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U.S. DEPARTMENT  
of ENERGY

# *Brief overview of the radiation shielding calculations for the NEXT-II and NEXT-III projects at NSLS-II*

*R. S. Augusto, R. J. Lee, D. M. Bacescu, S. Antonelli, J. Dvorak, M. Johanson, L. Lienhard, O. Chubar, M. Breitfeller, Y. Li, A. L. Walter, Y. Yang, A. Broadbent, W.-K. Lee, J. Adams*

**Radsynch 25**  
*CNPEM, Campinas/SP, Brasil*  
24-27 June 2025

X f i @BrookhavenLab

# Outline

**NSLS-II** overview

The **NEXT-II** & **NEXT-III** projects

**ARI** & **SXN**

- *GB shielding*
- *SR shielding*
- *Top Off Safety analyses*

**QCT**

- *Ongoing GB studies*
- *Top Off Safety assessment*

Concluding remarks

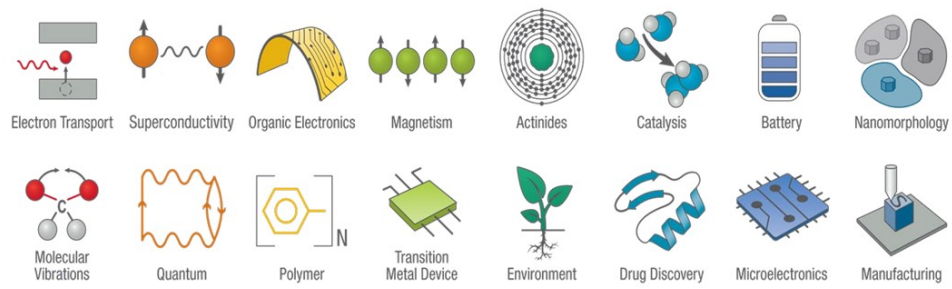
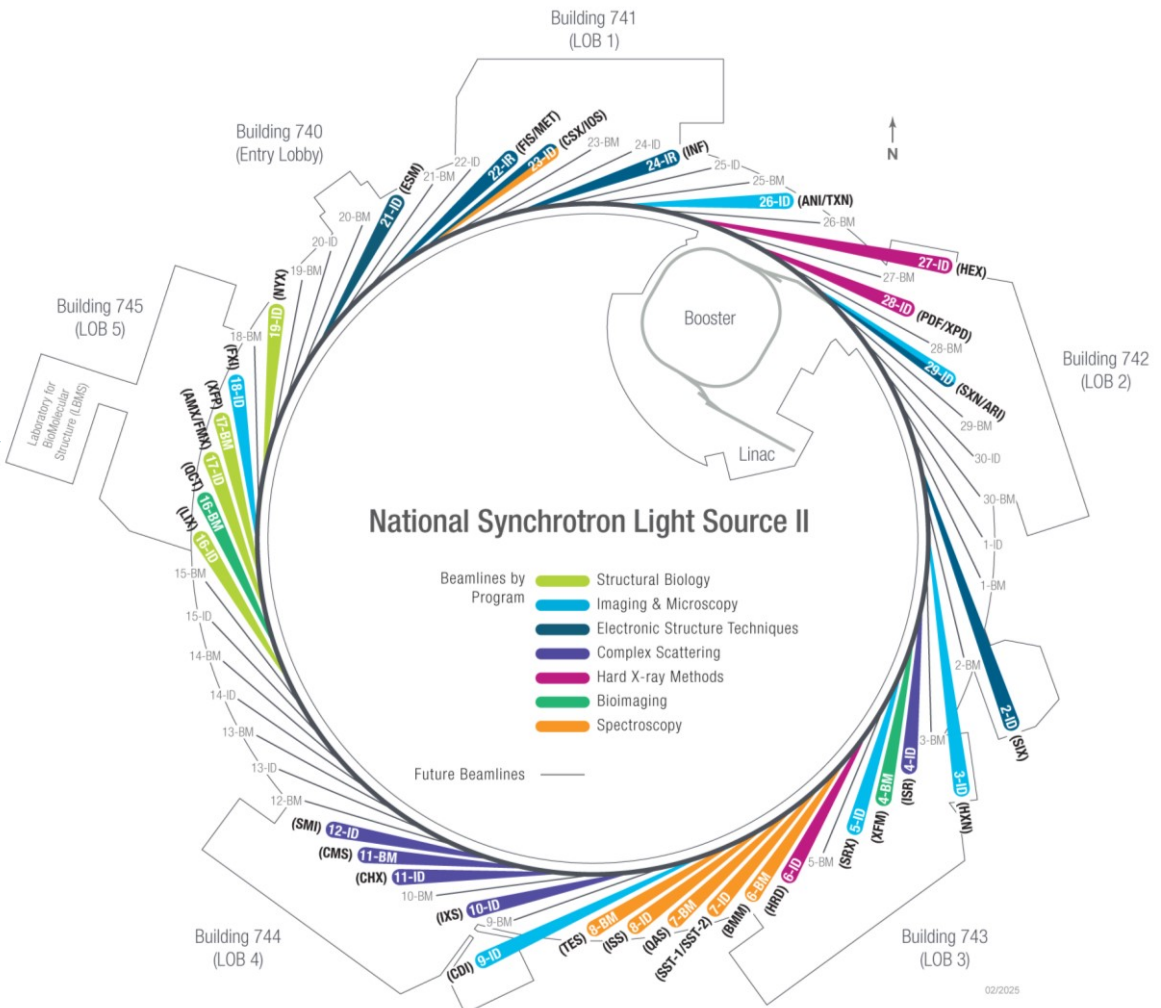
*“NSLS-II is one of the newest, most advanced synchrotron light sources in the world providing research capabilities to scientists working on complex scientific challenges in materials science and processing, condensed matter physics, chemistry, life and biosciences, as well as earth and planetary sciences.”* - NSLS-II Strategic Plan | 2025-2029



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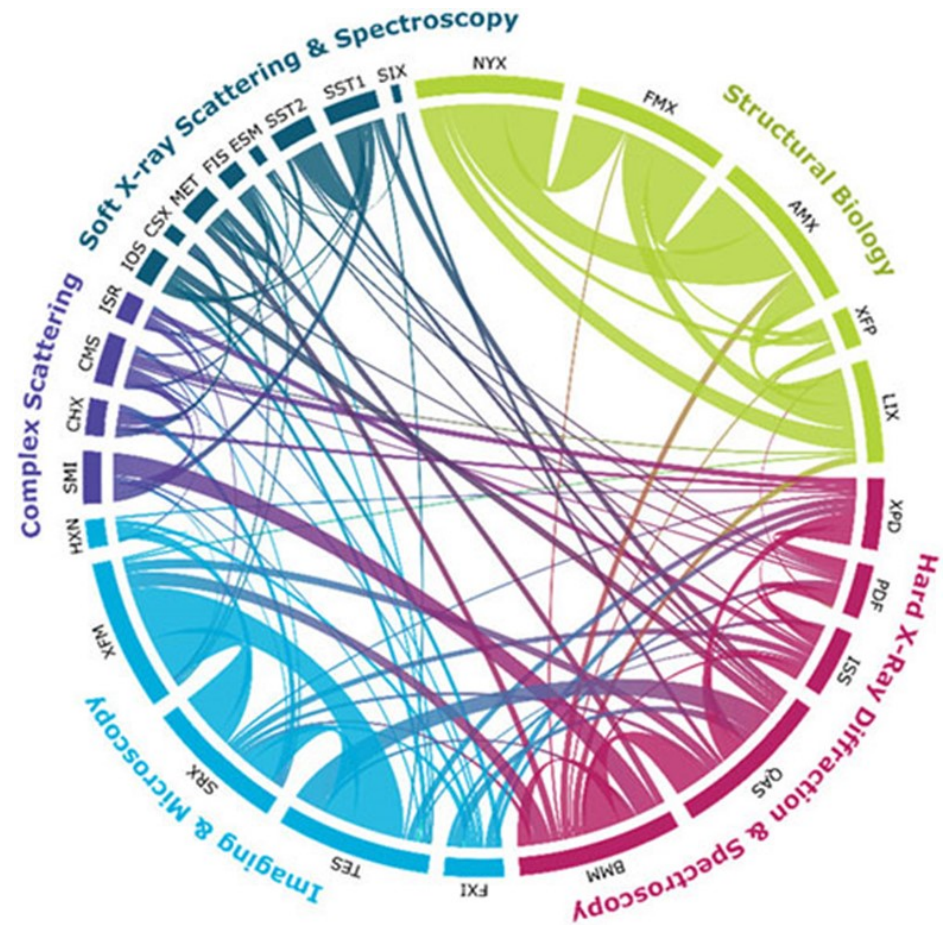
# NSLS-II Factsheet

- 3 GeV electron storage ring
- up to 500 mA current
- Top-off injection
- ~800 m circumference
- 29 out of ~60 beamlines constructed
- Over 2300 users (350 institutions)
- Wide spectral range: 0.1 eV ~> 300 keV



# NSLS-II Factsheet

- 3 GeV electron storage ring
- up to 500 mA current
- Top-off injection
- ~800 m circumference
- 29 out of ~60 beamlines constructed
- Over 2300 users (350 institutions)
- 25% of users at NSLS-II request more than one beamline



Multimodal experiments capabilities are potentiated by beamline quantity and diversity as well...

# NEXT-II and NEXT-III projects

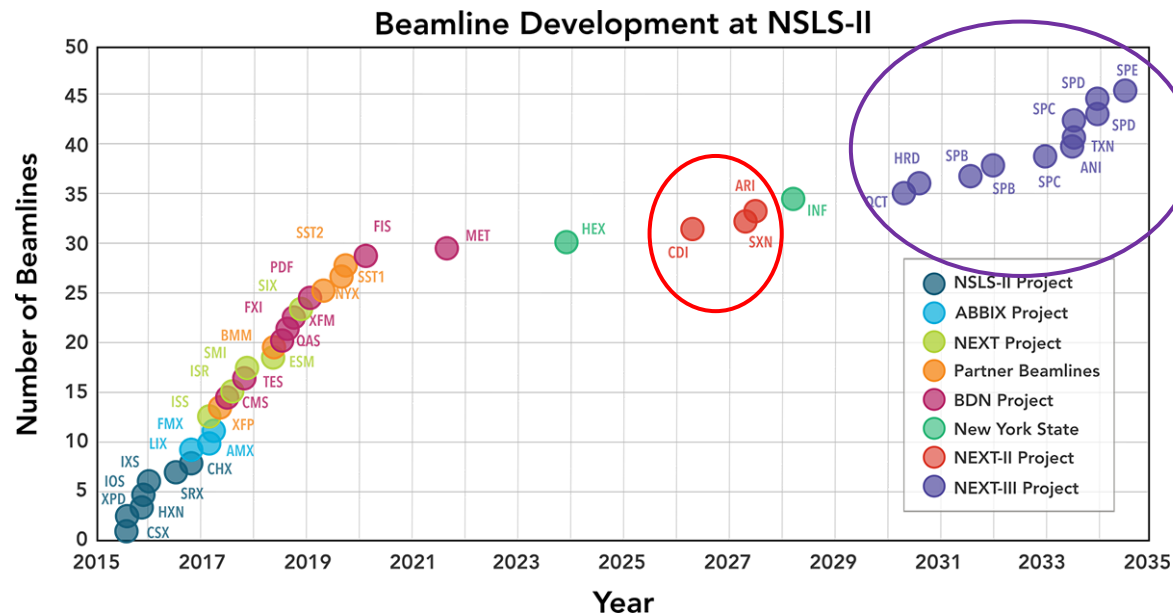
NLS-II EXperimental Tools II and III

## NEXT-II:

CDI - getting ready for commission (out of scope from today's presentation).  
ARI & SXN - scheduled to see first light before 2028.

## NEXT-III:

8 to 12 new beamlines alongside their supporting infrastructure in 10 to 12 years.  
Flexible approach that adapts to evolving scientific needs – 1<sup>st</sup> beamline: QCT



# NEXT-II and NEXT-III projects

NSLS-II EXperimental Tools II and III

## NSLS-II ALARA Radiological limits and design goals

- $H^*(10) < 0.05$  mrem/h in occupied areas on the experimental floor
- Access to experimental floor is controlled (but no TLD required)
- $H^*(10) < 25$  mrem/y to individuals not involved in the operation of the facility.
- Dose rates calculated for 500 mA stored electron beam intensity
- Top-off results are based on a conservative charge rate of 45 nC/min.
- Exposure to personnel due to a fault event  $< 100$  mrem in controlled area ( $< 20$  mrem otherwise)



# NEXT-II and NEXT-III projects

NSLS-II EXperimental Tools II and III

## NSLS-II Shielding design paradigm and radiological tools

First optical enclosures shielded with lead - other shielding enclosures typically shielded with either lead, steel or concrete. Local beamline shielding is customized to mitigate enclosure's radiation leaks or reinforce transport pipes.

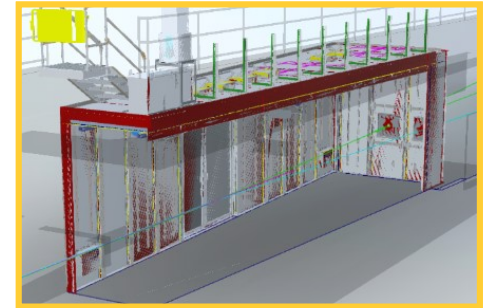
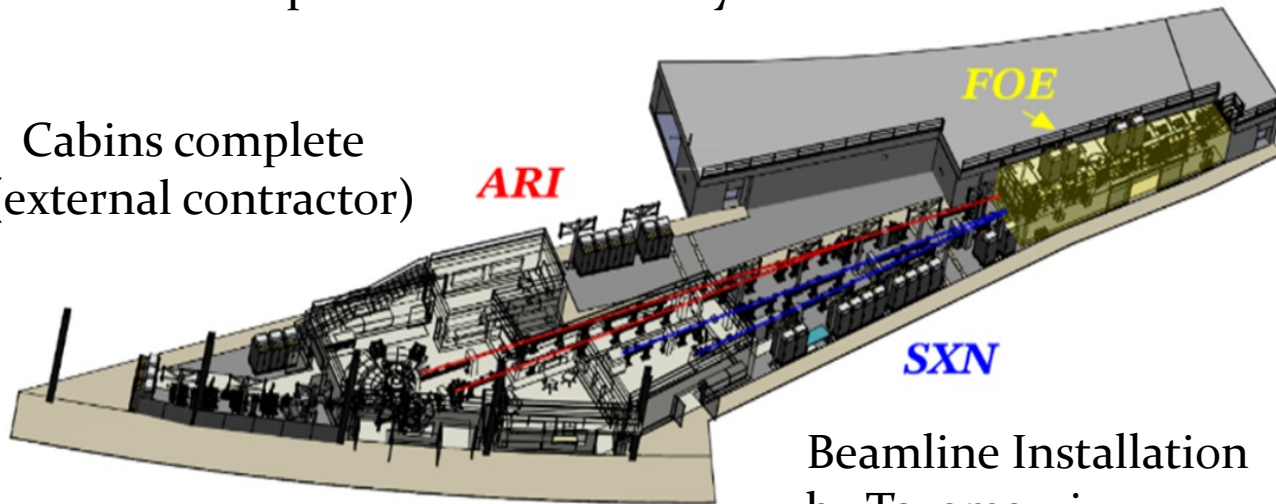
- Beamline and shielding design aided by GB and SR Ray tracings (horizontal/vertical), used to define the impact (position/angle) on beamline components.
- Complete shielding analysis via MC code **FLUKA**<sup>1</sup> and analytical code **STAC8**<sup>2</sup>
  1. F. Ballarini et al., [The FLUKA code: Overview and new developments](#), *EPJ Nuclear Sci. Technol.* **10**, 16 (2024)
  2. Y. Asano and N. Sasamoto, [Development of shielding design code for synchrotron radiation beamline](#). *Radiat. Phys. Chem.* **44**, 133 (1994).
- Radiation Survey for each beamline, from commission → maximum intensity
- Configuration Control for every shielding component strictly enforced

# ARI & SXN

Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability  
Soft X-ray Nanoprobe

Unlike previous cases the NEXT-II hutches were designed and installed by BNL  
- Hutches components fabricated by a NY based metal fabrication shop

Cabins complete  
(external contractor)



Beamline Installation  
by Toyama - *in progress*

Apparently trivial, but:

- Two beamlines in one FOE (same FOE size)
- Source term is monochromatized inside the FOE

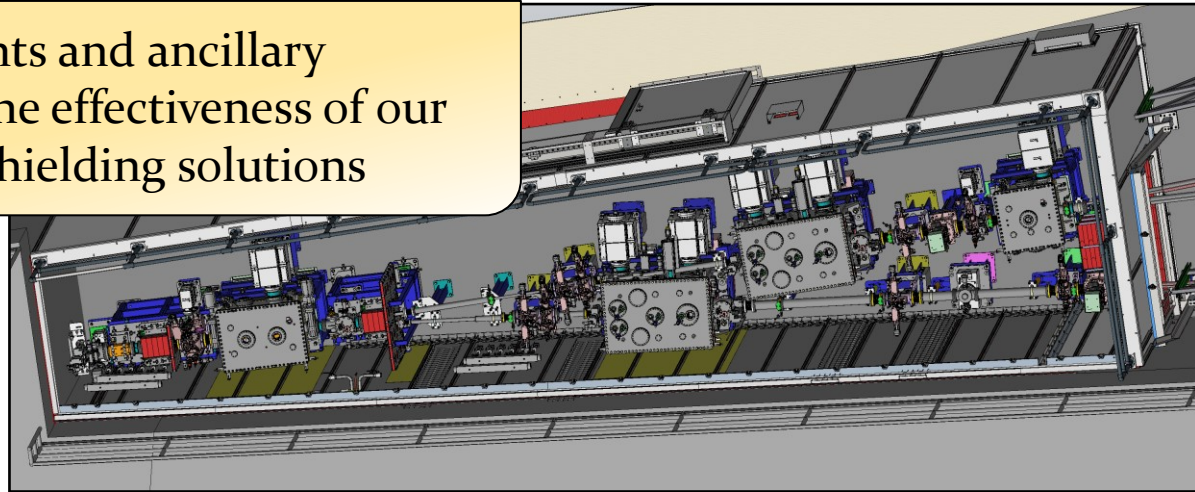
*Due to space constraints  
shielding cannot be  
placed optimally!*

# ARI & SXN

Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability

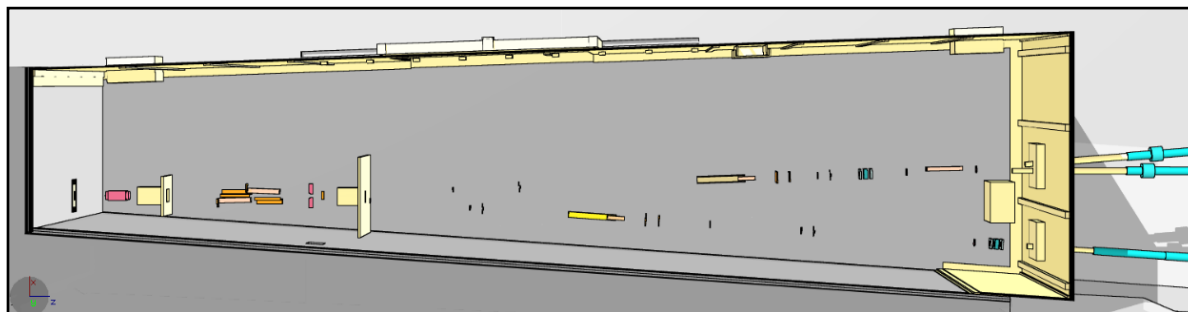
Soft X-ray Nanoprobe

Optical components and ancillary equipment limit the effectiveness of our typical radiation shielding solutions



## FLUKA Model

- Based on the engineering models; iterated until shielding design is validated
- Credits **only** shielding components and/or other scattering relevant features



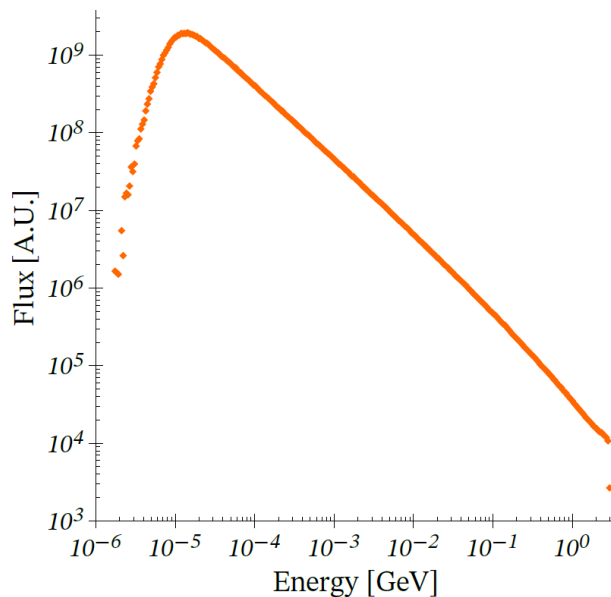
# ARI & SXN

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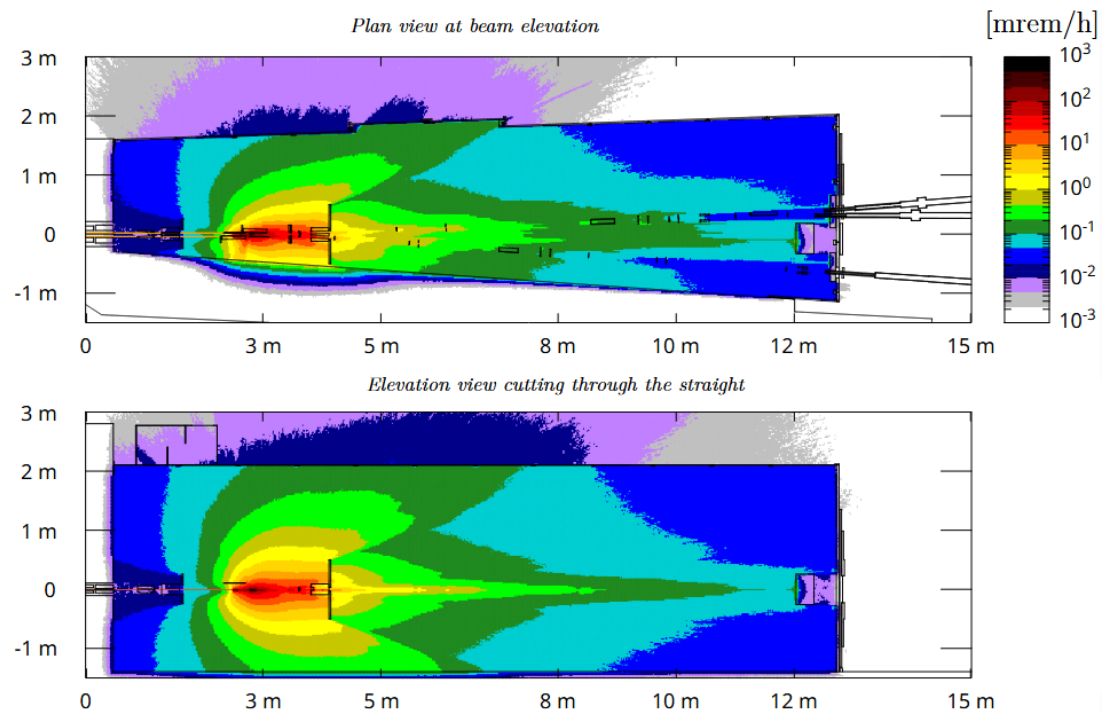
## Gas Bremsstrahlung

Parameter	Value
Undulator section length [m]	15.5
Residual gas pressure [ntorr]	1
Electron beam energy [GeV]	3
Electron beam current [mA]	500
GB power [ $\mu$ W]	17



Source term generated via a two-step FLUKA simulation using an estimated residual gas composition.

- R. S. Augusto et al., "ARI-SXN beamlines radiation shielding analysis" *Proceedings from SATIF-15, 2022*



# ARI & SXN

Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability

Soft X-ray Nanoprobe

## Gas Bremsstrahlung

Shielding optimization accounts for the different types of radiation produced.

- Shielding material and dimensions specified accordingly.

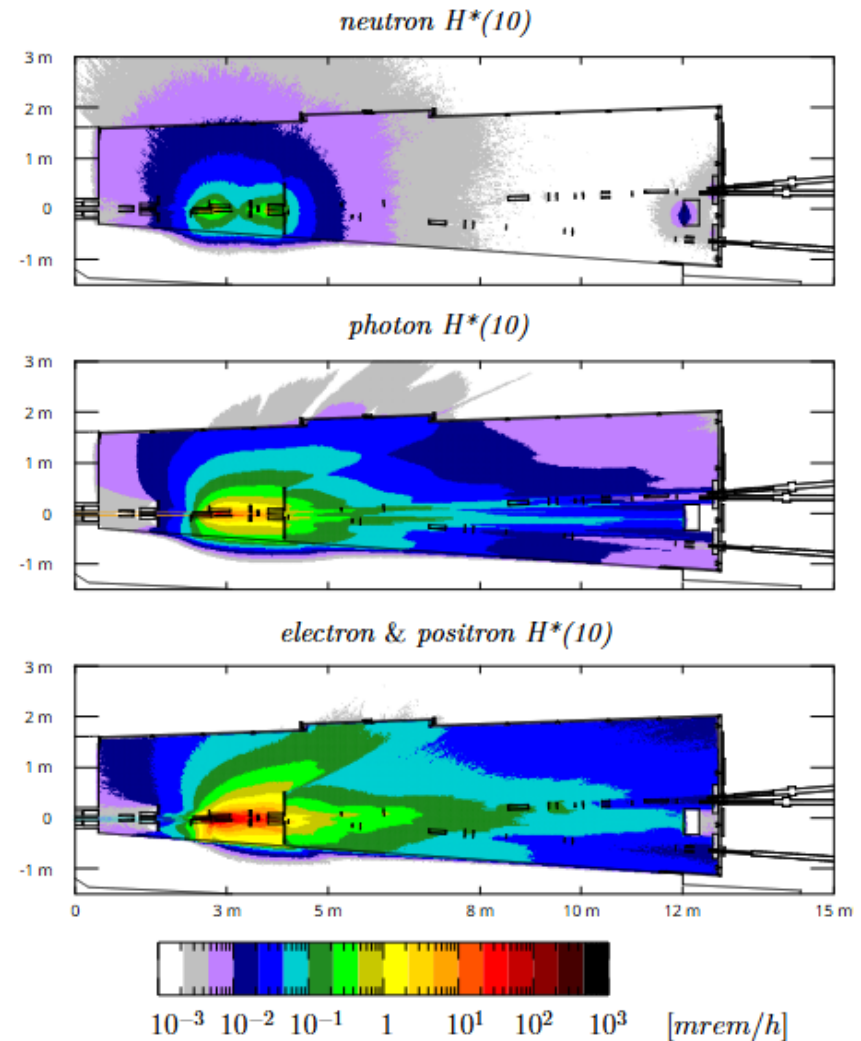
Multiple scattering scenarios are simulated based on the ray tracings beam limits.

- Validation of shielding for worse case scenarios

Whenever shielding or credited beamline components are changed during design the results are re-calculated

- Ensuring compliance with radiological limits

Minor GB radiation leaks downstream

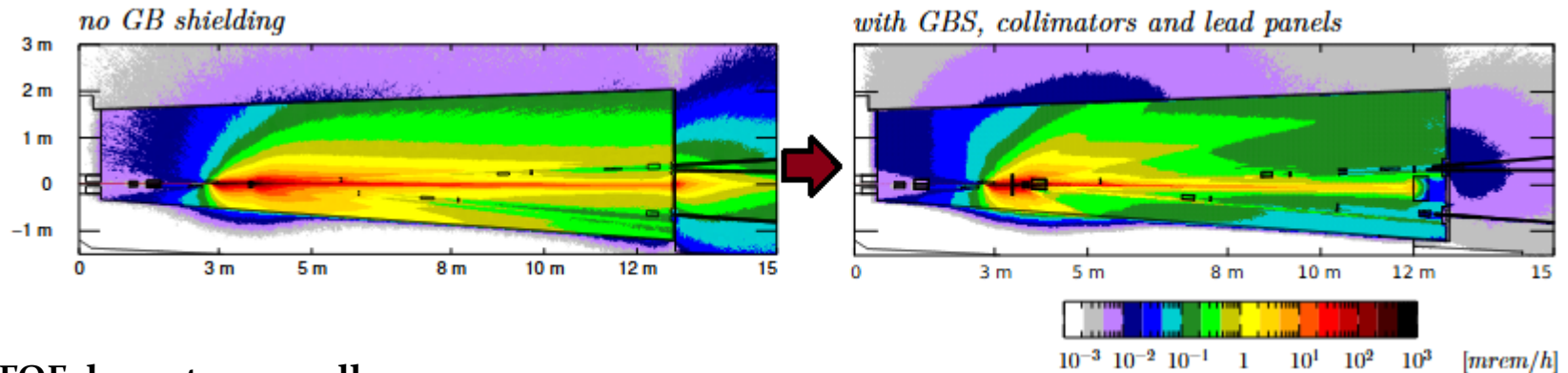


# ARI & SXN

Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability

Soft X-ray Nanoprobe

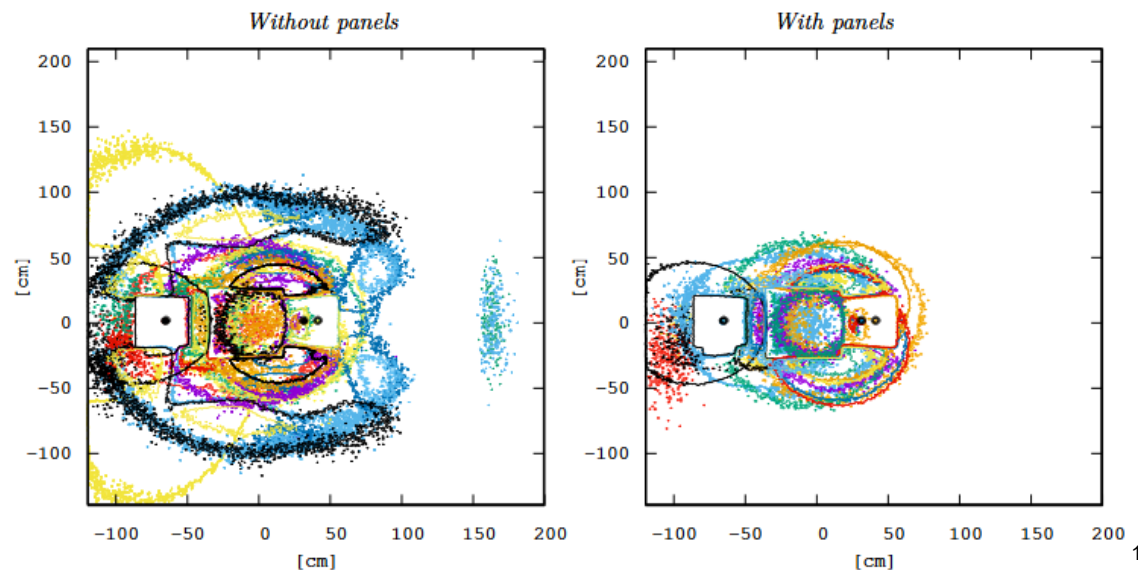
Determine preliminary shielding needs inside the FOE



**FOE downstream wall analysis:**

Each contour color represents a contact  $H^*(10) > 0.05$  mrem/h for a different case.

**Shielding inside the FOE optimized to minimize the need for customized shielding outside of the FOE.**



# ARI & SXN

Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability  
Soft X-ray Nanoprobe

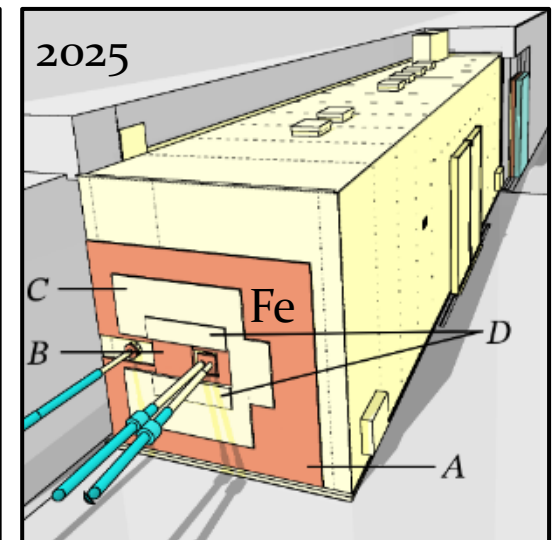
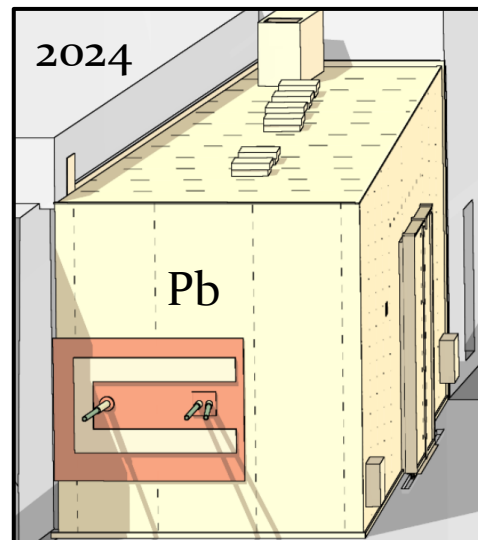
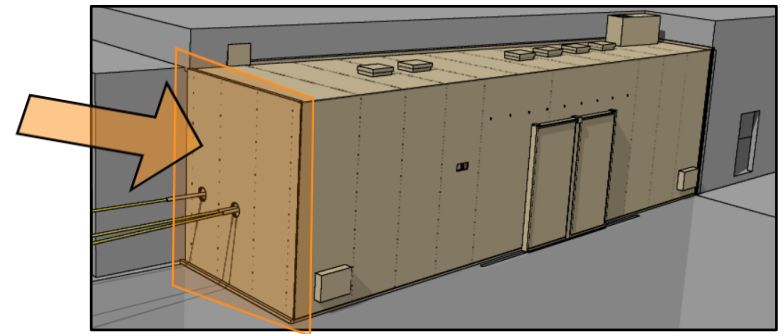
**External shielding** defined using attenuation factors for worst case scenarios and adapted as design matures. Flexible but still a risk...

## Pros:

- 1 – Still less costly than doubling the FOE D/S wall;
- 2 – no risk delaying the beamline validation due to shielding interference with components.

## Cons:

- 1 – Definitely not elegant;
- 2 – More simulation work than when addressing the problem “at the source”.



# ARI & SXN

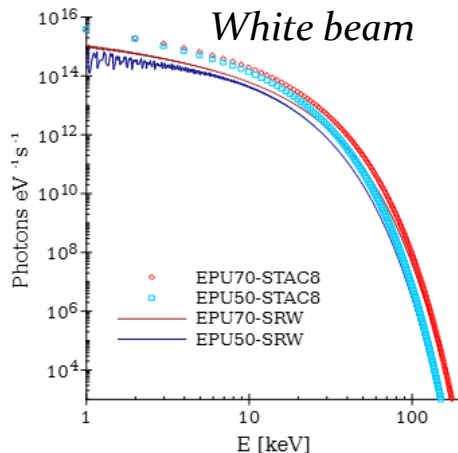
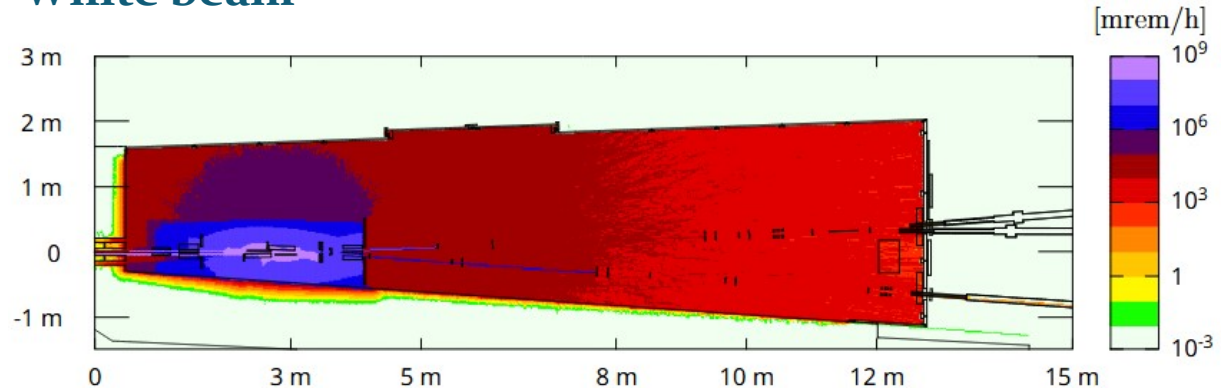
Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability

Soft X-ray Nanoprobe

## Synchrotron radiation – White beam

Beam line	ARI	SXN
Length [m]	2	2
Period [mm]	70	50
Peak Magnetic Field [T]	1.149	0.981
Undulator parameter $K_{eff}$	7.70	4.63
Horizontal fan angle [mrad]	1.68	1.15
Vertical fan angle [mrad]	0.73	0.71
Maximum Power [kW]	7.9	5.4

NB: Power entering the FOE is at most 893.5 W (ARI) and 544.5 W (SXN)



### SRW<sup>3</sup> & STAC8 to validate source term

3. O. Chubar and P. Elleaume, "Accurate And Efficient Computation of Synchrotron Radiation In The Near Field Region", *EPAC98 Proceedings*, 1177-1179 (1998).

FLUKA used to mitigate floor- and sky-shine, and leaks through penetrations - Shielding tested with conservative radiological assumptions (via power assumptions, ray tracing, minimal shielding).

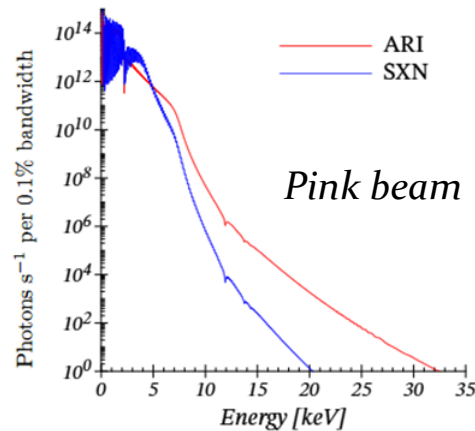
Help identify locations where excursions from the background are more likely and to be more thoroughly examined during the commissioning process.

# ARI & SXN

Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability

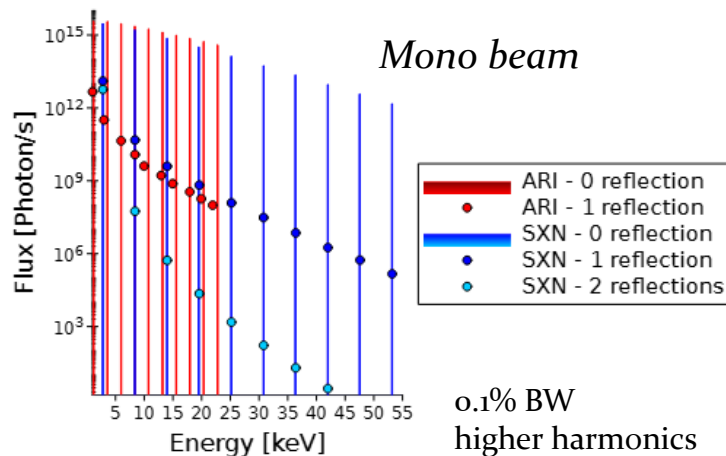
Soft X-ray Nanoprobe

## Synchrotron radiation – Pink beam & monochromatic beam

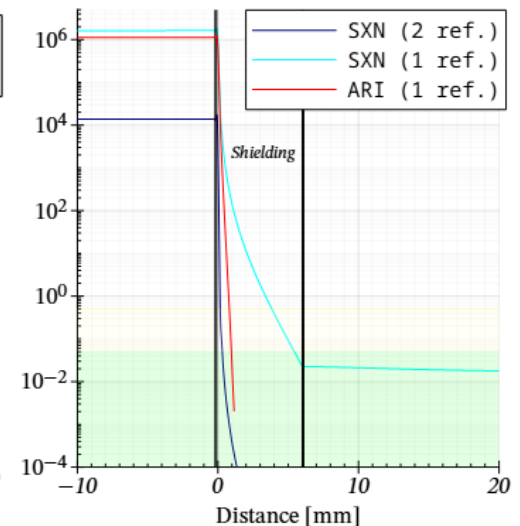
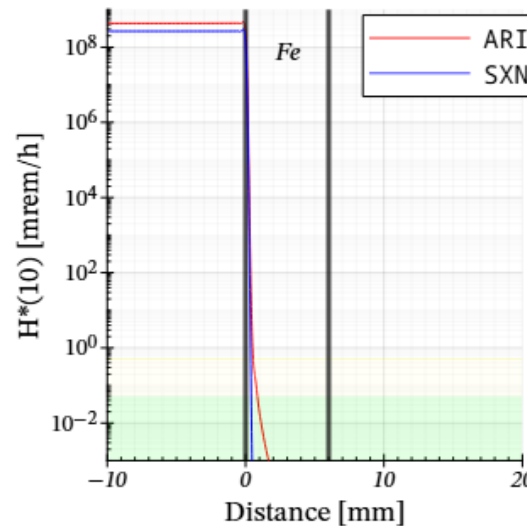


**Beam is monochromatized inside the FOE; Pb covering the upstream section of beam transport pipe due to SGB shine**

- Worst case pink beam sources and monochromatic information provided by NSLS-II scientists and reproduced via STAC8/FLUKA
- FLUKA employed to “stress the shielding” in scenarios with conservative beam direction, shielding or higher harmonics



0.1% BW  
higher harmonics



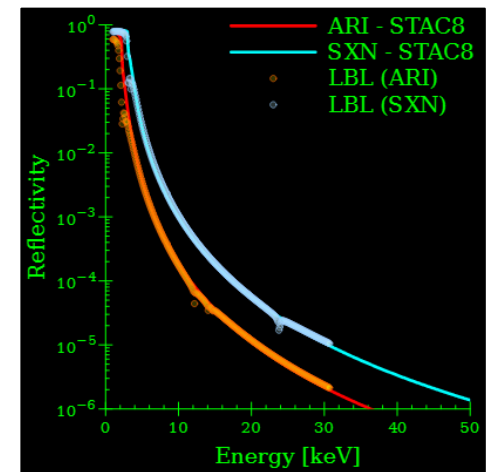
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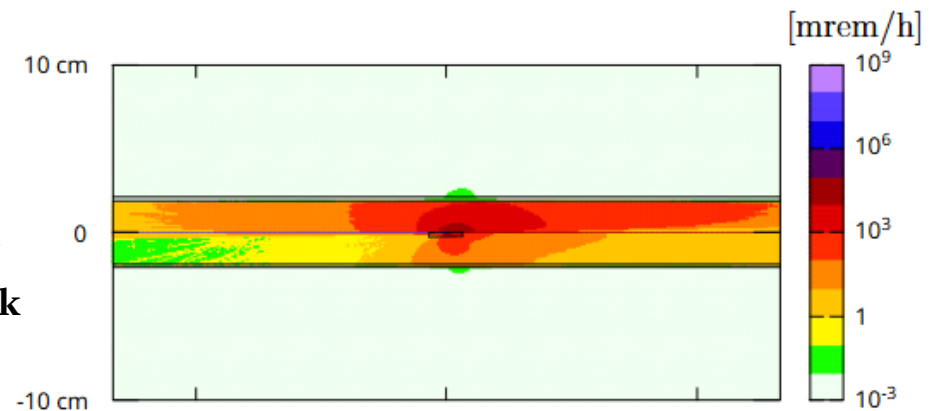
- Validation of reflectivity results when performing radiological calculations with pink and monochromatic beam via STAC8 and LBL data from - B. L. Henke, E. Gullikson, and J. Davis, *X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92, Atomic Data and Nuclear Data Tables* 54(2), 181 (1993).

Since 2024 also FLUKA (see K. Batkov's presentation in this Radsynch edition: "Current FLUKA status and Synchrotron Radiation Sources application examples")



## Soft X-ray dosimetry studies to define beam transport pipe thickness

- Shielding is specified for conservative source terms and scattering events.
- Special attention given to sensitive locations such as bellows and viewports.
- **Simulation of fault scenario when the SXN (1 reflection) mono beam intercepts a Si disk at a glancing angle inside of the pipe.**



# ARI & SXN

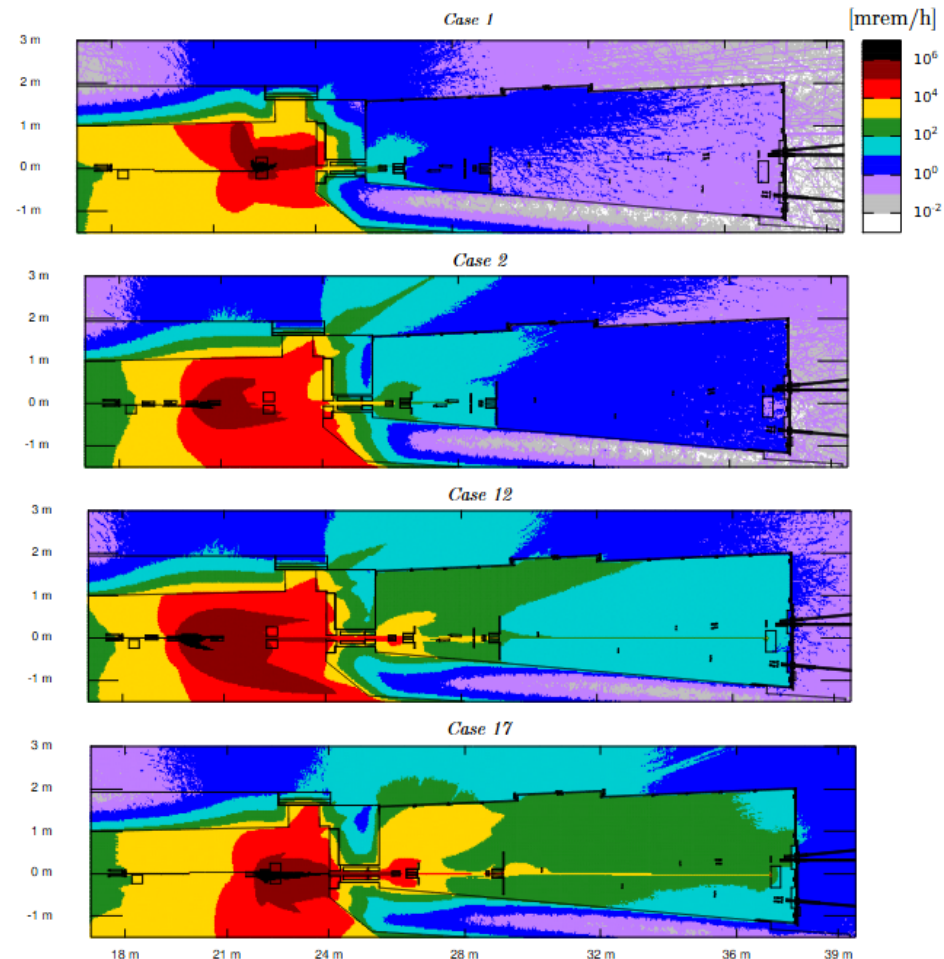
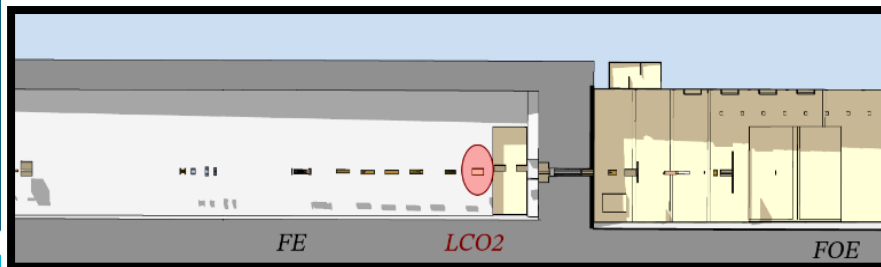
Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability

Soft X-ray Nanoprobe

## Top Off Radiation Safety (TOSS)

Parameter	Value
Electron beam energy [GeV]	3
Injection beam charge [nC]	15
Booster to storage ring injection charge rate [ $\text{nC min}^{-1}$ ]	45

- To establish the safety of top-off injection, the TOSS must ensure that *in the event of a faulty combination of lattice magnetic field settings and beam energy all errant particles will be captured before reaching a designated safe point - LCO<sub>2</sub> – in the front end*



# ARI & SXN

Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability

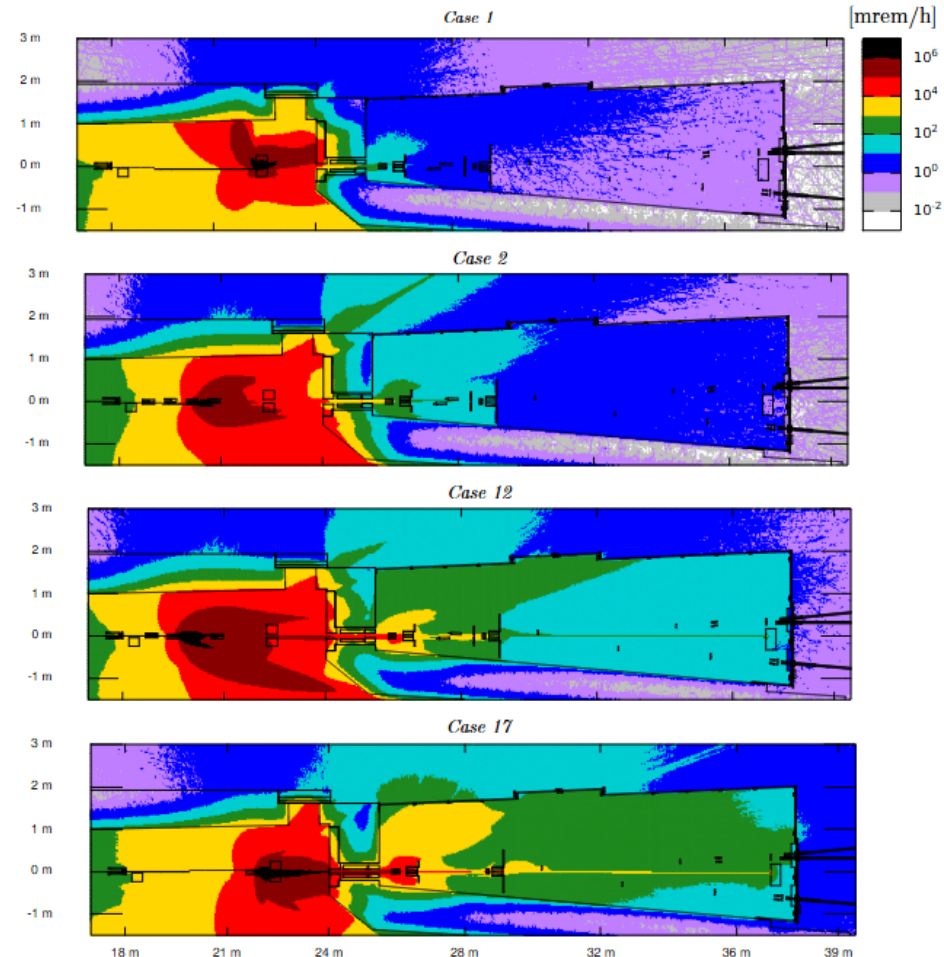
Soft X-ray Nanoprobe

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- ARI & SXN have **wider front end apertures** and justified a detailed backward particle tracking analysis to ensure validity of safe points.
- FLUKA is employed to systematically map the dose rates outside of the shielding in various conservative configurations – e.g., beam impinging the LCO<sub>2</sub> near its aperture

**Focus on shielding weakpoints!**



# ARI & SXN

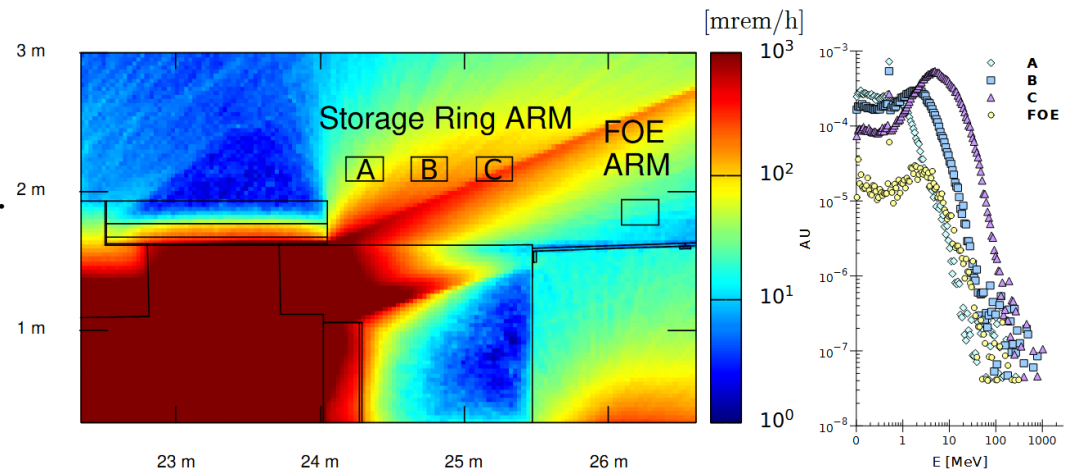
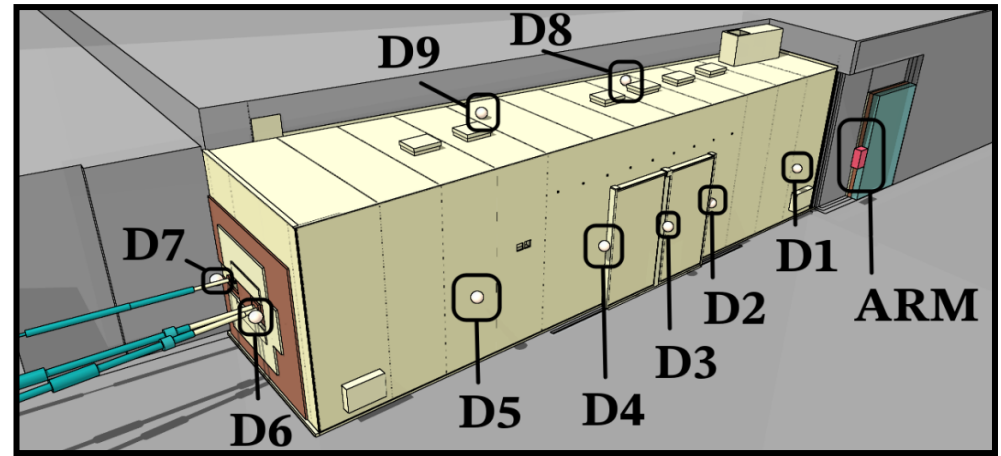
Angle-Resolved Photoemission Spectroscopy (ARPES) and Resonant Inelastic X-ray Scattering (RIXS) with Imaging capability  
Soft X-ray Nanoprobe

## Top Off Radiation Safety (TOSS) – Radiation monitoring

**Rationale** - Rather than completely shield for fault events, radiation monitoring is utilized to shut off the beam at 5 mrem/h, ensuring accrued doses remain lower than 100 mrem. (control room is notified at 1 mrem/h).

A Storage ring ARM location was defined downstream of the Ratchet Door to promptly detect excursions.

- Its location was optimized to more effectively detect radiation leakage.
- Depending on the results, an FOE ARM might be needed as well.

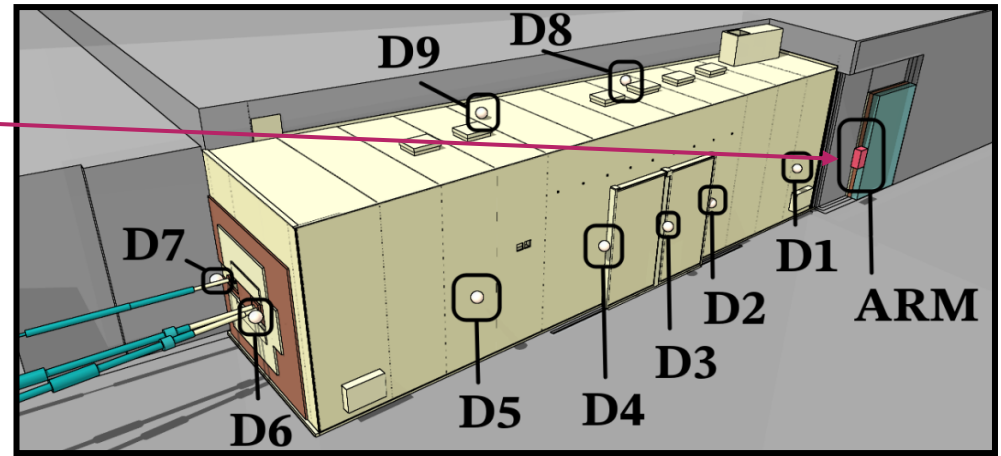
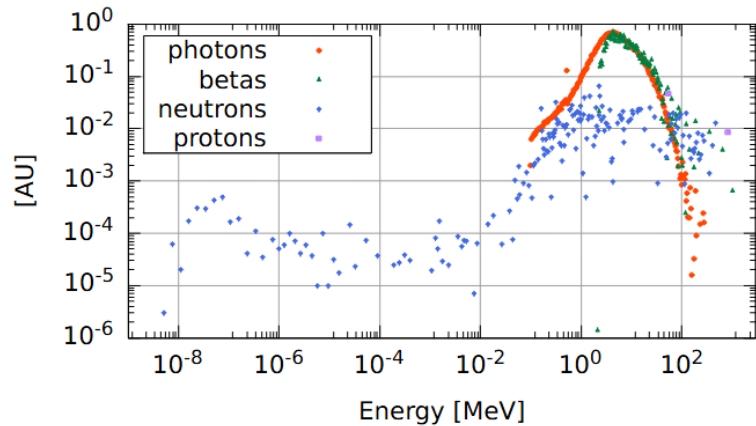


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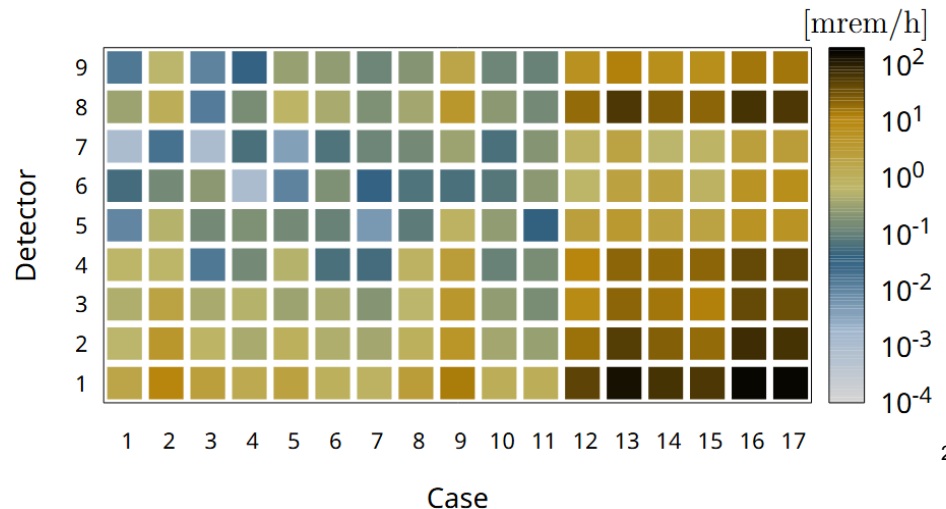
Soft X-ray Nanoprobe

## Top Off Radiation Safety (TOSS) – Radiation monitoring



Virtual dosimeters (D) placed around the FOE assist in fully characterizing radiation fields for fault events.

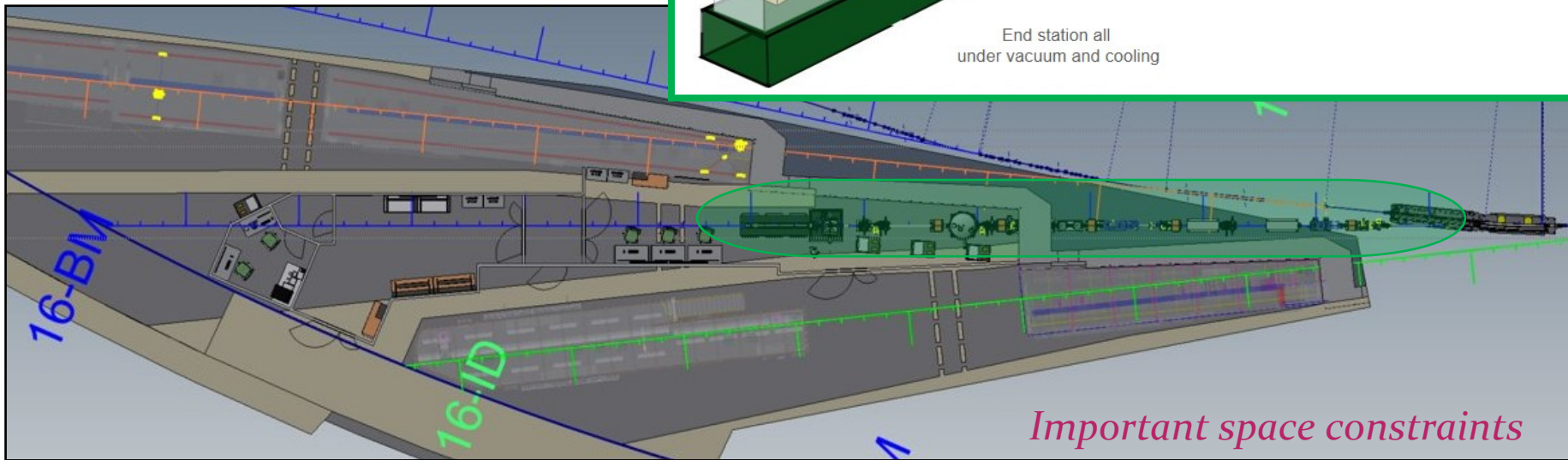
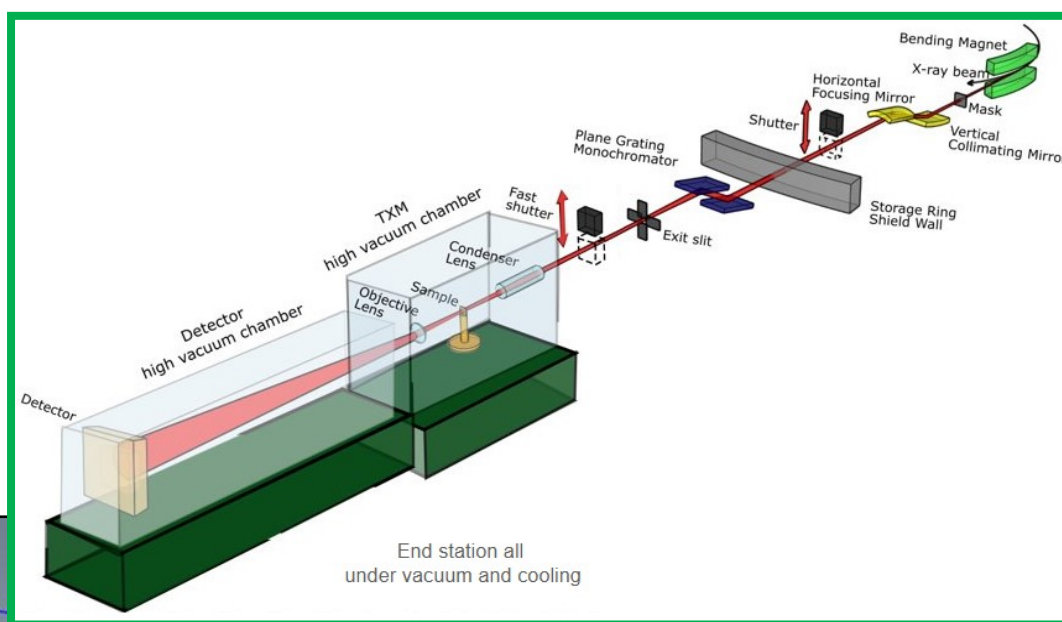
- Essentially helping define the optimal location for the FOE ARM.
- Extensive number of fault scenarios simulated for each configuration.



# QCT

Quantitative Cellular Tomography

1<sup>st</sup> NEXT-III project beamline  
- Currently in the design phase



*The QCT beamline design is optimized for high-throughput and high-resolution 3D bioimaging that fills an important gap between atomic-resolution structural biology and spectroscopic microscopy and imaging at NSLS-II.*

- D. Yazak et al, [NEXT-III at NSLS-II: A New Approach to Beamline Design and Development](#),  
*Synchrotron Radiation News*, **38**(1), 10–13, 2025.

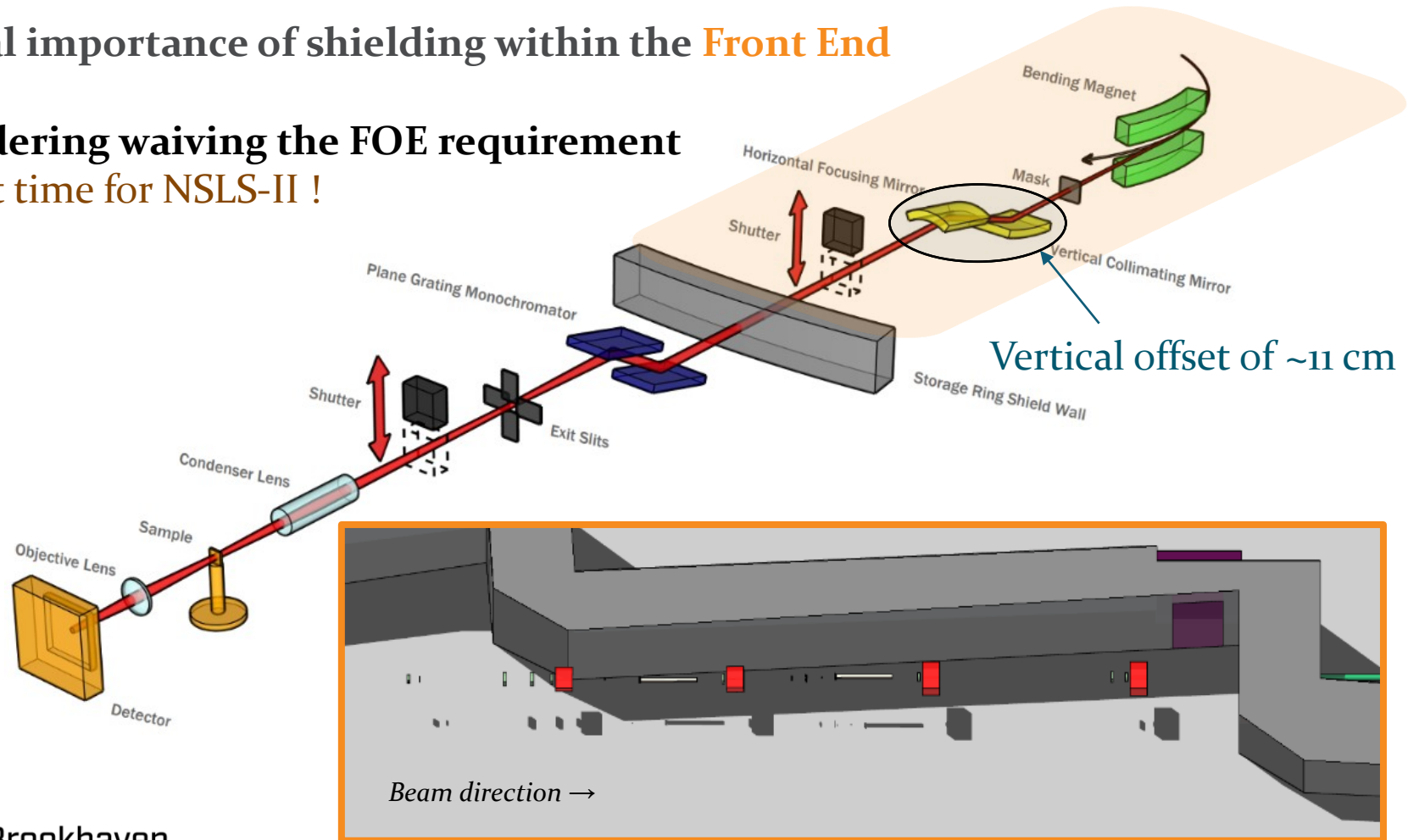
# QCT

Quantitative Cellular Tomography

Critical importance of shielding within the **Front End**

Considering waiving the FOE requirement

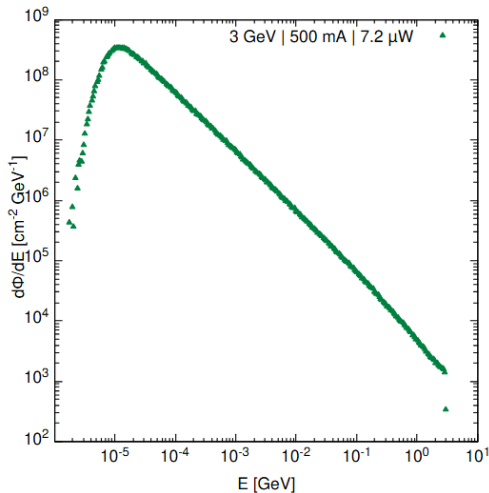
- First time for NSLS-II !



# QCT

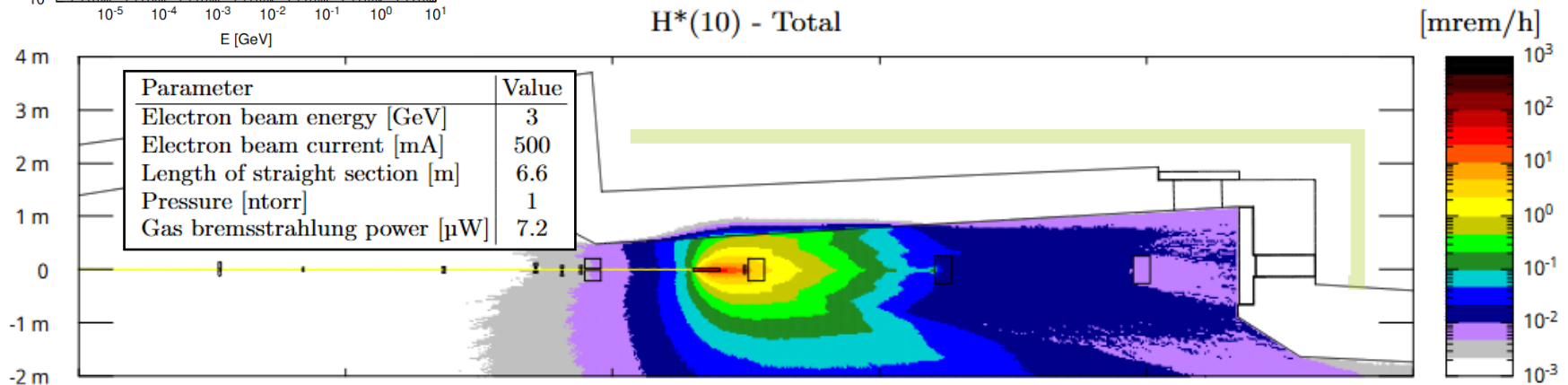
## Quantitative Cellular Tomography

### Gas Bremsstrahlung



Preliminary FLUKA calculations to determine whether the absence of an FOE would be acceptable from a radiological standpoint

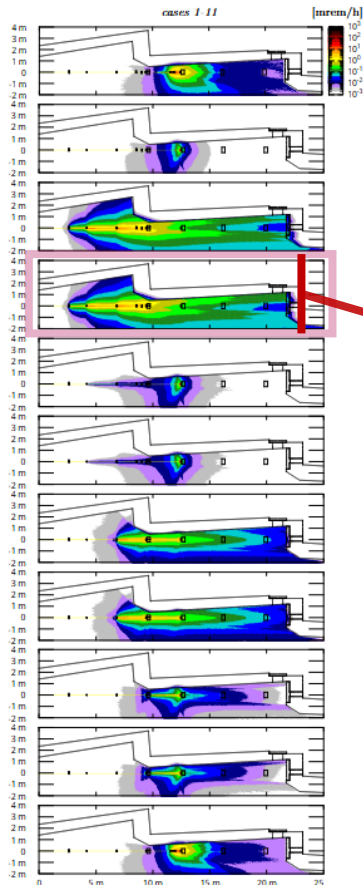
- Beamline design & shielding optimization ongoing to ensure GB-derived leaks cannot proceed outside the Front End.
- **Ideally** - full access to the beamline in the experimental hall (no exclusion zone, no shielding enclosure)



# QCT

## Quantitative Cellular Tomography

### Gas Bremsstrahlung

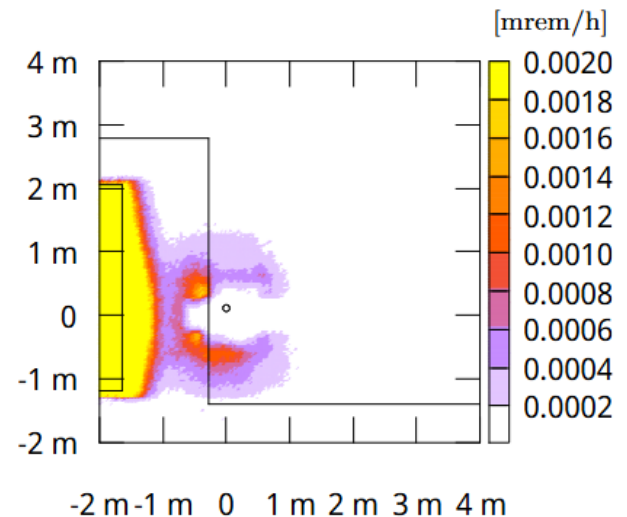


Preliminary FLUKA calculations to determine whether the absence of an FOE would be acceptable from a radiological standpoint

- Beamline design & shielding optimization ongoing to ensure GB-derived leaks cannot proceed outside the Front End.
- **Ideally** - full access to the beamline in the experimental hall (no exclusion zone, no shielding enclosure)

Example of contact  $H^*(10)$  scored outside of the storage ring in one of the worst case scenarios.

This design has also the potential to be more exposed to **injection faults**



# QCT

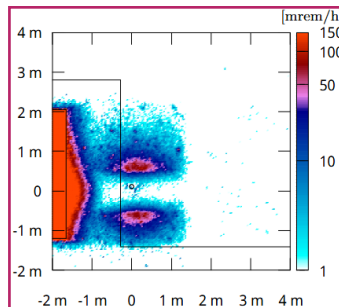
## Quantitative Cellular Tomography

### Top Off Radiation Safety (TOSS)

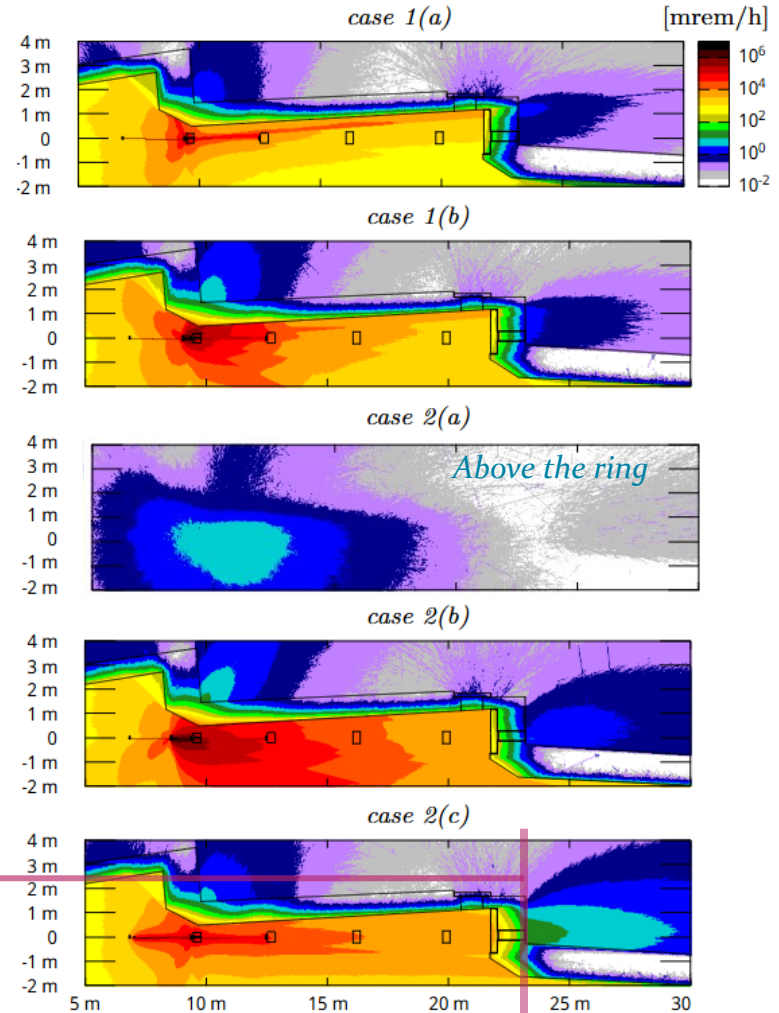
Parameter	Value
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Booster to storage ring injection charge rate [nC min <sup>-1</sup> ]	45

- Given its non-standard design, and the fact that might not rely on the FOE shielding, the effect of injection faults is being evaluated at a very early stage.
- Placement of ARMs will be determined once design is finalized - simulations will be useful to minimize the number of monitors required for TOSS

Contact H\*(10) outside of the storage ring

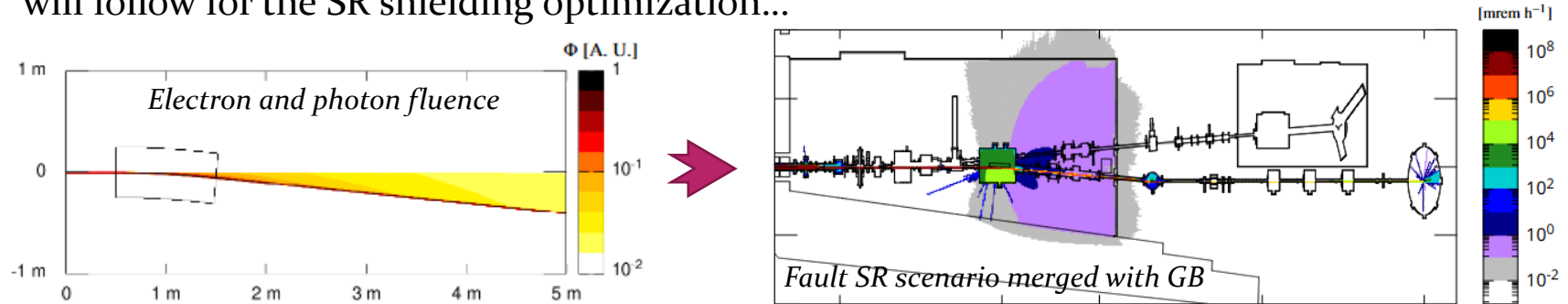


### Top-Off fault cases



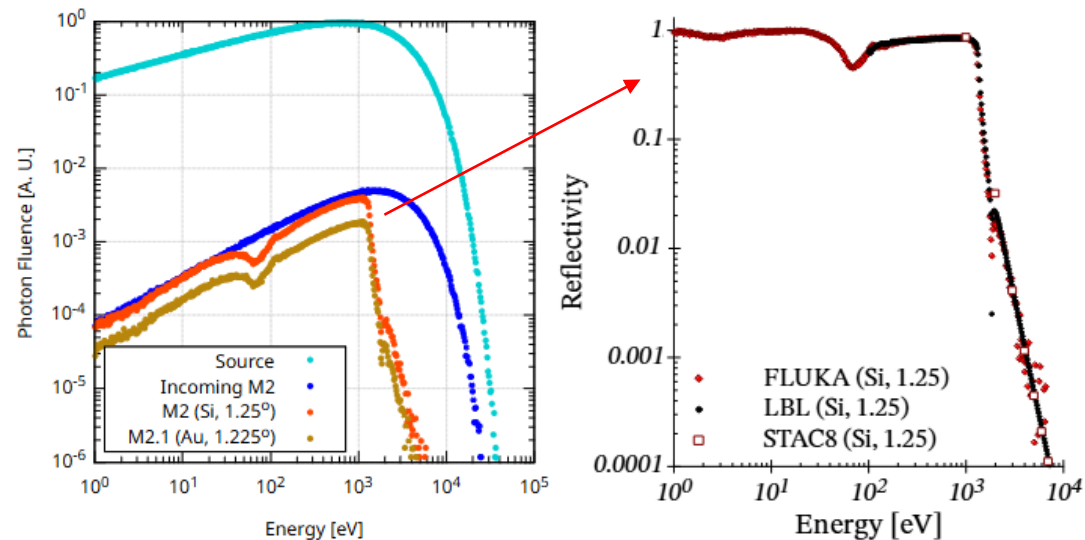
# Ongoing and Future Work

- Design evolving quickly to mitigate risks due to GB and TOSS Injection faults
- “Source to endstation approach\*”, previously employed for another work (examples below), will follow for the SR shielding optimization...



...including employing recent FLUKA improvements (e.g., reflectivity with multi layer mirrors) and cross validation between platforms to ensure compliance and minimize errors

\*R.S Augusto & R.J. Lee, [Recent radiological studies at NSLS-II using the Monte Carlo code FLUKA](#), *SATIF-16*, 2024 (in press)



# Concluding remarks

As the end of the NEXT-II project draws near, the ARI & SXN shielding design experience showed that:

- Even relatively simple beamlines can create challenging issues from a radiological standpoint if shielding cannot be optimally placed.
- Careful planning and frequent/numerous simulation iterations are needed to prevent an escalation of custom shielding complexity.
- Simulation work is invaluable to validate alternative configurations and ensure that the beamline operation will be radiologically compliant.

We are already applying the above lessons to NEXT-III, starting with QCT. The current priority is to finalize (critical aspects of) the beamline design and ensure dose rates remain compliant outside of the shielding.

## Acknowledgments

Past and present colleagues at NSLS-II and BNL's Radiological Control Division

# END

Questions?

