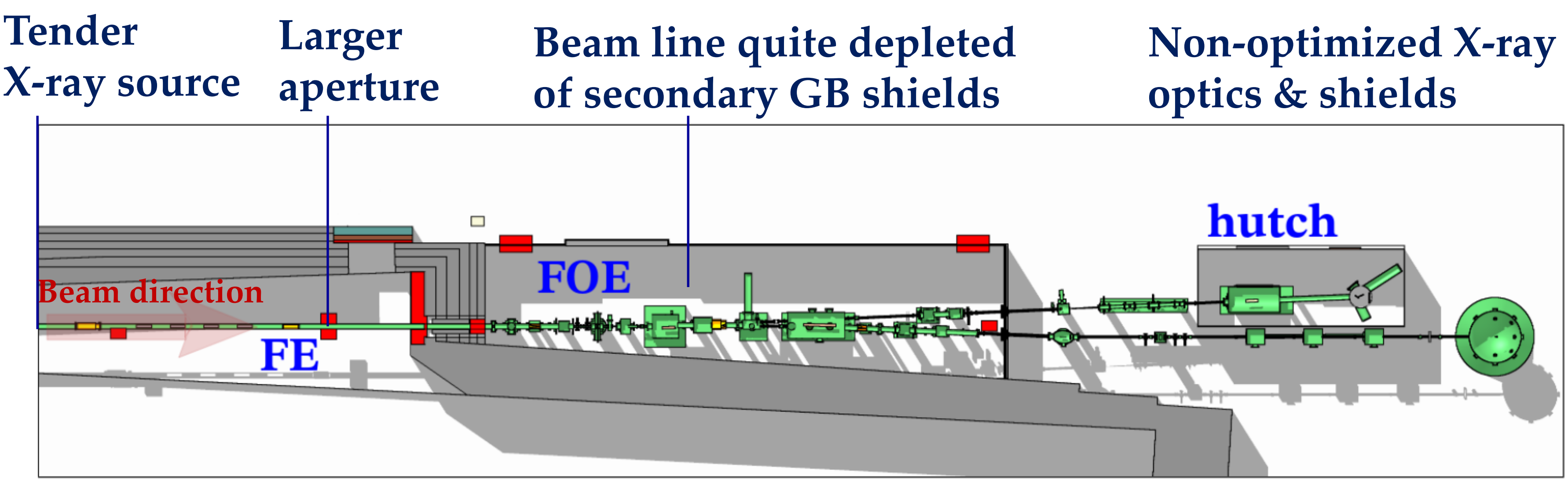
An *in silico* beam line

-› Test-bench for shielding performance evaluation.

Contains several features which makes it more susceptible to radiation leaks in the Front End (FE) and First Optical Enclosure (FOE)

Description	Material	Thickness [cm]
FE	Concrete	60
FOE roof	Lead	0.6
FOE outboard wall	Lead	1.8
FOE downstream wall	Lead	5
Guillotine	Lead	5
Transport pipe outboard	Steel	0.55
Transport pipe inboard	Steel + Lead[a]	0.48+0.53
Hutch	Steel	0.6

[a]80 cm downstream of the FOE the lead is converted to steel



Definitely not one of the next beam lines at NSLS-II !

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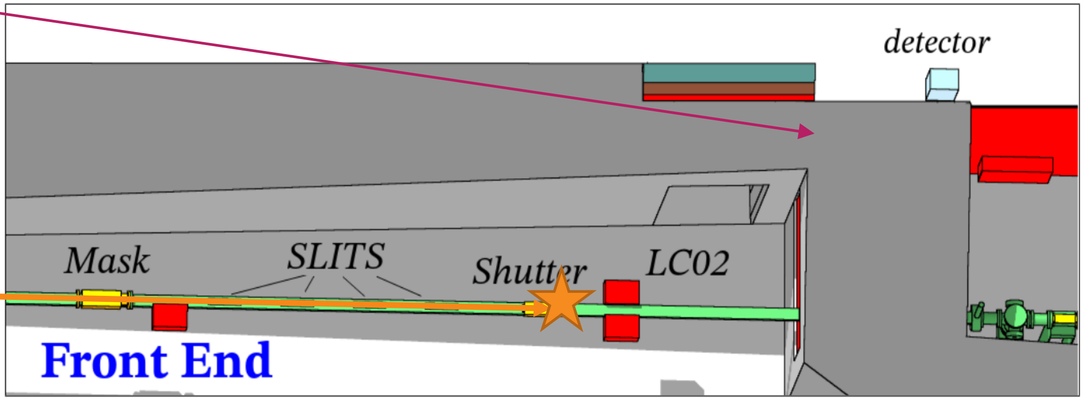
Injection faults

- NSLS-II operates in top off mode
- Maintaining the same maximum injection rate (max. 45 nC min^{-1}) with upgraded energies will increment the potential for radiation leakage
- Looking at a **weak spot** in the shielding:



Errant Electron Beam

Directed to the LCO2 collimator upstream face, 2 mm outboard from its aperture, intercepting the downstream flange of the FE Photon Shutter ~40 cm upstream of the LCO2 upstream aperture with slits removed.

Example: *FLUKA calculated dose rates increment [%] outside the shielding at the weak spot vicinity*

Energy [GeV]	3.0	3.5	4.0
Increment [%]	-	*12.2*	*30.6*

- That location ***is heavily monitored*** *allowing us to stop operation when faulty conditions are detected*

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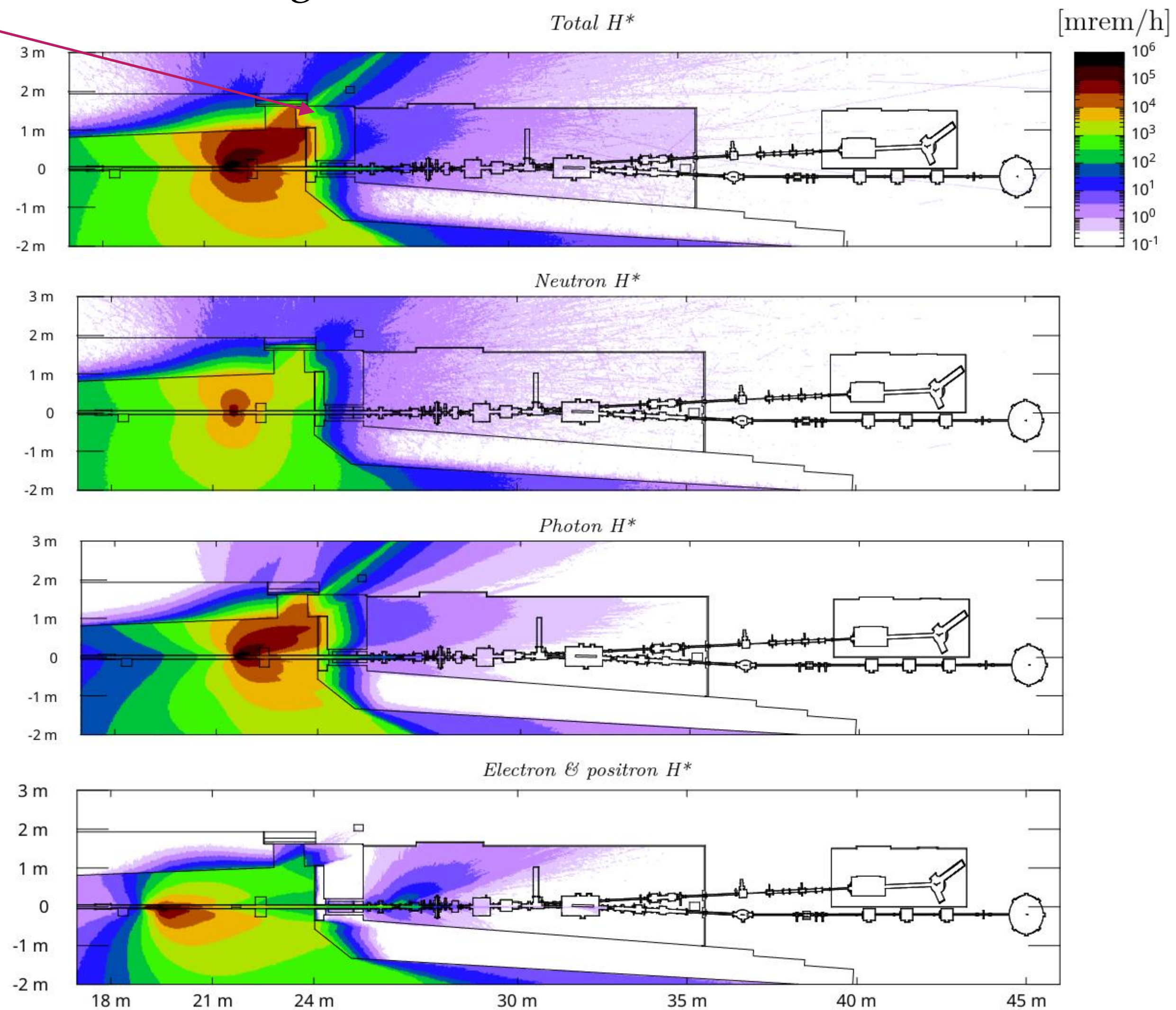
Injection faults

- Looking at a **weak spot** in the shielding:

One of multiple cases that will be simulated!



FLUKA 2023

F. Ballarini et al., "FLUKA: status and perspectives", Proceedings of the "15th Workshop on Shielding Aspects of Accelerators, Targets, and Irradiation Facilities" (SATIF-15), East Lansing, Michigan, USA, September 20-23, 2022

A. Ferrari, P. R. Sala, A. Fasso`, and J. Ranft,"FLUKA: a multi-particle transport code", CERN 2005-10 (2005), INFN/TC_05/11, SLAC-R-773

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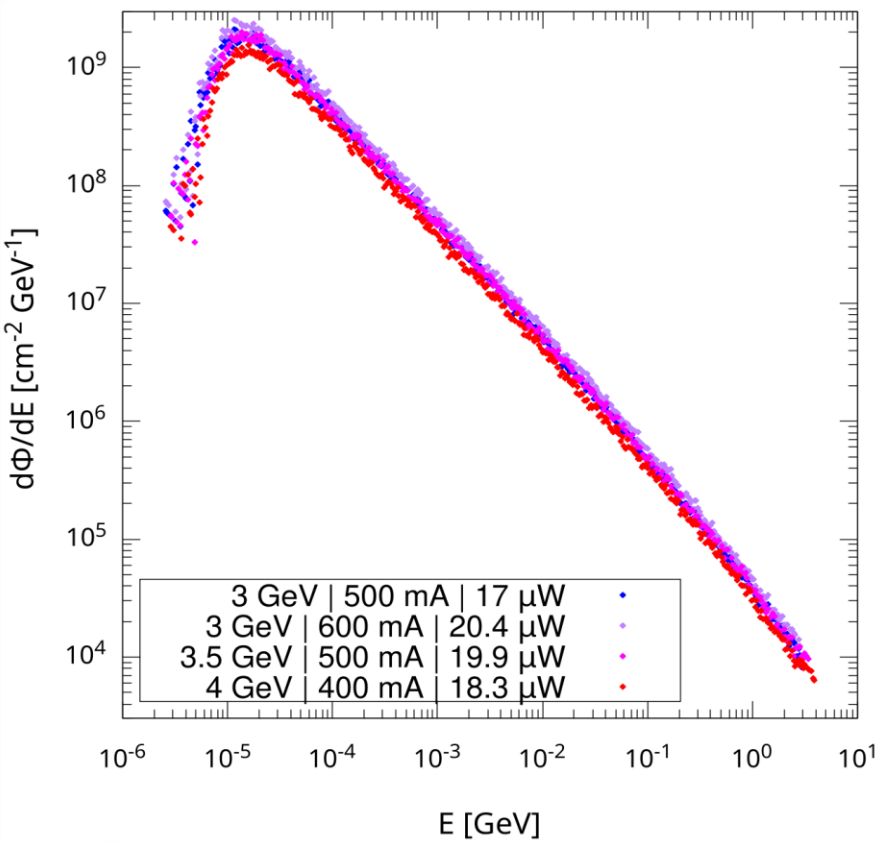
Gas Bremsstrahlung

Parameter	NSLS-II	NSLS-IIU 3	NSLS-IIU 3.5	NSLS-IIU 4
Electron beam energy [GeV]	3	3	3.5	4
Electron beam current [mA]	500	600	500	400
Gas bremsstrahlung power [W]	1.7×10^{-5}	2.04×10^{-5}	1.99×10^{-5}	1.83×10^{-5}

FLUKA was used to generate
and simulate three GB source terms with:

-- **Different energies** -› slightly different distribution

-- **Different power** -› the intensity in the ring will also contribute to the source term scaling



Source terms might appear deceivingly similar but details do matter when it comes to secondary GB
- Scattering angles, penetrability, etc.

GB generated in two steps:

1 – Electrons interact with residual gas molecules in the storage ring vacuum chamber. Phase space data is recorded at the end of the straight section.

2 – The source term is then transported in the FOE for the shielding analysis, including primary and scattered GB due to the interaction with the beamline.

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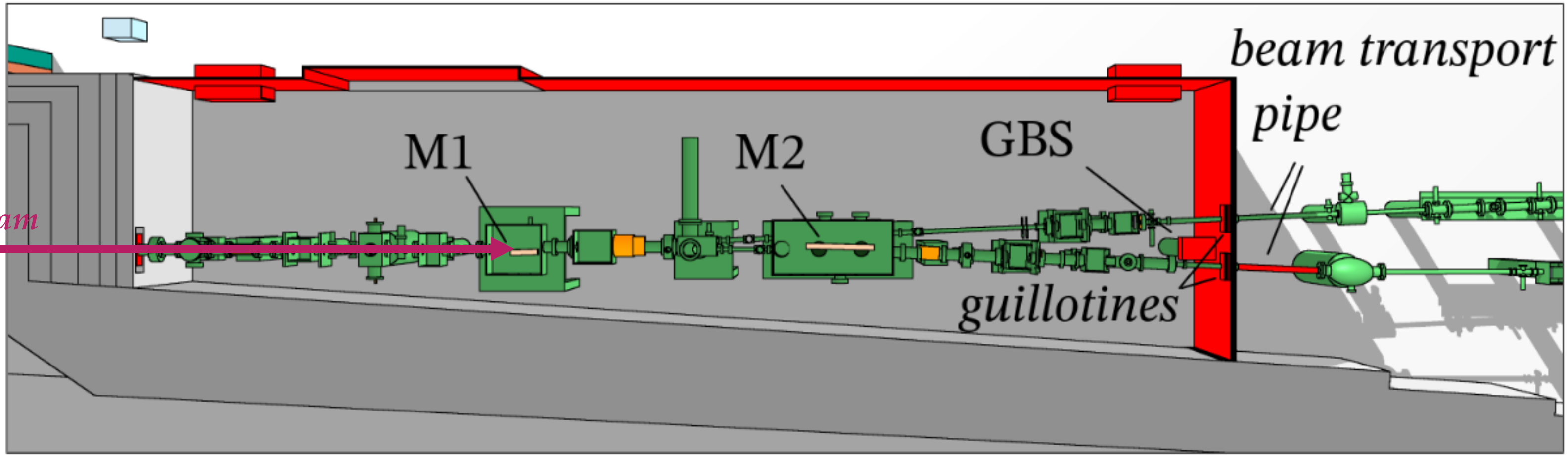
Dose rates due to secondary GB assessed outside of the shielding for silicon scattering mirrors oriented at 1.25°:



- Will require the evaluation of multiple cases

Example: *FLUKA calculated dose rates increment [%] outside the shielding when GB impinges at full power on M1*

Shielding	FOE Outboard wall	FOE Roof	FOE Downstream wall	Transport Pipe
NSLS-II	-	-	-	-
NSLS-IIU 3	*20.6*	*20.0*	*19.5*	*20.8*
NSLS-IIU 3.5	*4.4*	*-29.3*	*11.5*	*-10.4*
NSLS-IIU 4	*-38.2*	*-40.0*	*4.6*	*2.1*

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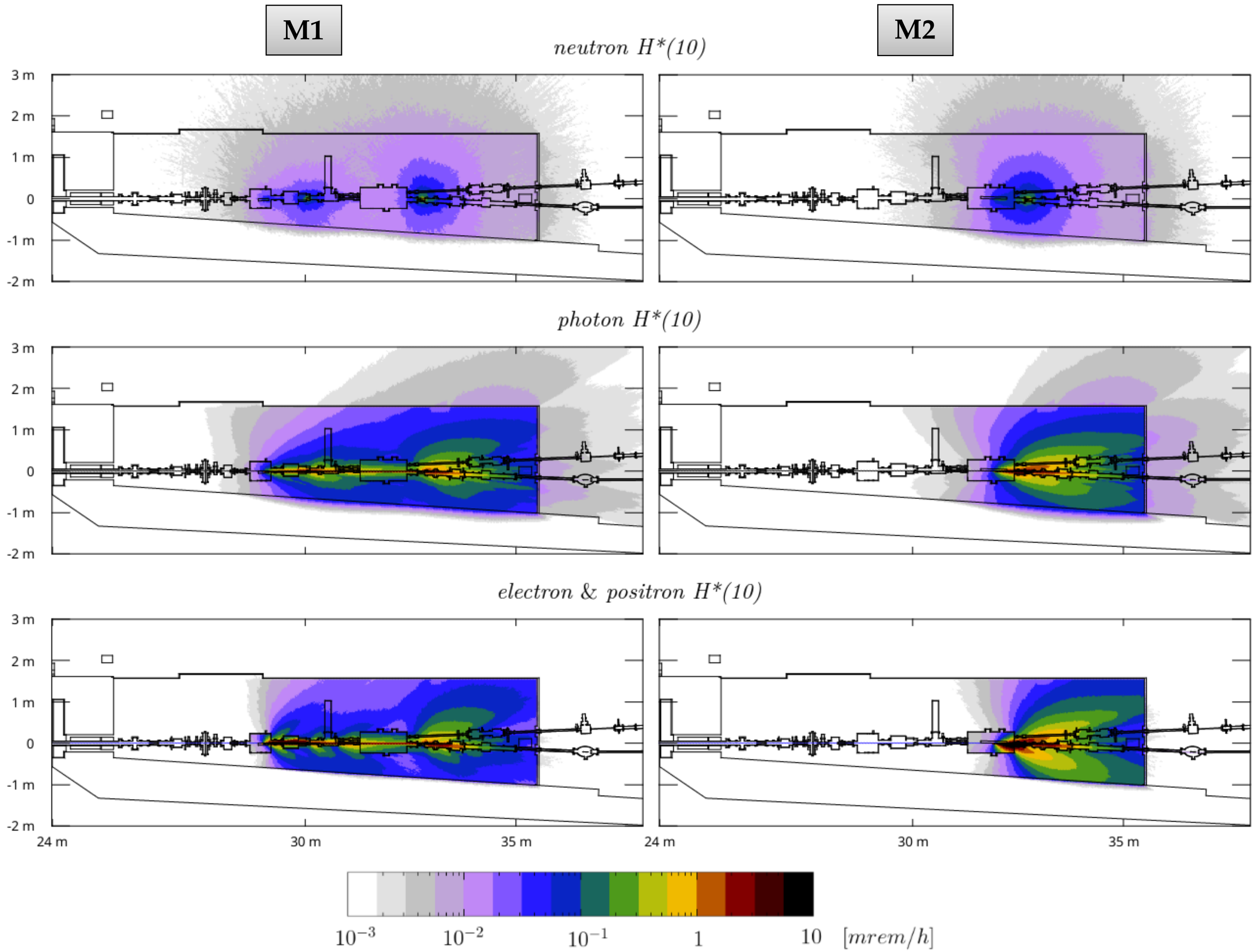
Dose rates due to secondary GB assessed outside of the shielding for silicon scattering mirrors oriented at 1.25°:



H* vs H*(10)

A tale of two dosimetry quantities

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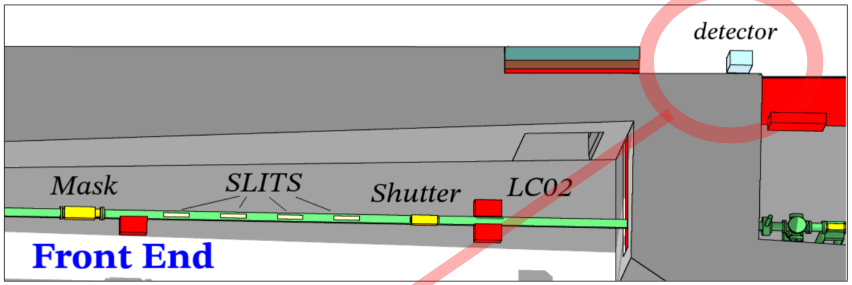
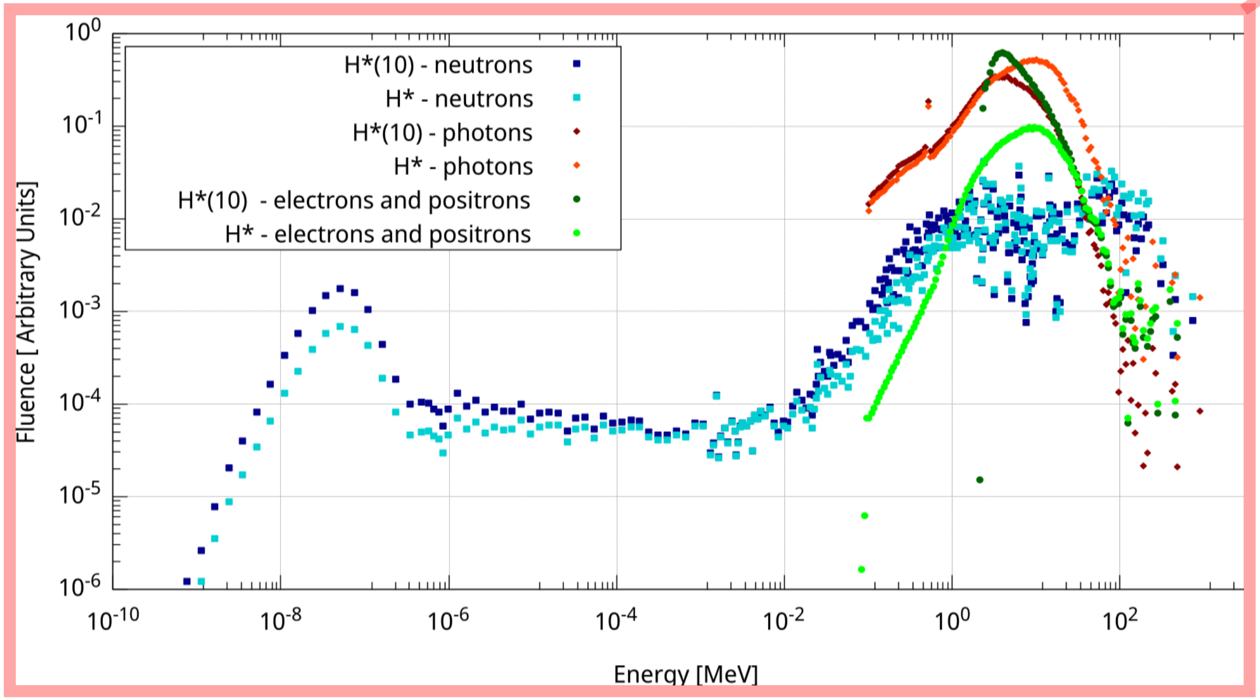
Despite the similar name H* and H*(10) are quite different quantities.

- We wanted to understand if, given the energies involved, the adoption of H* weight factors would cause it to be more conservative than H*(10)

- ICRU95 driven
- H* conversion factors a default since FLUKA 2023.3

As per ICRP116, H* tends to be more severe for higher energies (particularly from the GeV range onwards) for photons and to a lesser extent for electrons too.





But at energies below a few tens of MeV, which are predominant outside of the shielding in our facility, the tendency is slightly reverted and H*(10) often appears to be the most stringent quantity, with e^- & e^+ contribution significantly lower for H*

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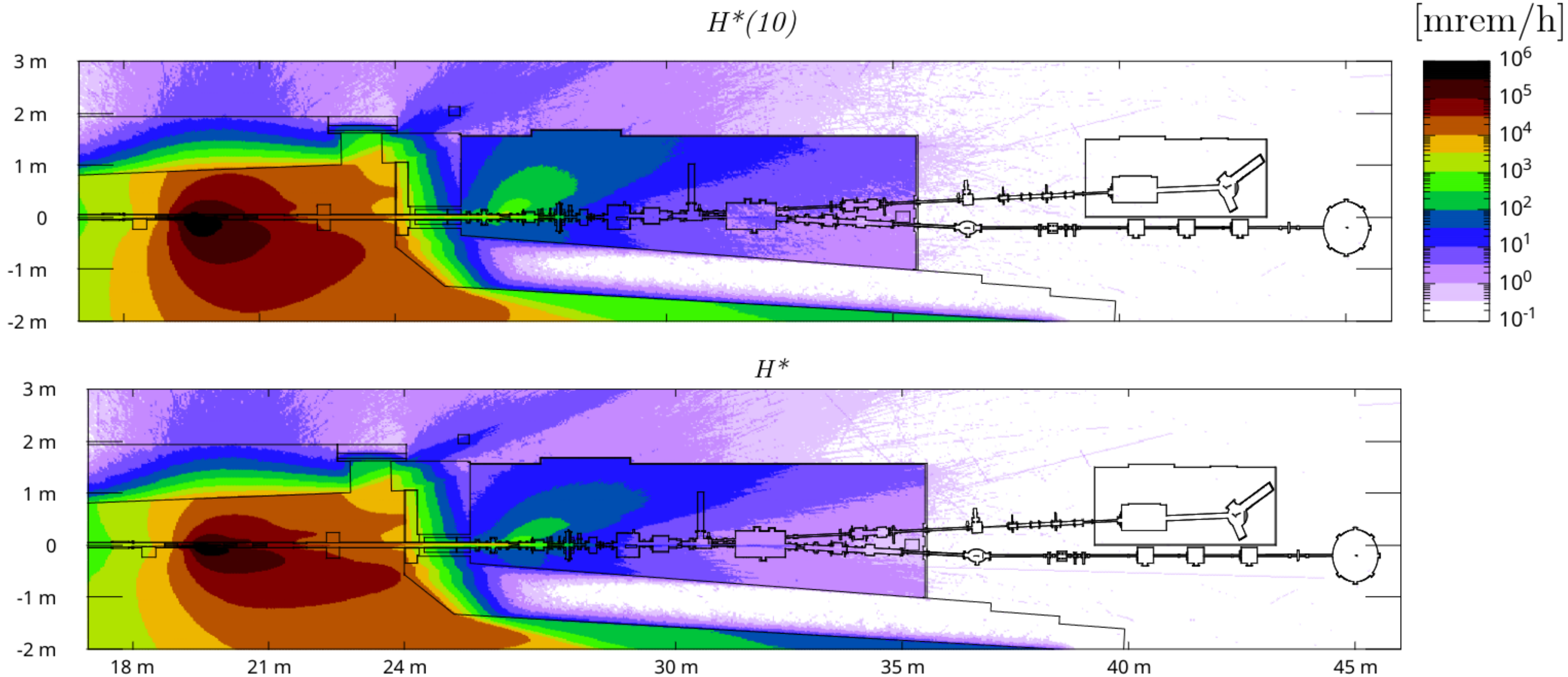
*Injection fault depicting an errant beam impinging on slits – **NSLS-IIU 4***



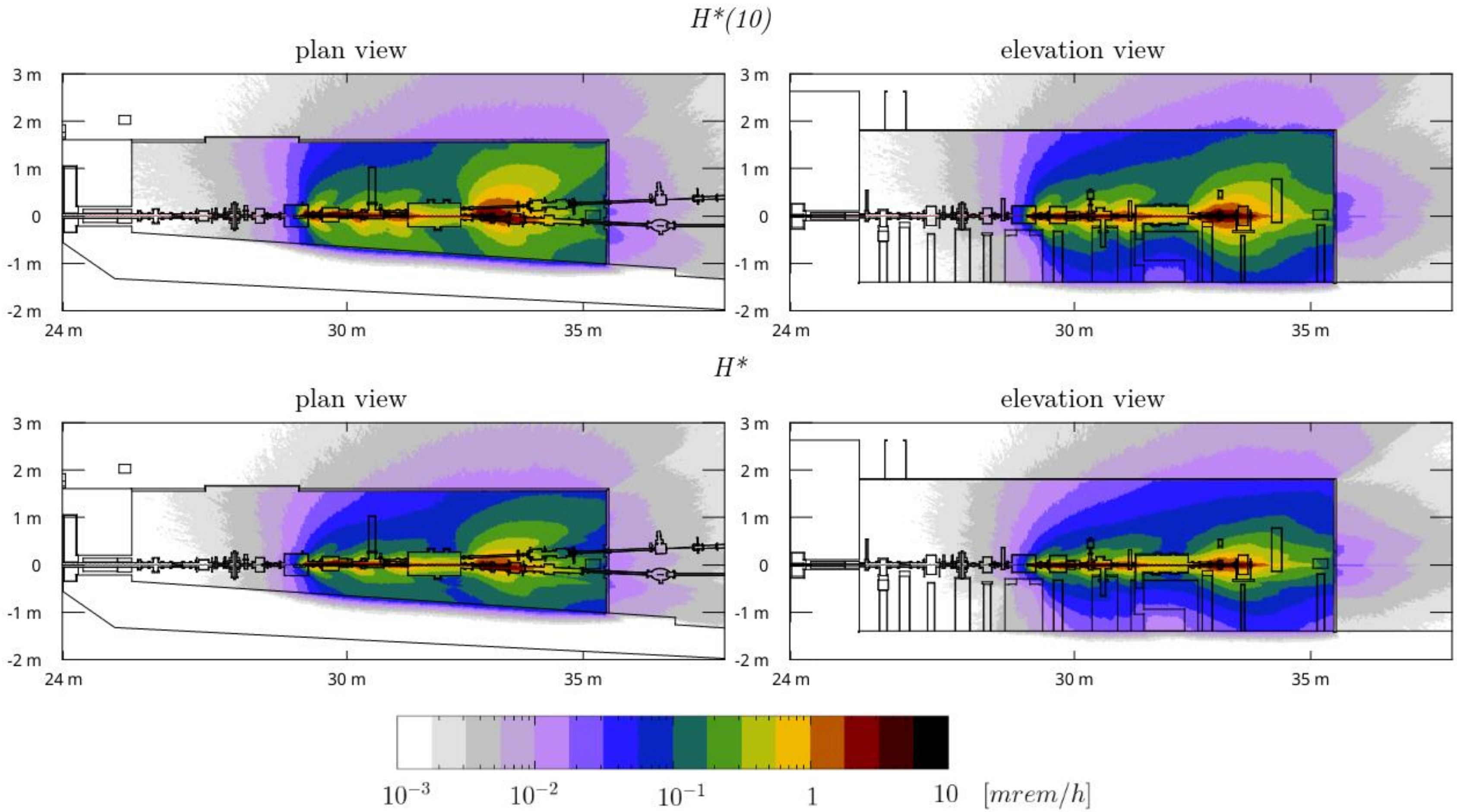
Systematic studies showed that H(10) tends to yield more conservative results than H* both for Injection faults and Gas Bremsstrahlung scenarios at NSLS-II even for the highest energy upgrade.*

- Very much problem/spectrum specific! H would be the most conservative estimator at higher energies..*

Despite the similar name H* and H*(10) are quite different quantities

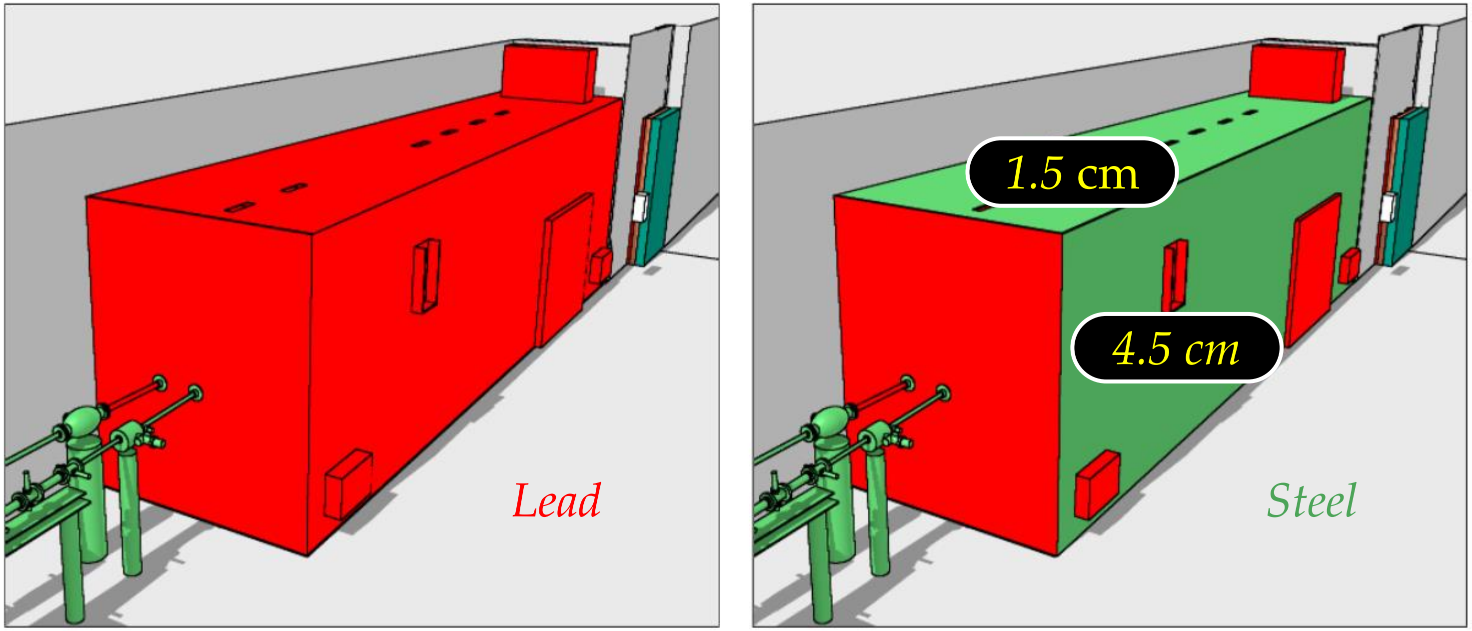
- We wanted to understand if, given the energies involved, the adoption of H* weight factors would cause it to be more conservative than H*(10)

GB impact on mirror M1 – ***NSLS-IIU 4***



Steel vs Lead

- Over the last decade NSLS-II built up considerable hutch engineering knowledge
- For the latest beam lines NSLS-II took the responsibility for hutch design fabrication (contract) and installation.
- Future beam lines might benefit from alternative shielding materials, even if these would be only partially applied to the hutches.
- Steel would be a relatively straightforward candidate, and despite its inferior shielding capacity it is a far easier material to work with than lead including easier to obtain, far less hazardous and better fabricator availability.



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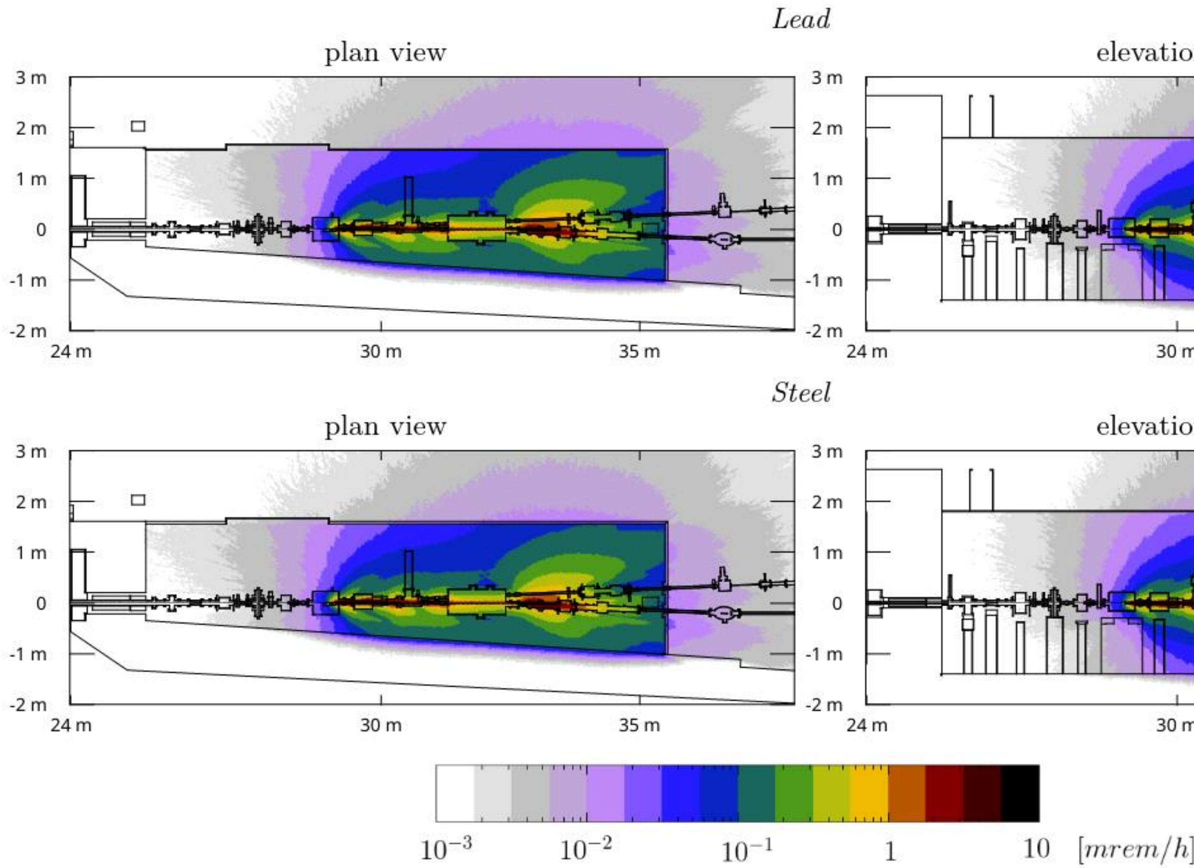
GB Shielding assessment with steel

> 0.05 mrem/h

Full GB power in M1 scattering mirror.

→ Steel version could meet current dosimetry limits, even outperforming the lead version. For the upgrade scenarios, some adjustments will be needed.

	Outboard wall	Roof
NSLS-II	.043	.050
NSLS-IIU 3	.052	.060
NSLS-IIU 3.5	.040	.051
NSLS-IIU 4	.036	.040

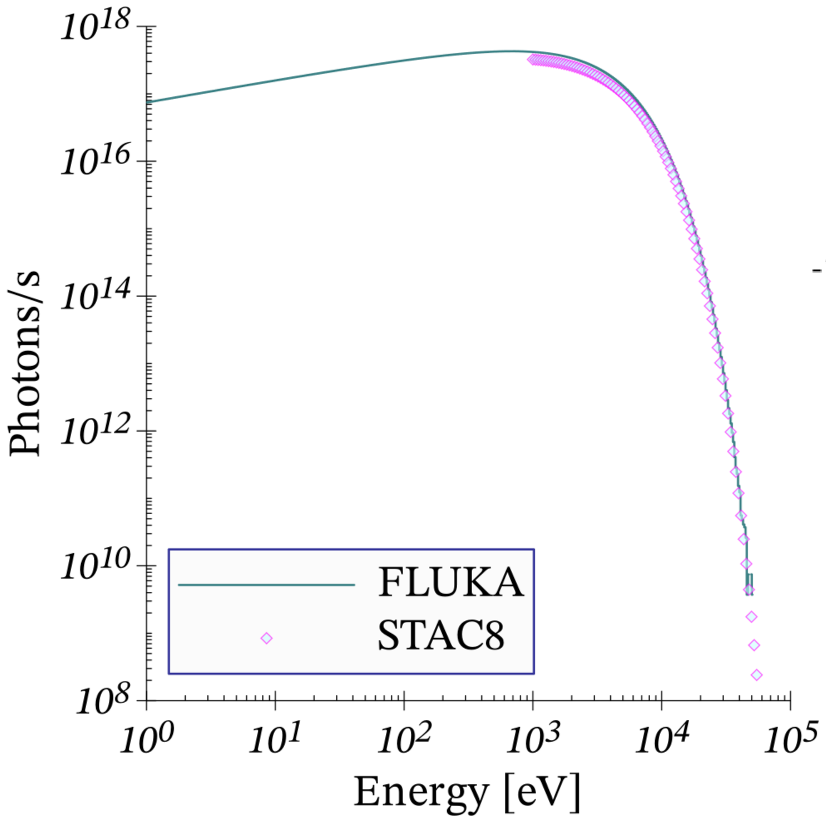


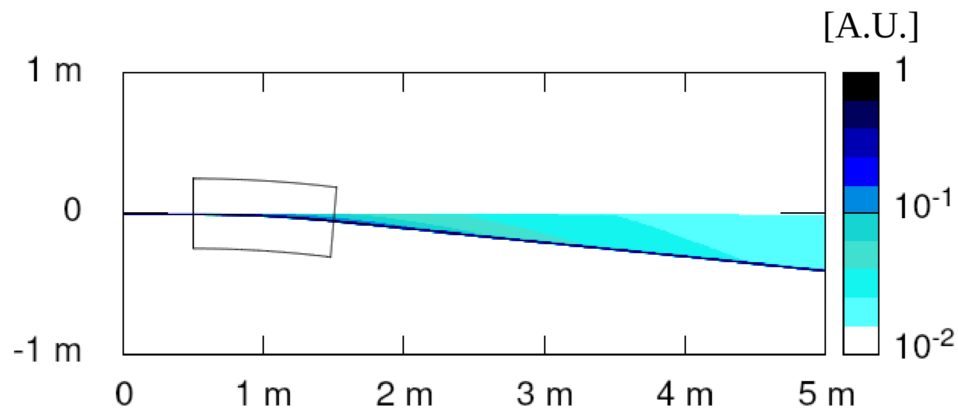
Synchrotron radiation

Integrated transport from source to endstation

Generating SR with a bending magnet

FLUKA allows for the reproduction of synchrotron radiation from bending magnets





Parameter	Value
Length [m]	*2.6*
Number of periods	*1*
Max. B_{eff} [T]	*0.4*
E_c [keV]	*2.4*
Horizontal max. source opening [mrad]	*10*

The source term was directed to the beamline for a radiological analysis considering scattering and reflectivity on the different mirrors

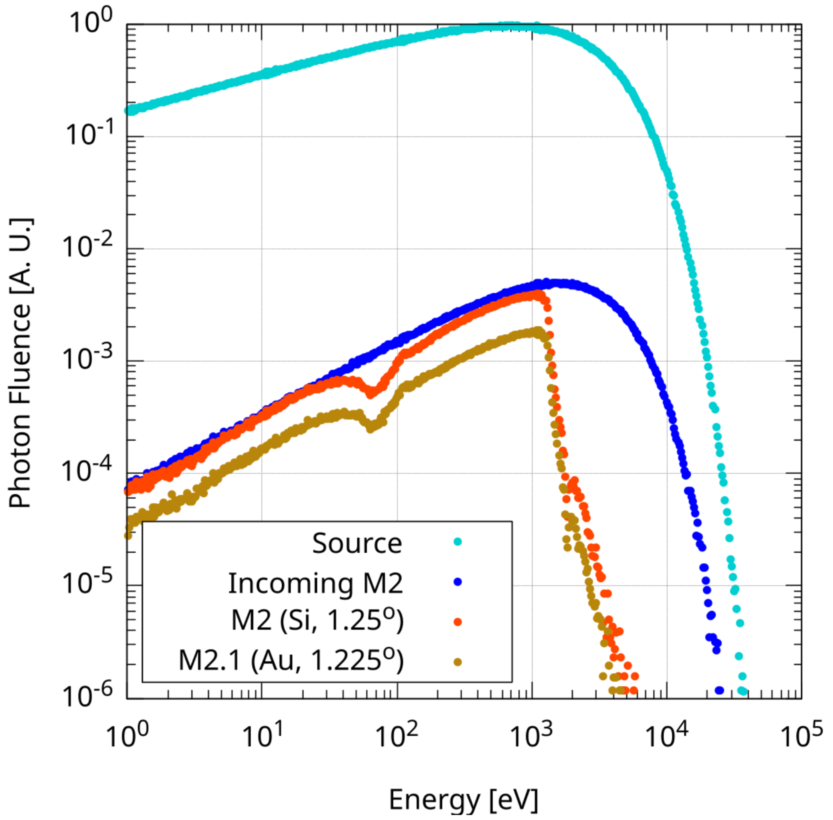
STAC8 version II.5, Y. Asano and N. Sasamoto., *Rad. Phys. & Chem.* **44** 133 (1994)

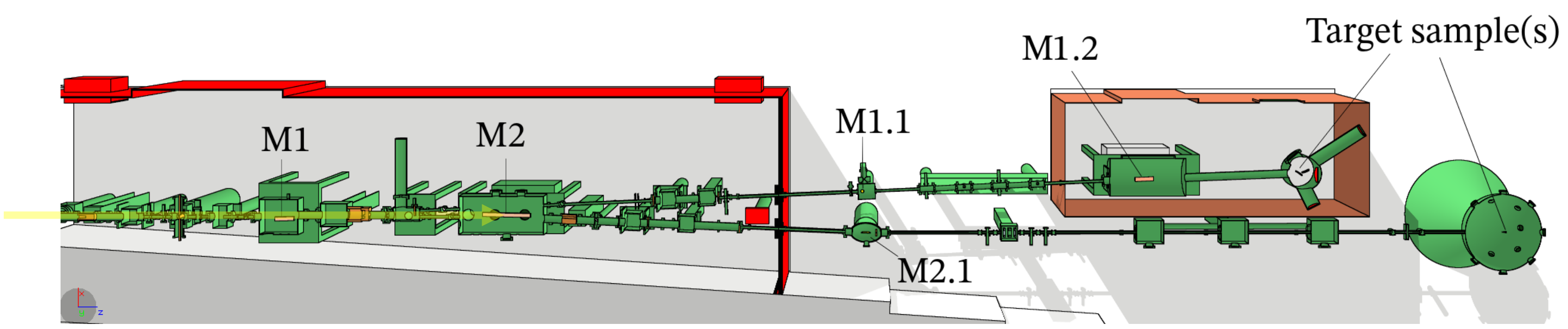
X-ray reflectivity

FLUKA 2024.1* allows the reproduction of the X-ray reflectivity effects for thick mirrors throughout a beam line ‘a la Monte Carlo’.

* FLUKA: status and new developments, A. Ferrari et al., this workshop

SR directed to mirror M2 and subsequently propagated throughout the beamline’s inboard section





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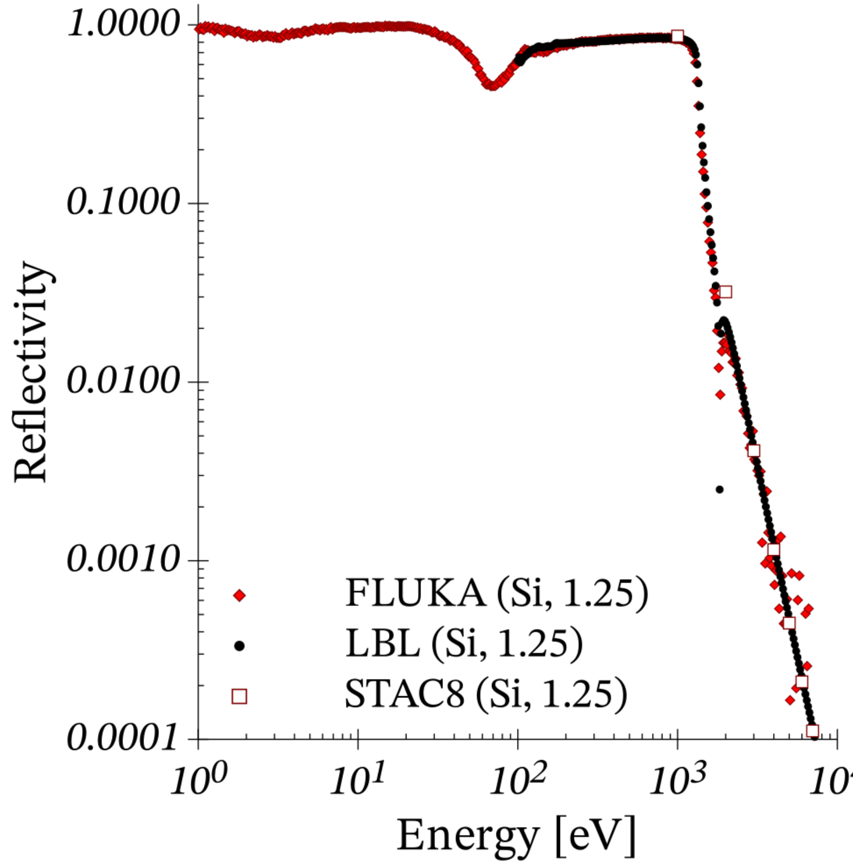
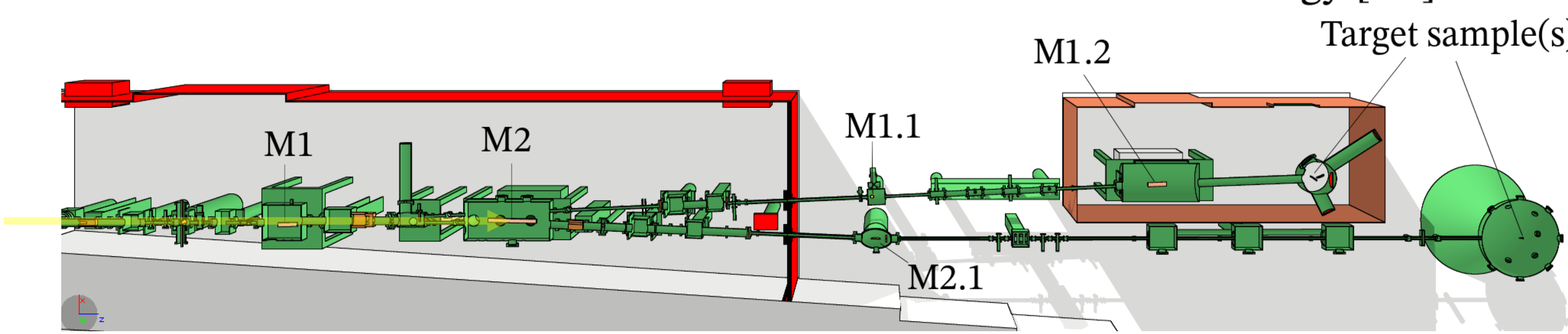


SR directed to mirror M2 and subsequently propagated throughout the beamline’s inboard section



LBL: B.L. Henke, E.M. Gullikson, and J.C. Davis. X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92, *Atomic Data and Nuclear Data Tables* **54(2)**, 181-342, 1993.

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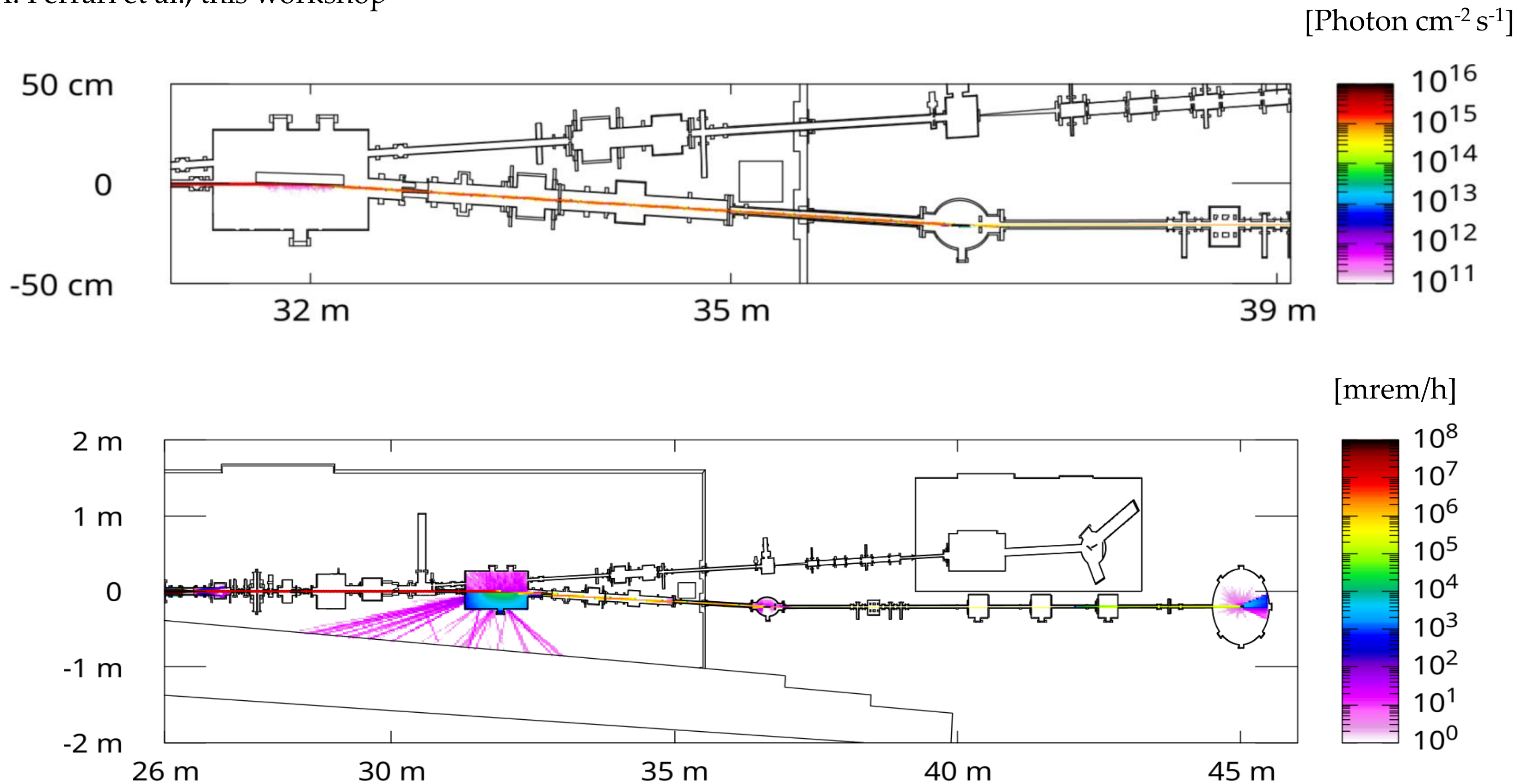
X-ray reflectivity

FLUKA 2024.1* allows the reproduction of the X-ray reflectivity effects for thick mirrors throughout a beam line 'a la Monte Carlo'.

* FLUKA: status and new developments, A. Ferrari et al., this workshop

SR directed to mirror M2 and subsequently propagated throughout the beamline's inboard section…via M2.1 (Au) up to the endstation



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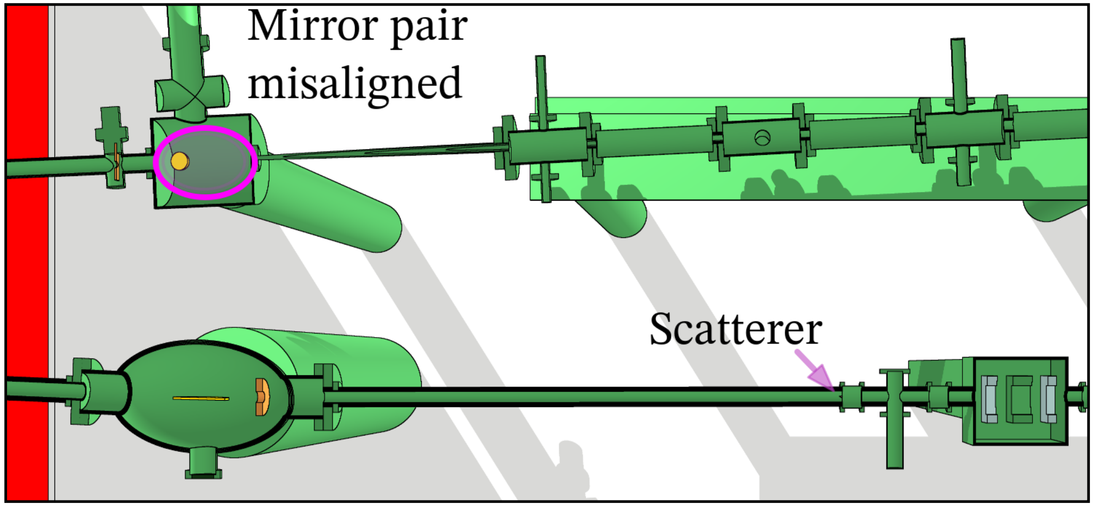
Radiological impact

Let's assume that one mirror pair in the outboard branchline is out of position and a conical scatterer is present at some point in the inboard branchline:



- Possibility to evaluate problems in complex geometries
- Definitely a slower methodology and requires time to prepare as well

Complementary: Dose rates could be estimated with analytical codes, but by transporting the radiation one gets a (often very helpful) visual perspective at how the radiation interacts with the different components

Radiological impact

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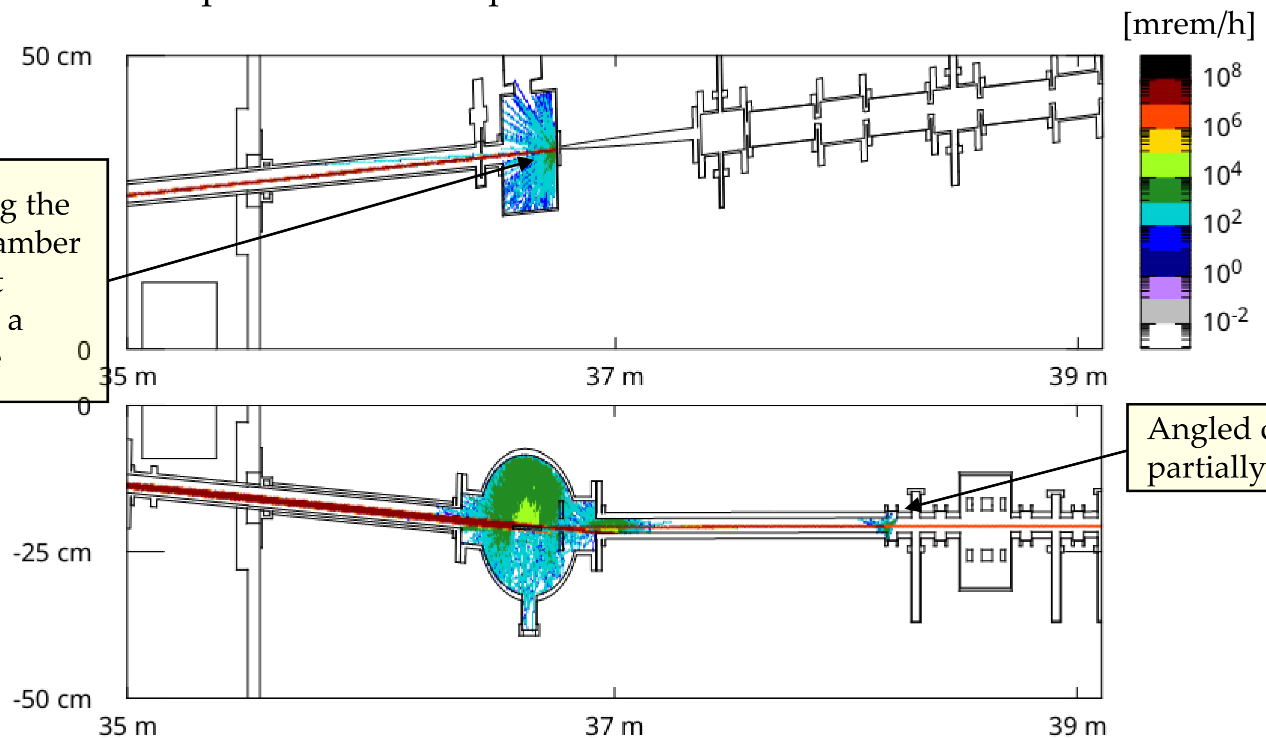

Beam hitting the vacuum chamber but without penetrating a thick flange

Angled conical scatterer, only partially intercepting the beam

Complementary: Dose rates could be estimated with analytical codes, but by transporting the radiation one gets a (often very helpful) visual perspective at how the radiation interacts with the different components

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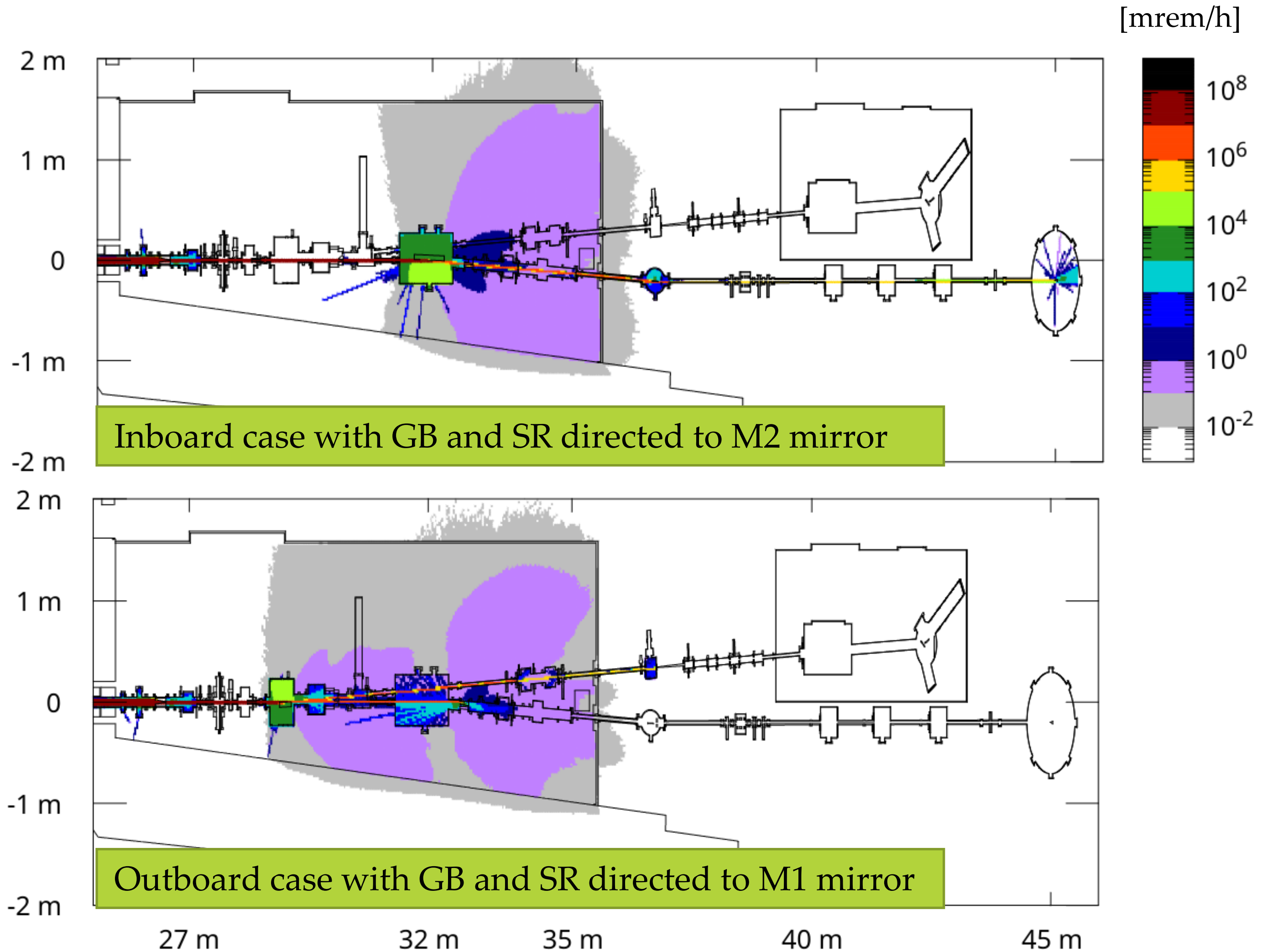
GB+SR Shielding assessment

Possibility to integrate the GB and SR results in order to have a more complete radiological evaluation. Considering the previously mentioned cases:



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Conclusion

FLUKA was extensively used at NSLS-II to evaluate the radiological impact related to...

- … some of the anticipated NSLS-II upgrade options
- … the different dose estimators
- … different shielding materials for the FOE outboard walls and roof
- … the propagation of synchrotron radiation throughout a beamline while accounting for X-ray reflectivity

Future Work

We will gradually include more realistic case scenarios, either in the context of upgrading currently existing beamlines, the NSLS-II Upgrade and/or the NEXT-III project.

Acknowledgments

We wish to thank the colleagues at NSLS-II and the FLUKA collaboration

The End

Thank you! Questions?

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