Preliminary neutronic design of the ECHIR beamline at ESS

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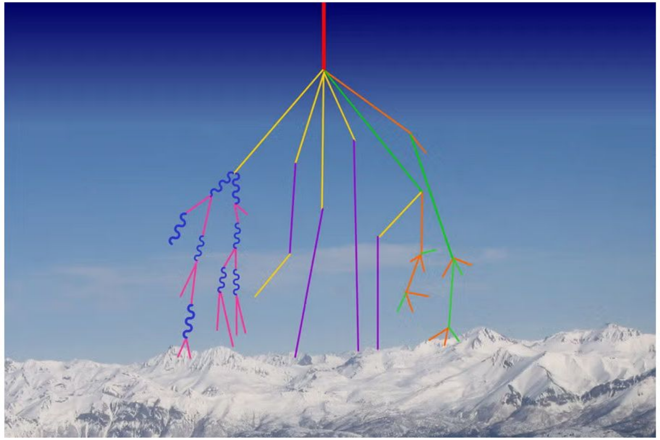
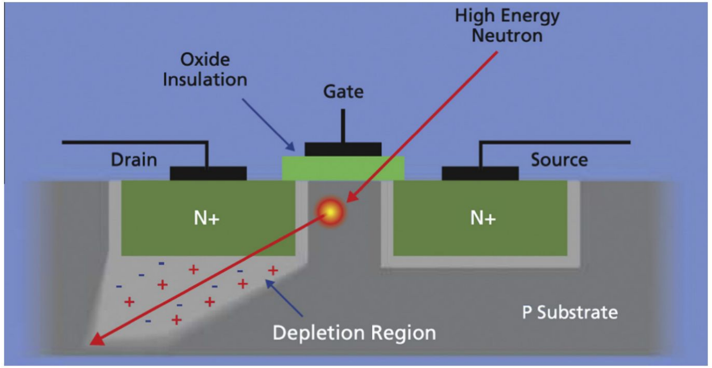
Outline

- Introduction and motivation
- ESS and ECHIR (ESS Chip Irradiation facility) concept
- ECHIR design
- Preliminary neutronic calculations with MCNP6
- Results
- Summary

Motivation

- Electronics used in sectors such as automotive, aviation, and space industries must be qualified against radiation-induced failures
- High-energy atmospheric neutrons may cause radiation-induced degradation (e.g. Single Event Effects (SEE) and displacement damage)
  - → Potential for severe malfunctions, data corruption, and structural damage
- The rate of radiation-induced effects in natural environment is low → accelerated neutron testing is necessary
- Currently, ChipIr at ISIS is the only facility in Europe able to provide a suitable energy spectrum for Cosmic Ray (CR) Robustness testing





Top: UCAR Center for Science Education (Gordon & Russell)
Bottom: L. Ciani & M. Catelani, *A fault tolerant architecture to avoid the effects of Single Event Upset (SEU) in avionics applications*, Measurement 54:256-263, 2014

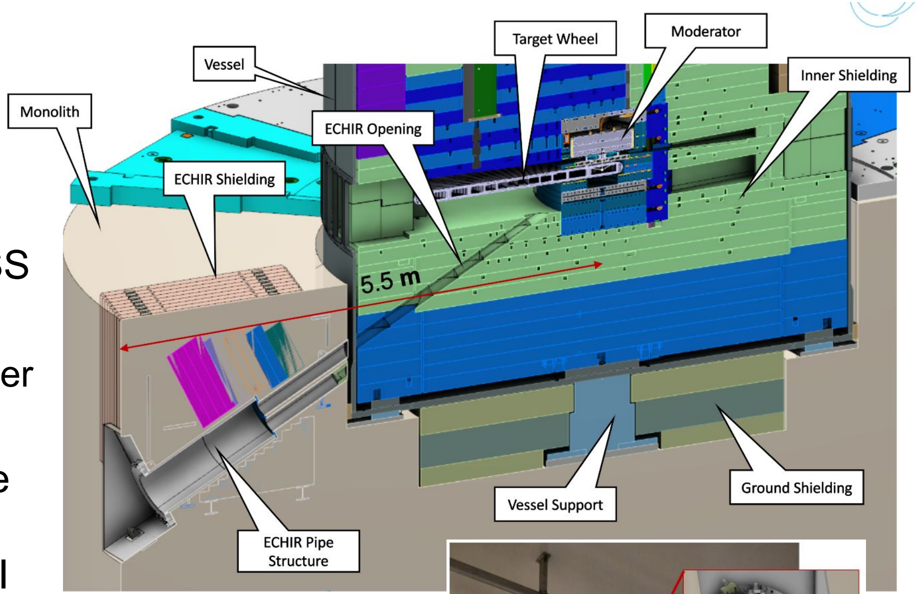
European Spallation Source (ESS) in Lund, Sweden

- Neutron production by spallation of 2 GeV protons on tungsten target
- Designed operation at 5 MW average beam power
- The high-flux and high-energy neutron field provides an ideal environment for CR robustness testing

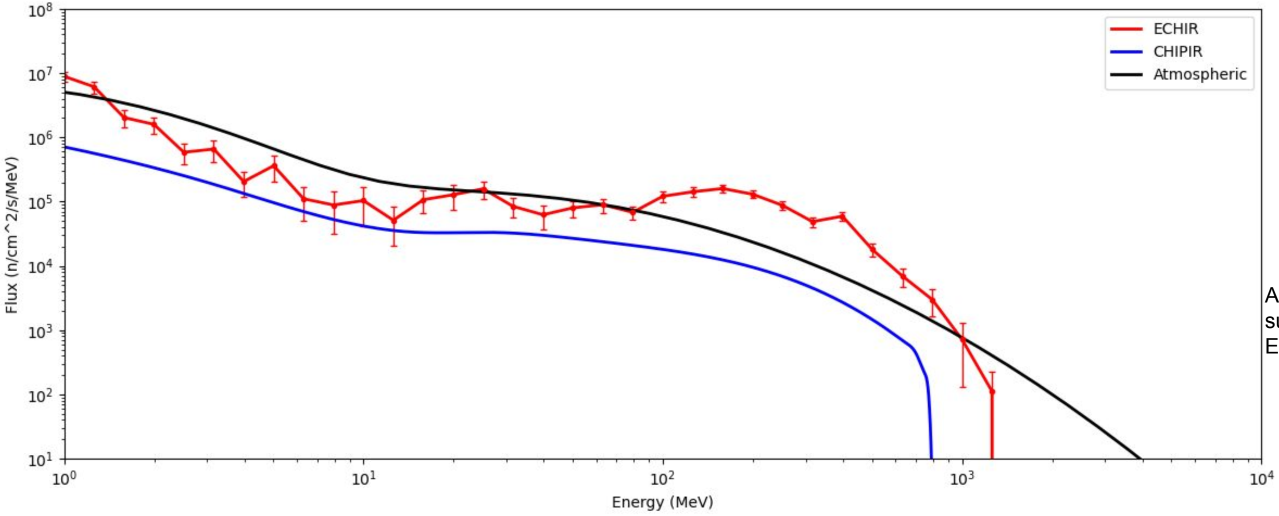
Image: Mickael Tannus/ESS

ESS Chip Irradiation facility - ECHIR

- The ECHIR beamline has been proposed at ESS for CR testing
  - Fast neutron channel and revolver-type shutter already in place
- The beamline is in the forward direction w.r.t the proton beam, and tilted 30° downward from the horizontal → this geometry provides the optimal neutron spectrum
- Once constructed, ECHIR would be able to deliver atmospheric-like neutron spectrum up to ~1 GeV, reaching a flux of $4.3 \cdot 10^7$ n/cm²/s (E > 10 MeV) at the sample position



Expected performance of ECHIR

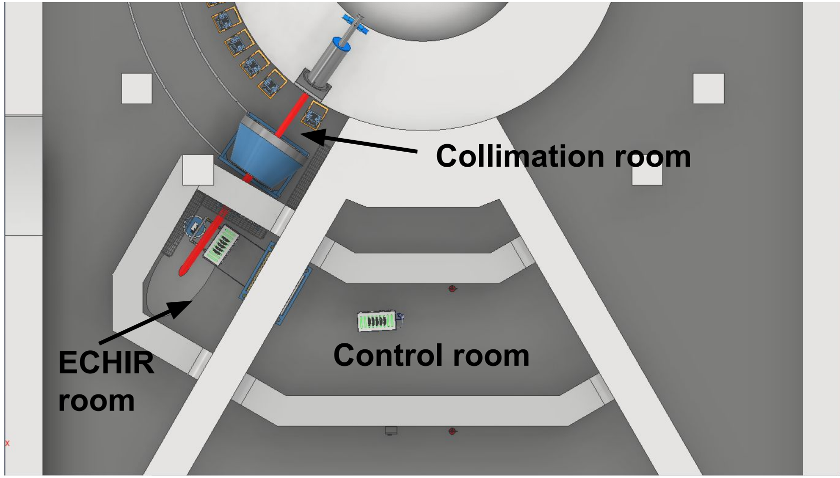


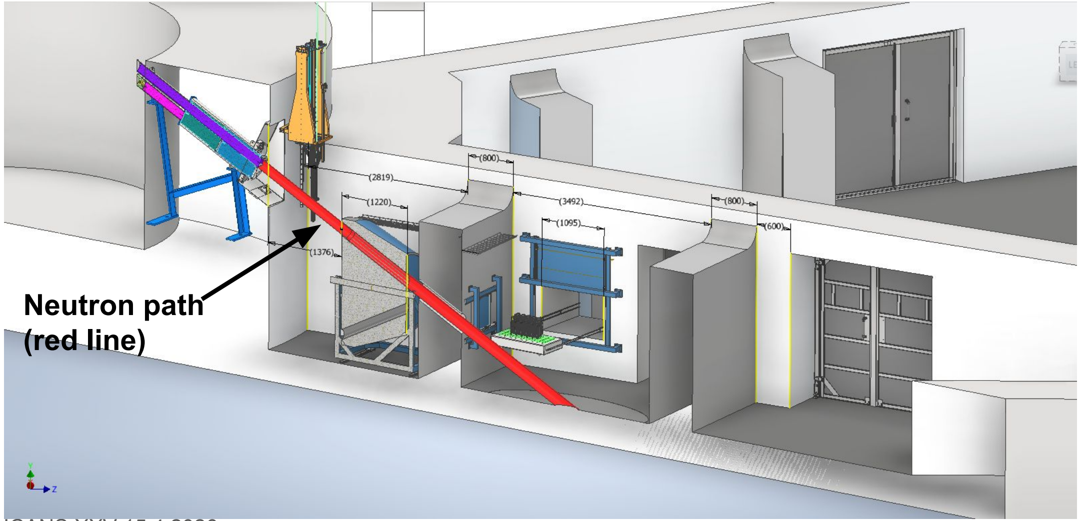
Atmospheric spectrum superimposed and aligned with ECHIR

- Expected neutron flux above 10 MeV approximately 10 times higher at the sample position compared to ChipIr

Proposed ECHIR design

- Neutron beam is collimated with rotating stainless steel collimation wheel
  - Apertures from 5 cm to 20 cm, and fully closed position
- Samples for testing can be directly installed in the room in safe conditions, or using a remote-handling system

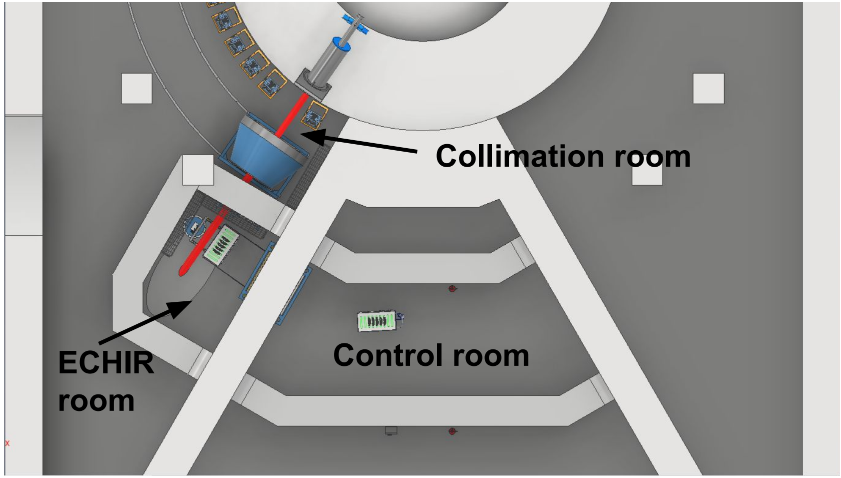




ESS radiation area classifications

- Regular instruments at ESS are classified as “green” supervised area, with a dose rate below 3 μSv/h
- Preliminary shielding studies have been performed with Monte Carlo simulations
  - The goal is to find a shielding configuration that would reduce the dose rate to acceptable level

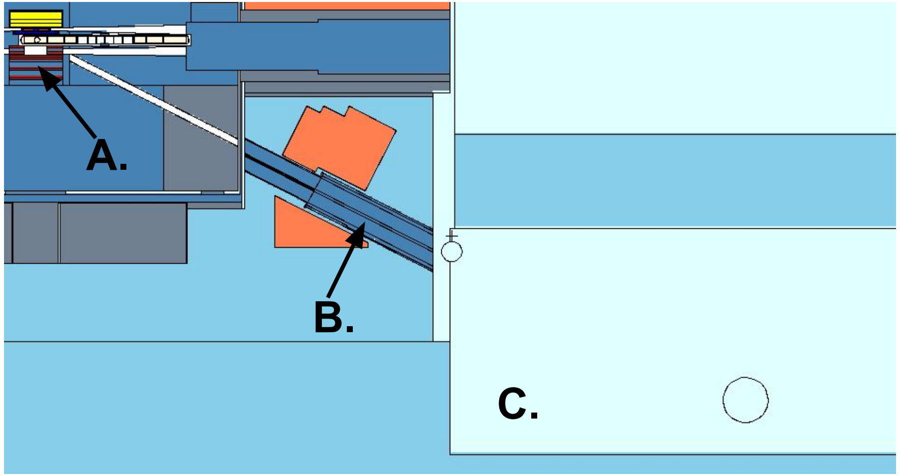
	Non-designated area	Designated radiation areas				
Dose and dose rate - definition						
Criteria/Area classification	White Non-designated area	Green Supervised Area	Blue Controlled Area	Yellow Controlled Area	Red Controlled Area	Magenta Prohibited Area
Potential annual effective dose	<1 mSv	<6 mSv	>6 mSv	>6 mSv	>6 mSv	N/A
Ambient equivalent dose rate	Permanent: 100 μSv/year Non-permanent: 0.5 μSv/h	<3 μSv/h	<25 μSv/h	<2.5 mSv/h	<100 mSv/h	>100 mSv/h



Computational methods: MCNP6.3

- Neutronic calculations were performed with Monte Carlo N-Particle transport code (MCNP6.3)
- Simulation models 2 GeV protons on tungsten target
  - Generated spallation neutron field is transported through the whole beamline geometry
- F4-tally and TMESH mesh tally used for dose rate calculations
- All results have been normalized by proton current corresponding to 5 MW beam power

MCNP model by A. Takibayev



A. Target and moderator
B. Revolver-shutter (closed with stainless steel)
C. (Empty/unmodified) ECHIR room

Starting point: empty ECHIR room

	Dose rate at pos. 1 [mSv/h]	Dose rate at pos. 2 [mSv/h]
Revolver-shutter closed	3.03 ± 0.38	0.34 ± 0.04
Revolver-shutter open	$(464 \pm 19)\cdot 10^3$	$(99 \pm 4)\cdot 10^3$

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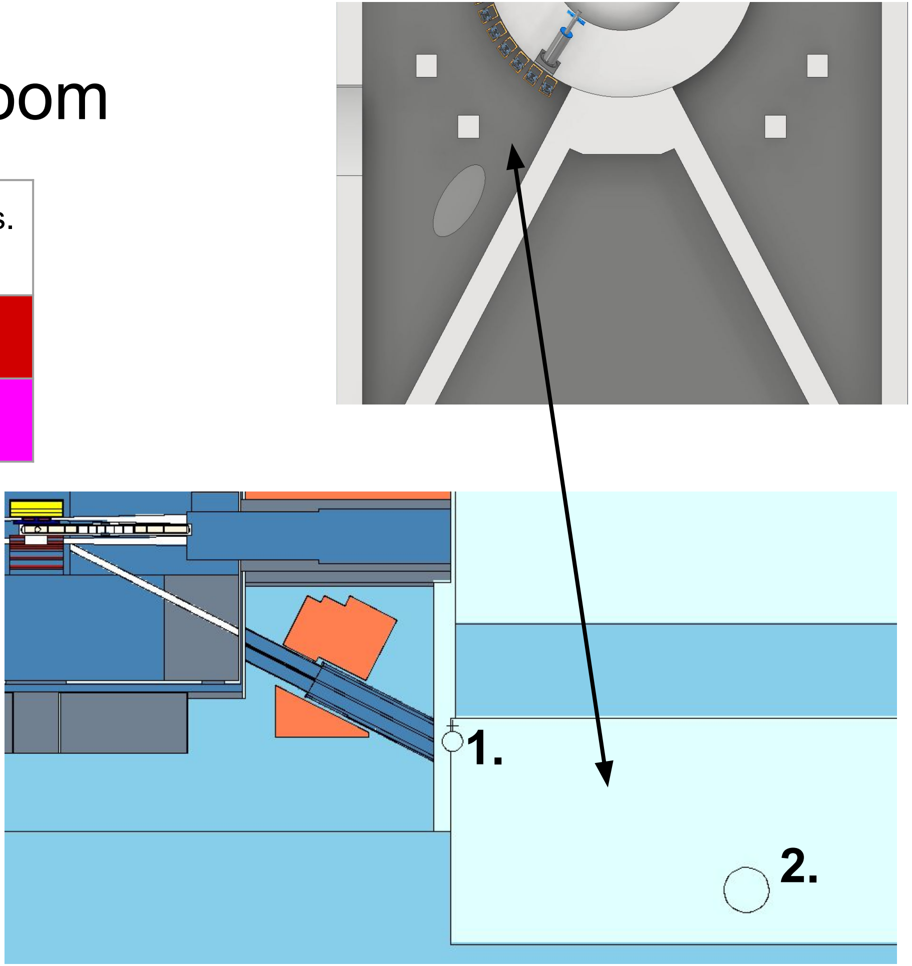
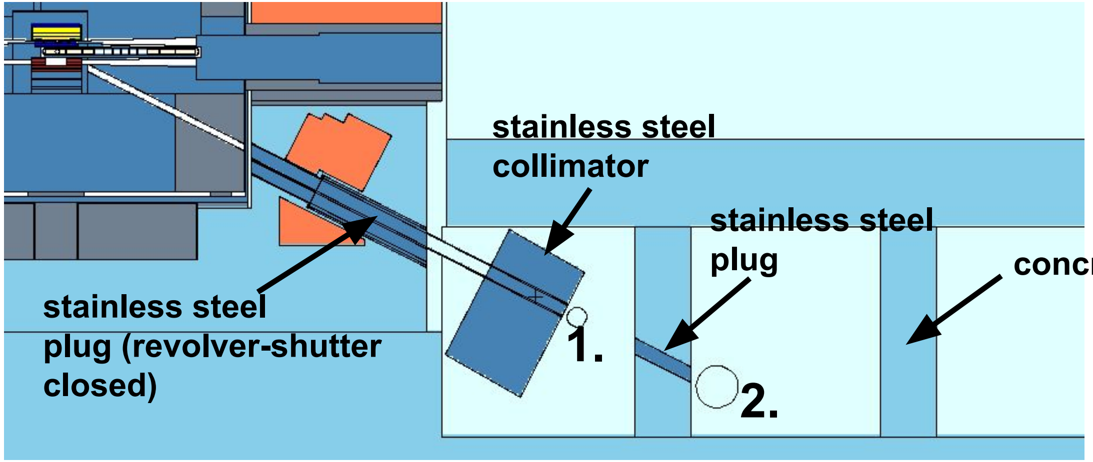
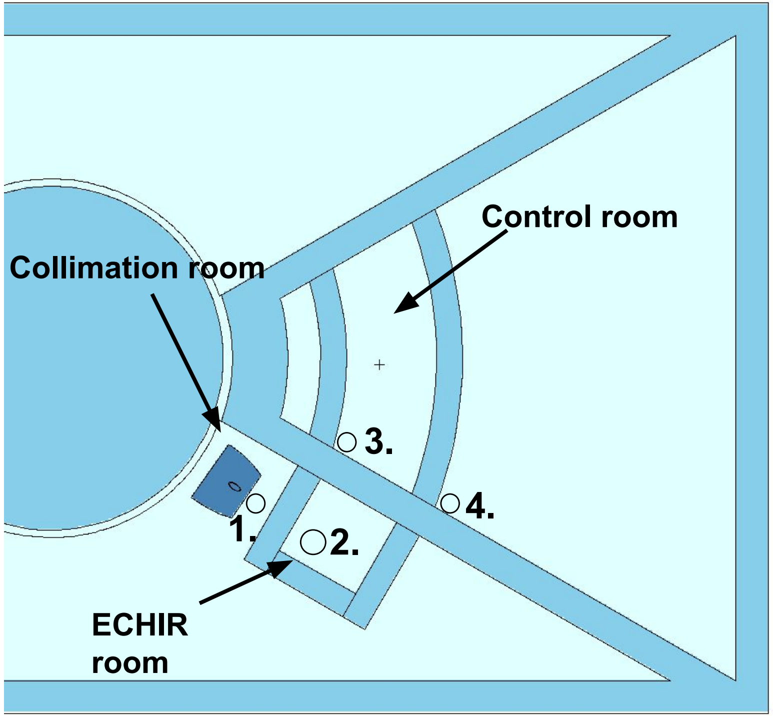


Dose rate with the neutron path closed is ~1000x too high for green level!

Simulation geometry: ECHIR beamline

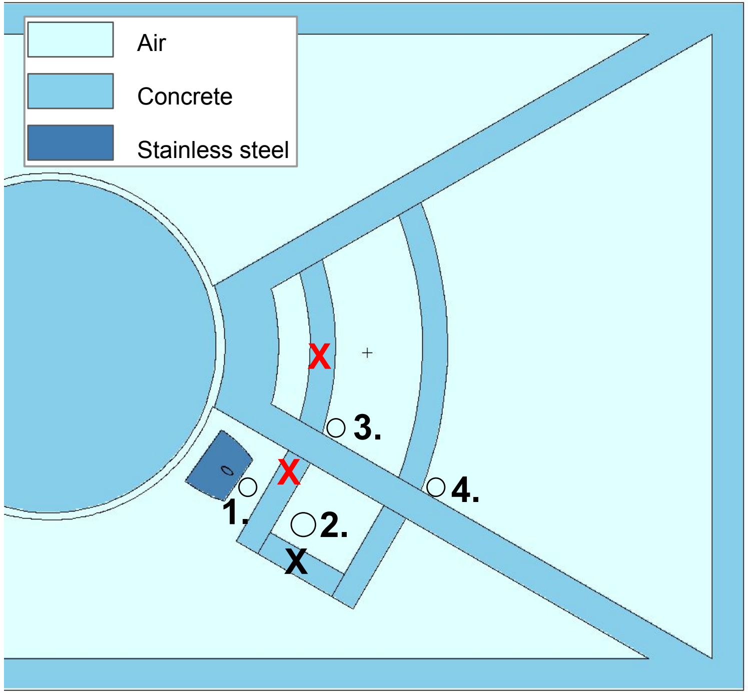
- Dose rate tallied at four key locations:
  1. Collimation room (exit of the collimator)
  2. ECHIR room (sample position)
  3. Control room
  4. Outside of control room

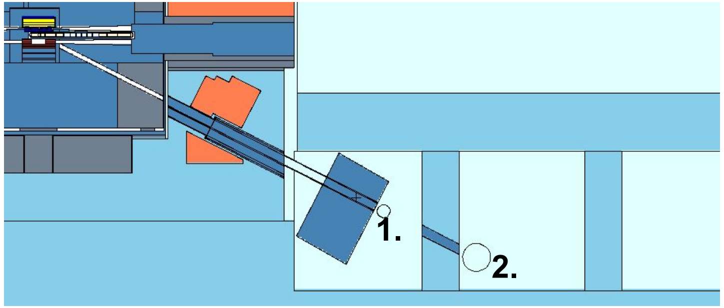




Materials and shielding geometry

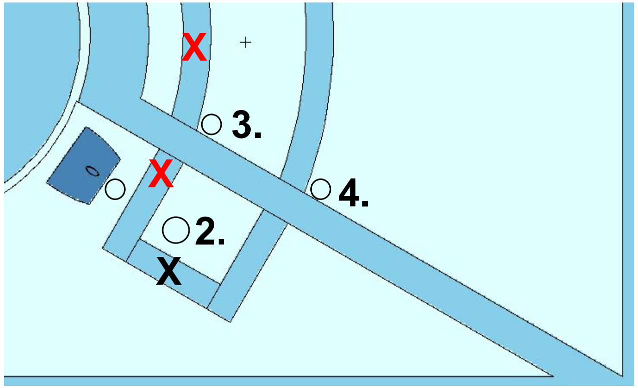
- Shielding materials used
  - Stainless steel (SS316L) (ρ = 7.85 g/cm³)
  - Regular concrete (ρ = 2.35 g/cm³)
  - Heavy concrete (with MagnaDense) (ρ = 3.8 g/cm³)
- Walls marked as '**X**' or '**X**' either regular or heavy concrete in the calculations
  - All other walls are regular concrete
- Walls marked as '**X**' can additionally be either 80 cm or 120 cm thick
- Revolver-shutter closed with stainless steel and collimator in closed position





Impact of the wall material and thickness to the dose rate

Material and thickness	Pos. 2 [µSv/h] (ECHIR room)	Pos. 3 [µSv/h] (Control room)	Pos. 4 [µSv/h]
Regular concrete, 80 cm wall	19.6 ± 2.5	22.8 ± 2.7	2.9 ± 0.5
Regular concrete, 120 cm wall	7.3 ± 0.7	9.2 ± 1.6	0.8 ± 0.3
Heavy concrete, 80 cm wall	8.7 ± 0.9	11.2 ± 1.8	1.2 ± 0.3
Heavy concrete, 120 cm wall	2.3 ± 0.2	5.0 ± 0.8	0.3 ± 0.09



- Maximum dose rate reduction is achieved with 120 cm of heavy concrete
- More shielding needed for the control room to bring dose rate to the green level

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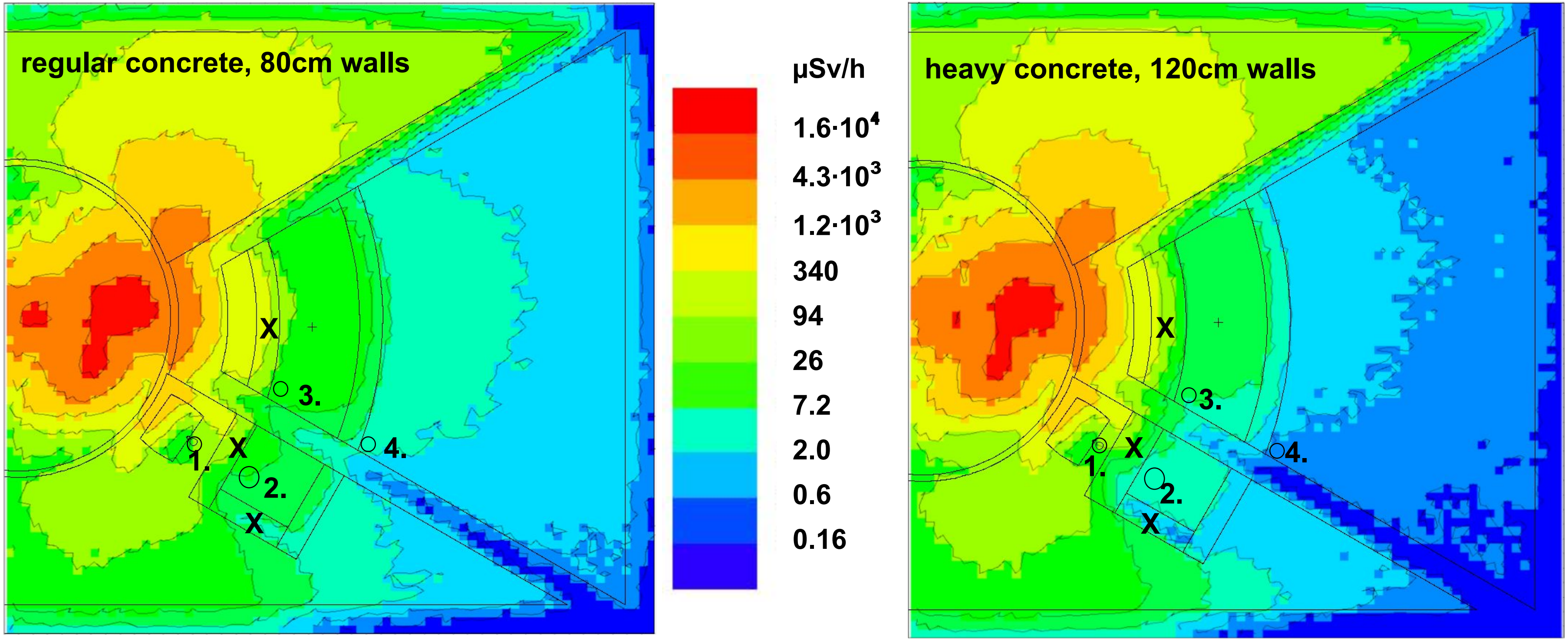
Dose rate maps: the "worst" vs "best" configuration



Summary and next steps

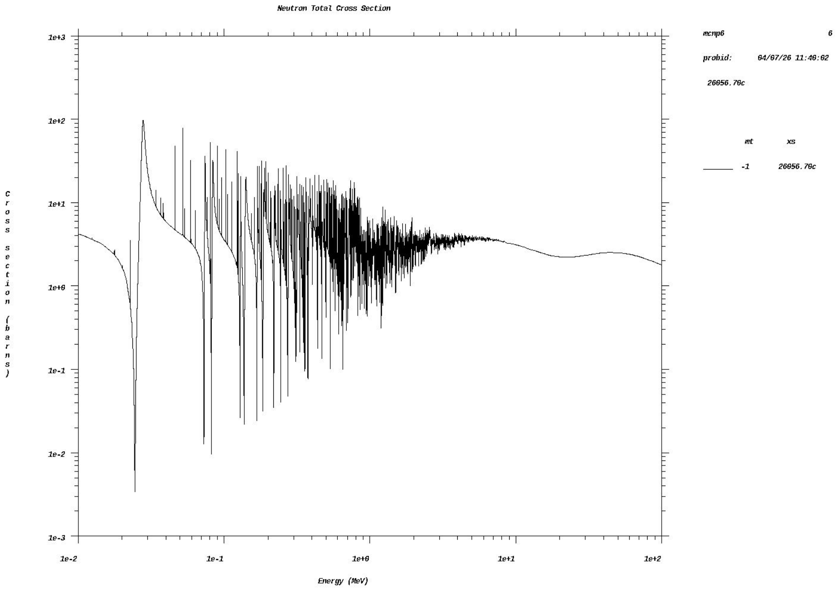
- A proposal for a new instrument, ECHIR, at ESS has been submitted
  - Significant investment has already been done by ESS with installing a fast neutron channel, additional shielding and a shutter system
- Preliminary neutronic calculations have been performed with MCNP6
- Future work includes
  - Optimizing the design: current configuration close to green level
  - Activation study of the materials
  - Comparison study: ECHIR in the instrument hall

Thank you!

Backup slides

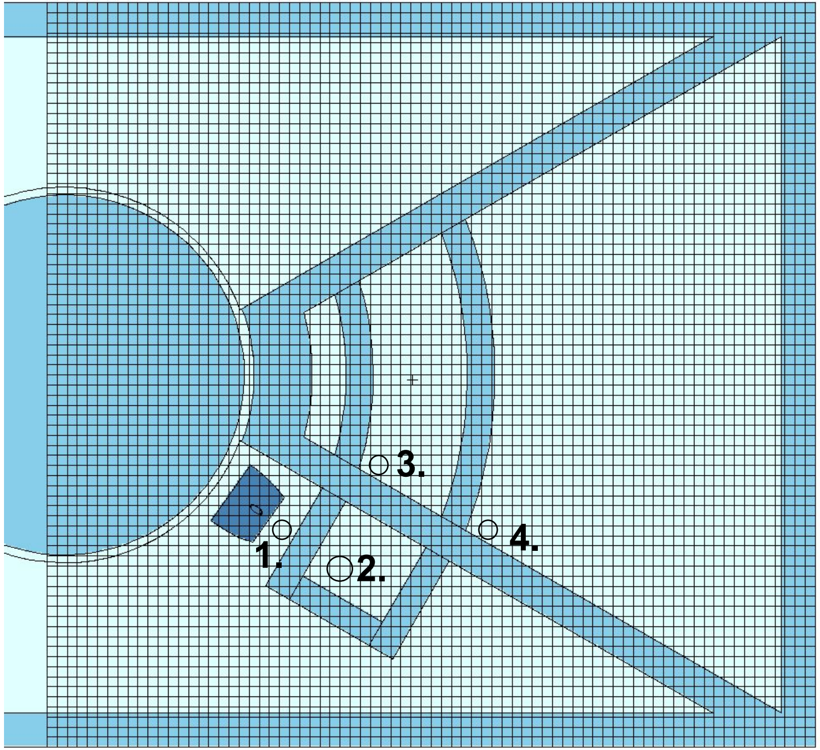
MCNP6: cross section libraries and physics models

- Neutron interactions: ENDF70 (.70c)
  - Based on ENDF/B-VII.0
- Proton interactions: ENDF70PROT (.70h)
  - Based on ENDF/B-VII.0
- Thermal scattering data: ENDF70SaB
  - Based on ENDF/B-VII.0
- Outside the data range for the tabulated libraries (up to 150 MeV depending on the element/isotope), the default MCNP6 physics models were used (CEM03.03)



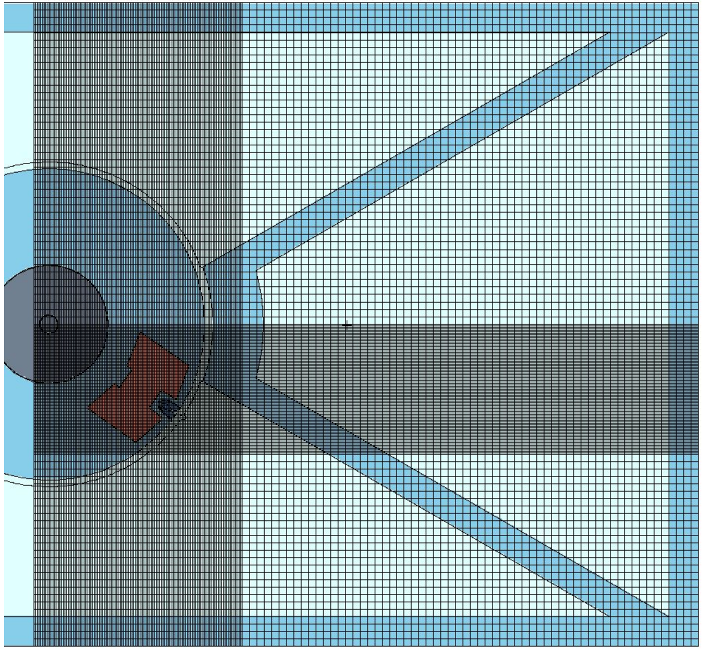
MCNP6: Dose rate tallies

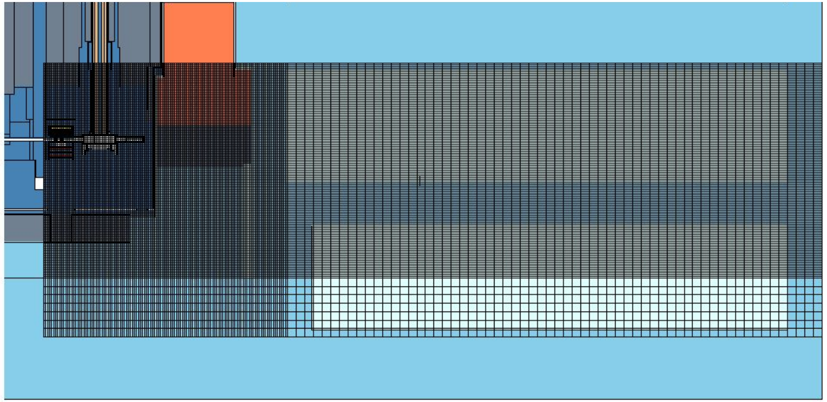
- A mesh tally (TMESH) was used to map the dose rates within the ECHIR beamline and surrounding areas
  - 30x30x30 cm³ voxels
- Dose rate was additionally tallied in key locations using the average cell flux tally (type F4)
- Flux-to-dose rate conversion factors derived as the maximum of the values reported in ICRP Publication 116: *Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures* (2010)



MCNP6: Variance reduction

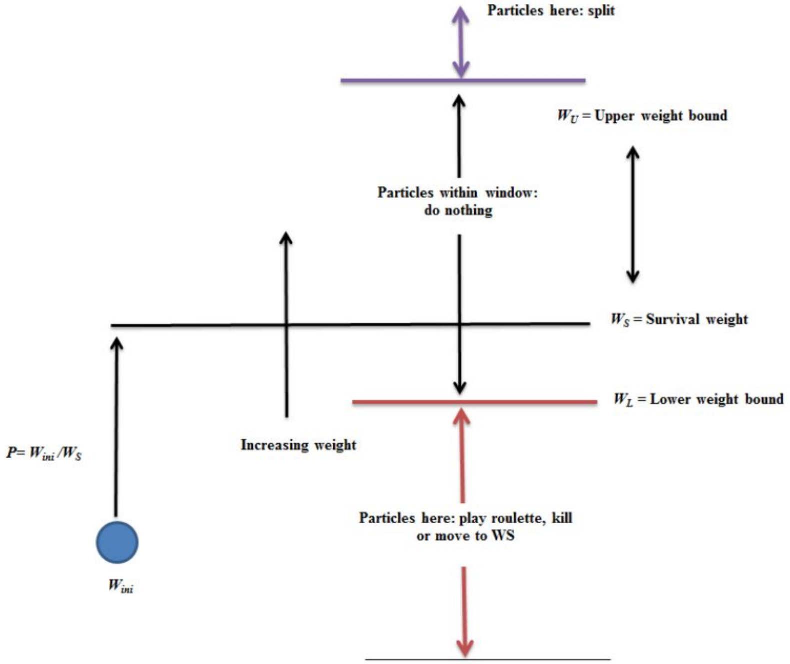
- Variance reduction needed for the simulation results to converge within reasonable timeframe
    - Space and energy-dependent weight windows are used to bias particle transport towards important regions
- Weight window file generated with Automated Variance Reduction Generator software (ADVANTG)
- Weight window mesh covers all essential rooms in the geometry
- Adaptive voxel size
    - 5x5x5 cm^3 voxels capture small-scale geometric features
    - Larger voxel size in low-complexity regions to optimize memory usage





Variance reduction: Weight window technique

- Combines splitting and Russian roulette
  - If a particle weight above window, the particle is split so that all particles are within the window → population of particles in important regions is increased, giving more statistics
  - If a particle weight below window, the particle is either terminated or its weight is increased → computational time is saved by terminating particles in regions of less interest



Saidi, Pooneh & Sadeghi, Mahdi & Tenreiro, Claudio. (2013). *Variance Reduction of Monte Carlo Simulation in Nuclear Engineering Field*. 10.5772/53384.

MCNP6: regular vs heavy concrete

	Regular concrete	Heavy concrete
Iron (Fe)	1.8%	26.5%
Hydrogen (H)	7.6%	13.4%
Oxygen (O)	54.6%	53.0%
Silicon (Si)	10.2%	4.2%
Calcium (C)	22.3%	1.2%
Density [g/cm³]	2.35	3.8