Neutronic design of the bunker

L. Zanini

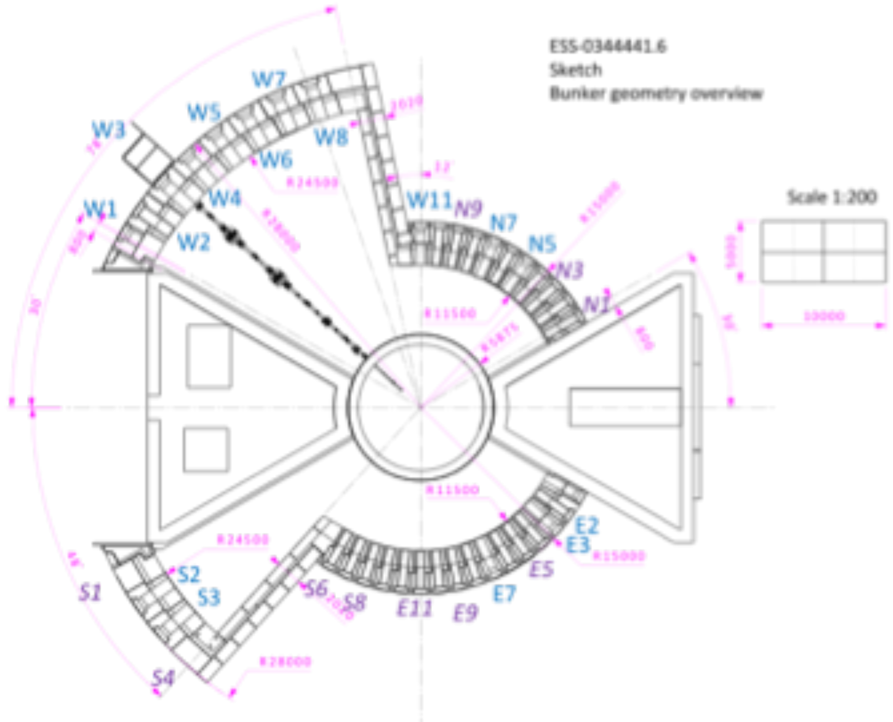
Group Leader Neutronics

ESS

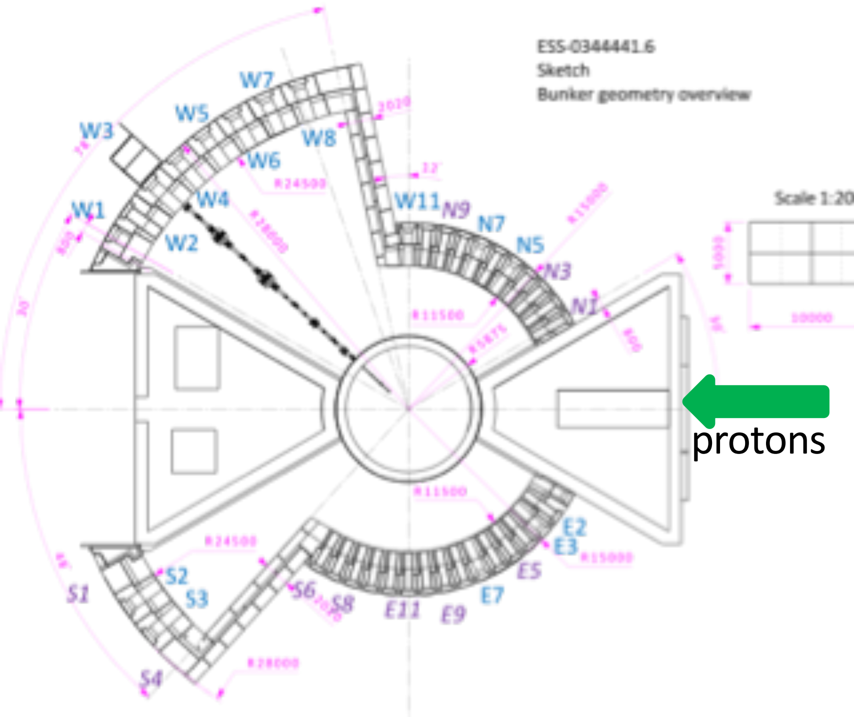
IKON 15, 10 September 2018

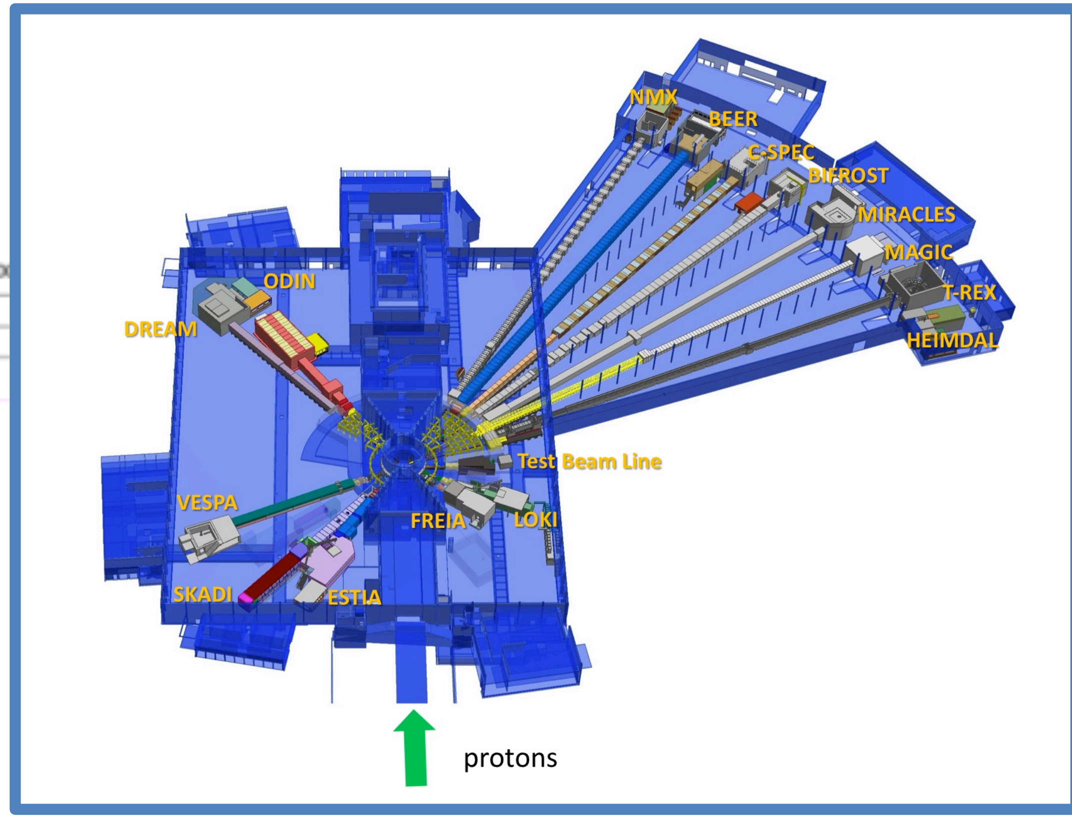
Contents

- ❑ Source term
- ❑ Wall
- ❑ Roof
- ❑ Skyshine
- ❑ Activation
- ❑ conclusions



View of the ESS neutron bunker and instrument suite

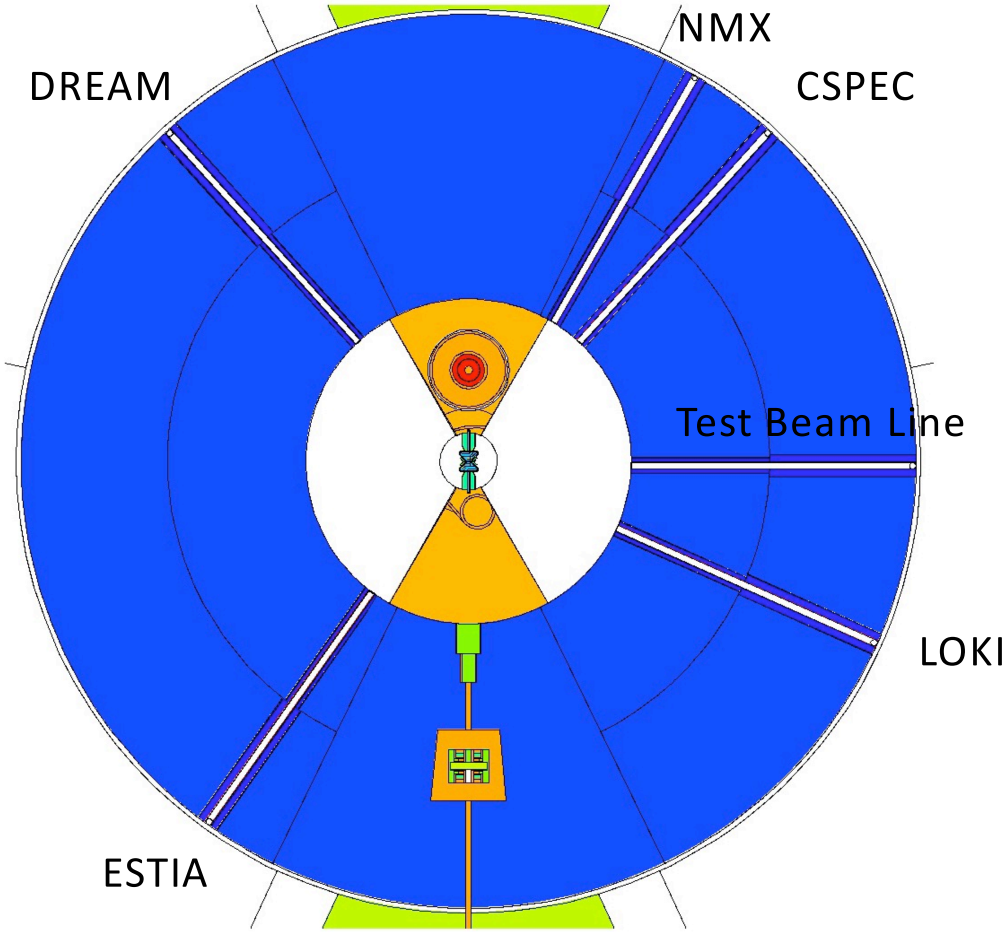




21 beamports are arranged at ~ 6° intervals on either side of the proton beam trajectory

Source term calculation

- MCNPX/6 used
- Detailed Monte Carlo model (geometry, materials) is mandatory
- Source of neutrons at 2 m from moderator center to be used for shielding design
- Requires
  - Information on energy, position and direction of neutrons exiting the monolith
  - Good statistics
- Draft report prepared for CDR



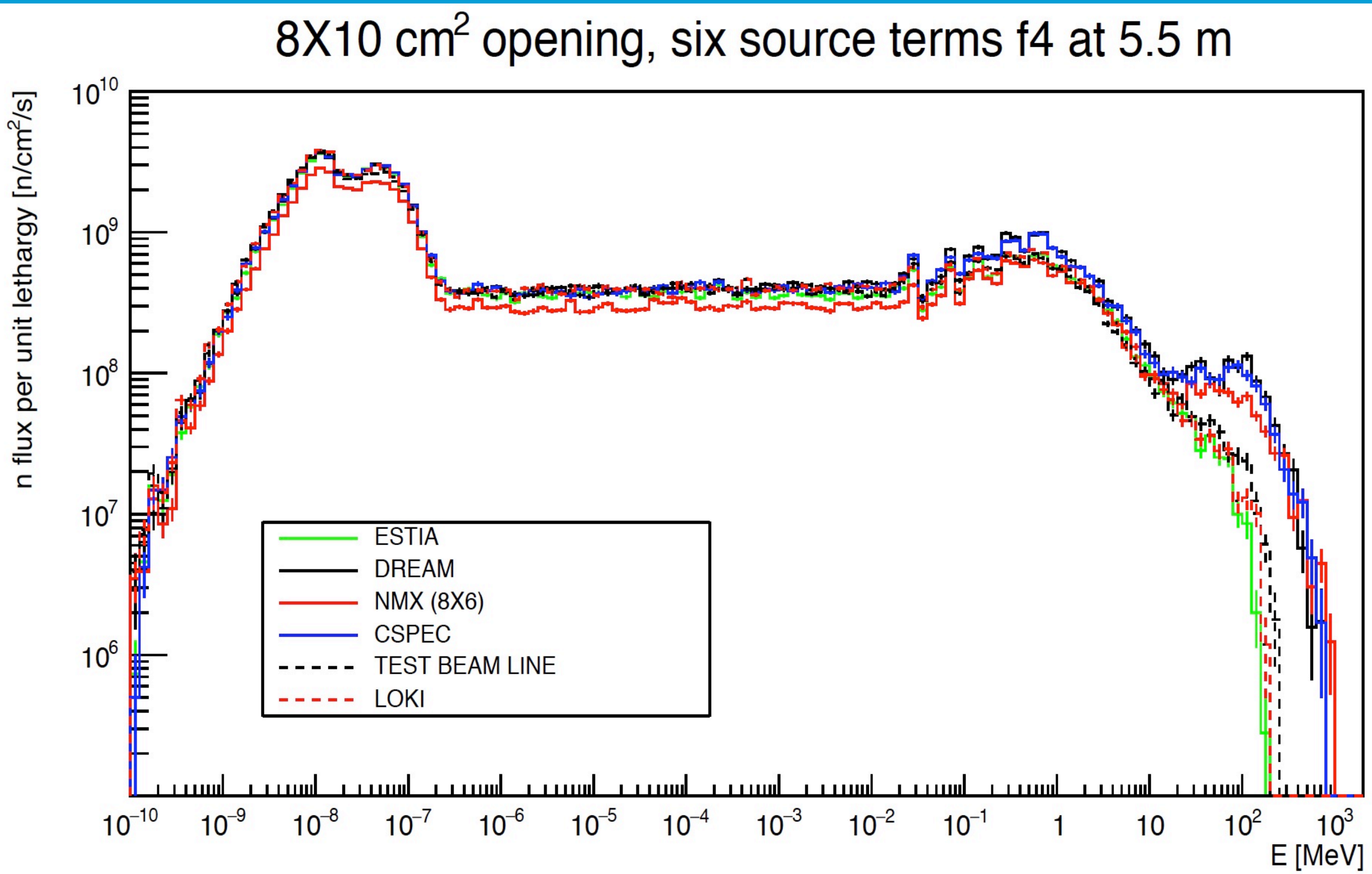
Source terms have been used at the different facility before: SNS, PSI etc..

Size of guide openings is taken into account in the design

- The source term must be known for several beamlines (ideally all)
- It changes with the guide opening size therefore we need source terms for different guide openings

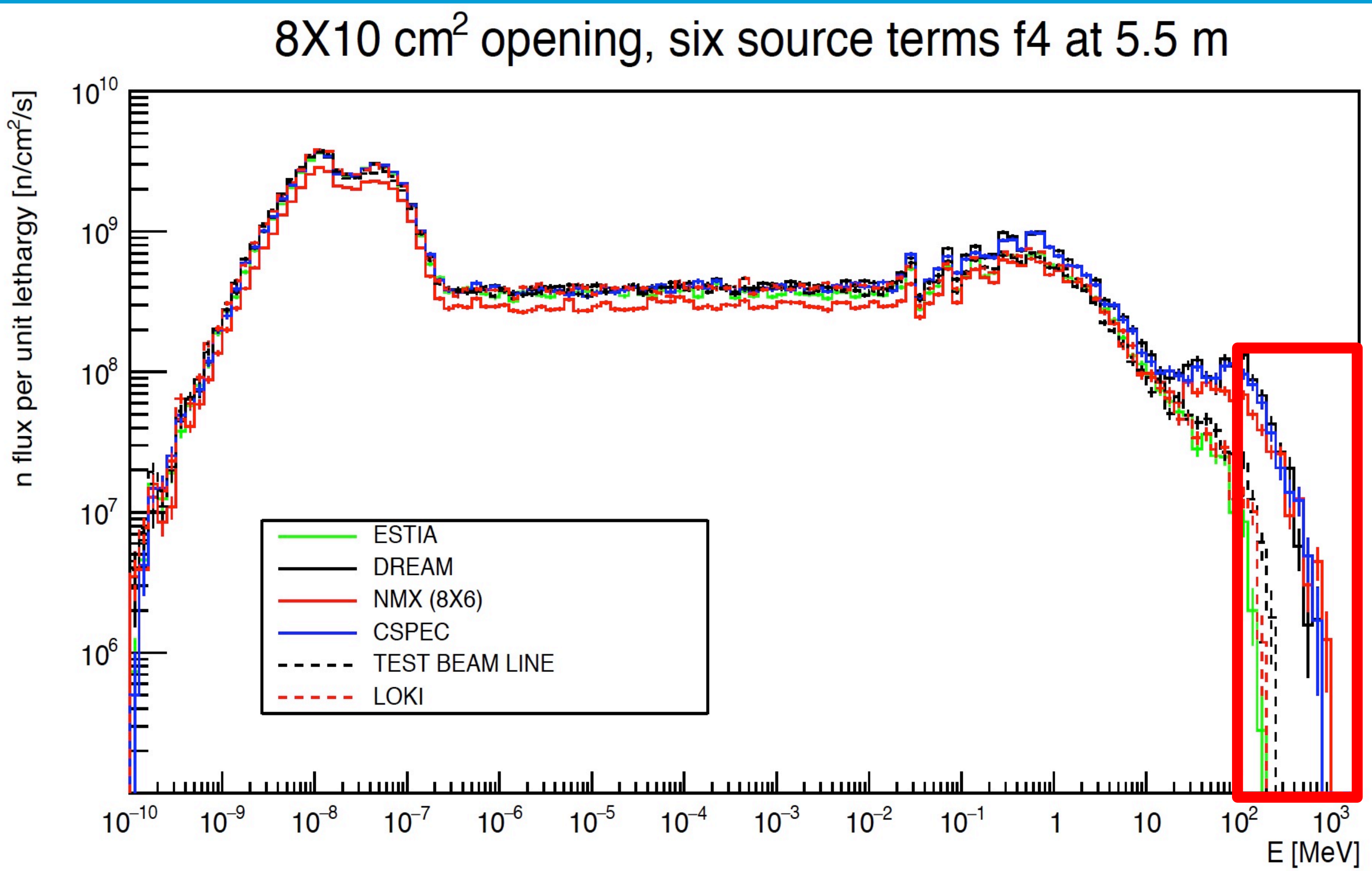
Instrument	Beamport location	Tip Width	Tip Height	area
		[cm]	[cm]	[cm^2]
ODIN	S02	3.8	3.5	13.3
DREAM	S03	3.4	4	13.6
VESPA	E07	3.6	3.6	13.0
SKADI	E03	3	3	9
ESTIA	E02	7	14	98
FREIA	N05	4	14.5	58
LOKI	N07	3	2.5	7.5
TEST	W11	12.1	4.5	54.5
HEIMDAL|A	W08	2	2	4
HEIMDAL|B	W08	4.7	3.6	16.9
TREX	W07	6.7	3.1	20.8
MAGIC	W06	5	3	15
MIRACLES	W05	4.8	5.1	24.5
BIFROST	W04	5.3	3.6	19.1
CSPEC	W03	7	5.5	38.5
BEER	W02	3.6	3.8	13.7
NMX	W01	3	3	9

Fluxes at the monolith exit for different beamlines



The high energy part is very different as a function of the position of the angle respect to the the proton beam

Fluxes at the monolith exit for different beamlines

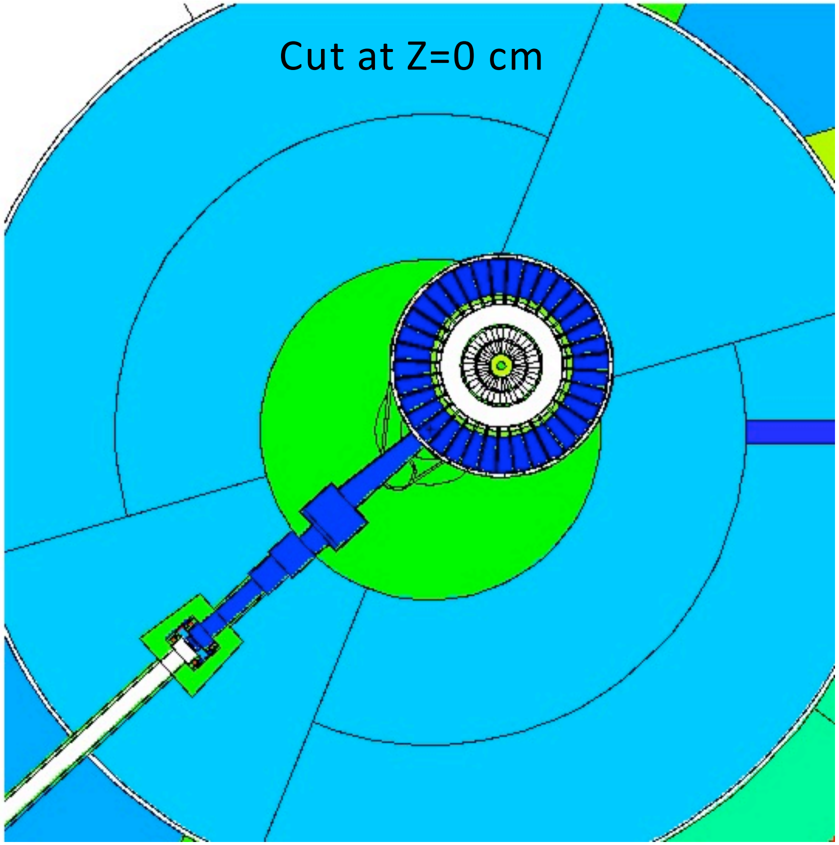


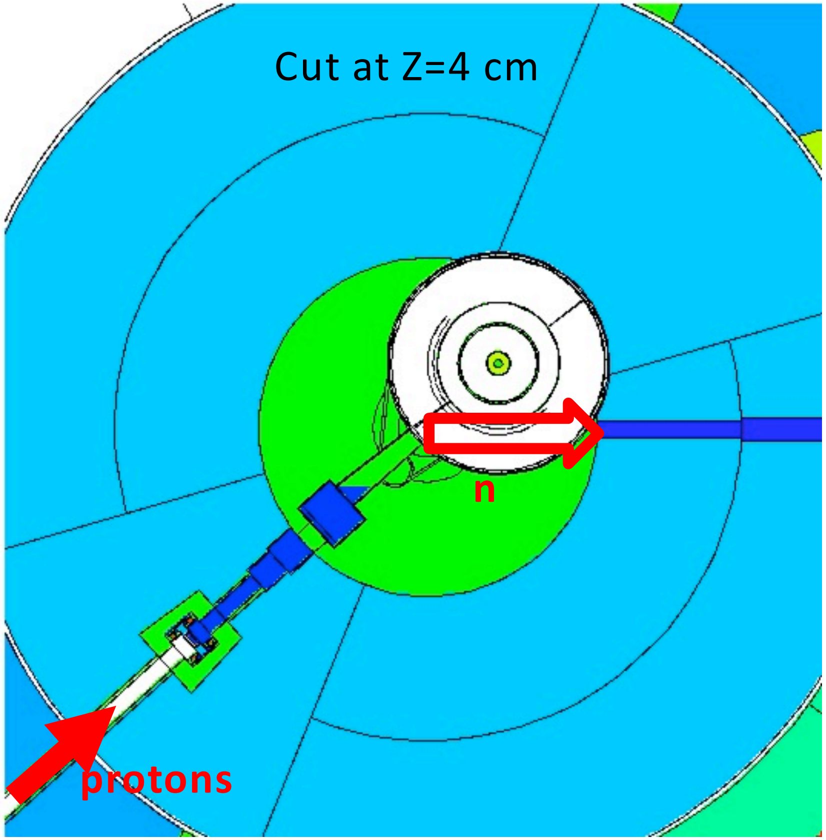
Critical part for shielding

CSPEC is the worst case for the long sector

For this reason we have used CSPEC beamline for the design of the roof and wall for the long sector

CSPEC beamline geometry (1)

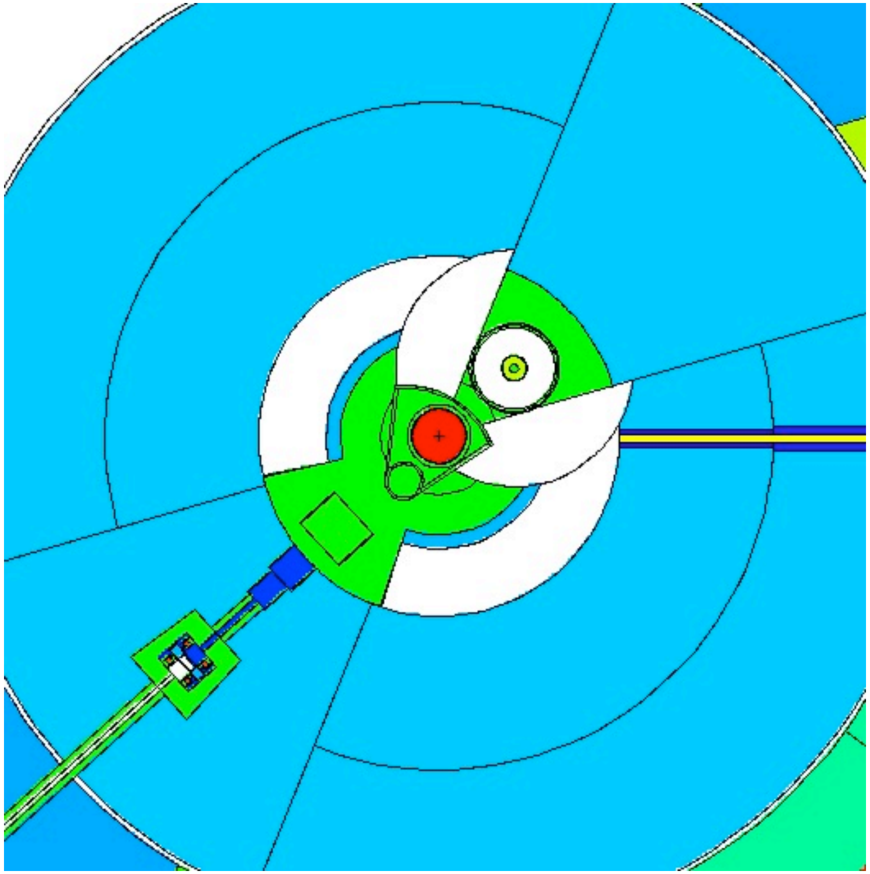




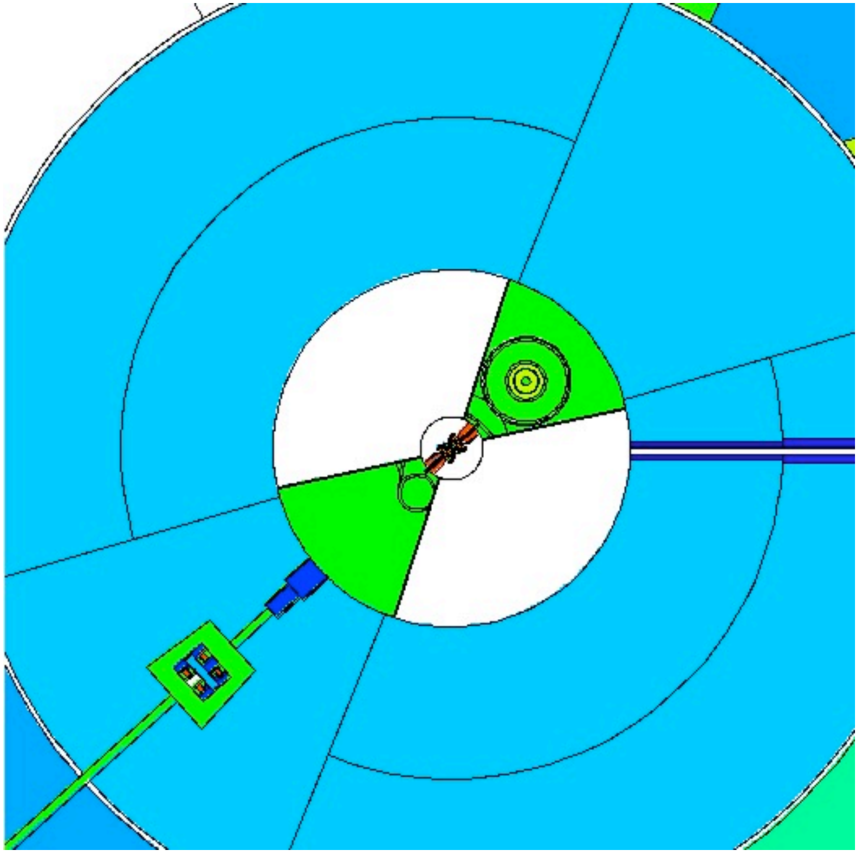
(Model by K. Batkov/S. Ansell)

CSPEC beamline geometry (2)

Cut at Z=10 cm



Cut at Z=13.7 cm



Very detailed geometry description

Importance of high energy neutrons and their proper modeling

Dose rate on roof for only the CSPEC beamline

n < 100 MeV: 0.24 μSv/h

n > 100 MeV: 1.72 μSv/h

All neutrons: 1.96 μSv/h

Importance of high energy neutrons and their proper modeling

EUROPEAN SPALLATION SOURCE

Dose rate on roof for only the CSPEC beamline

n < 100 MeV: 0.24 μSv/h

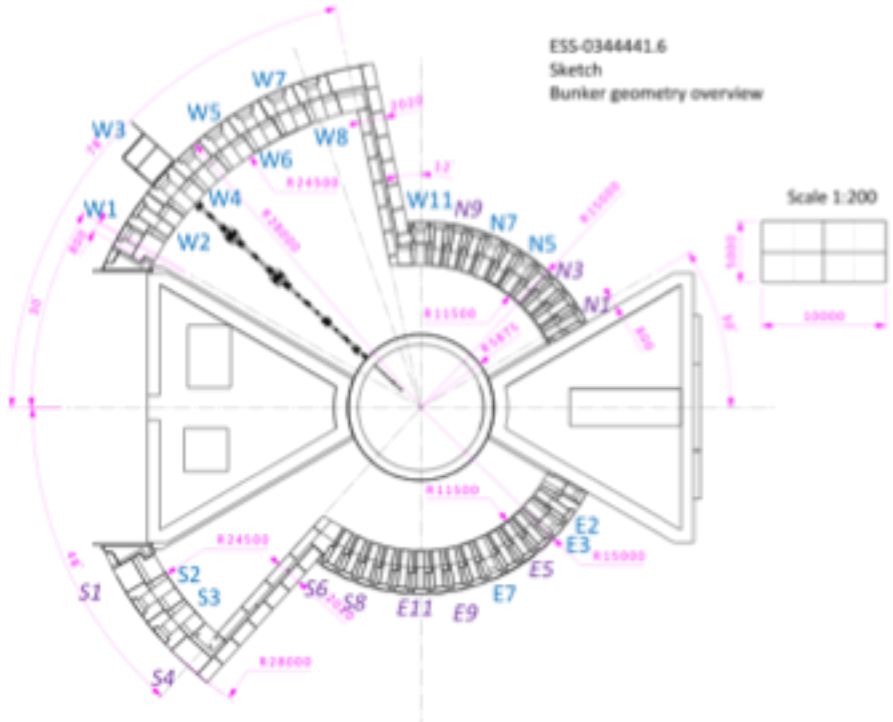
n > 100 MeV: 1.72 μSv/h

All neutrons: 1.96 μSv/h

75% of roof dose rate in long sector is due to neutrons with 100 MeV < E< 500 MeV

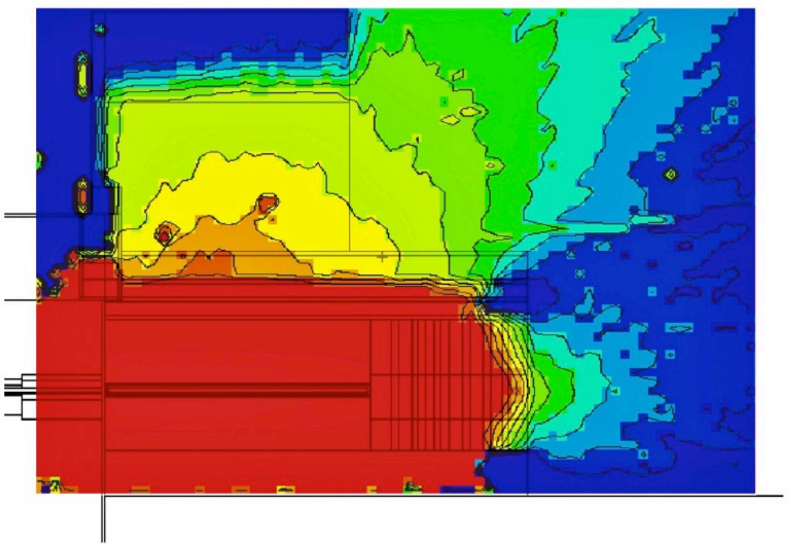
contents

- ❑Source term
- ❑Wall
- ❑Roof
- ❑Skyshine
- ❑Activation
- ❑conclusions

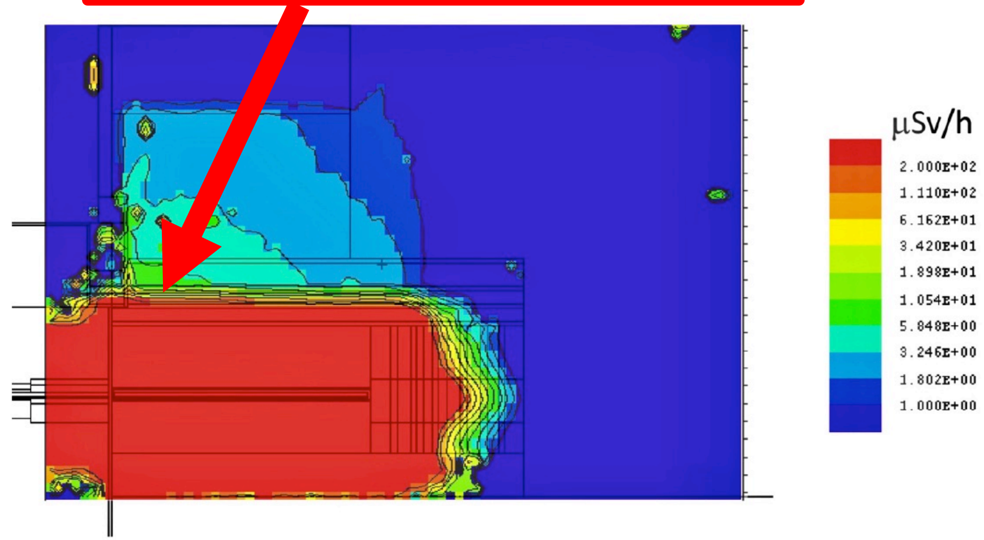


Neutron vs gamma dose rate

neutrons



Gammas: 7% of neutron dose rate

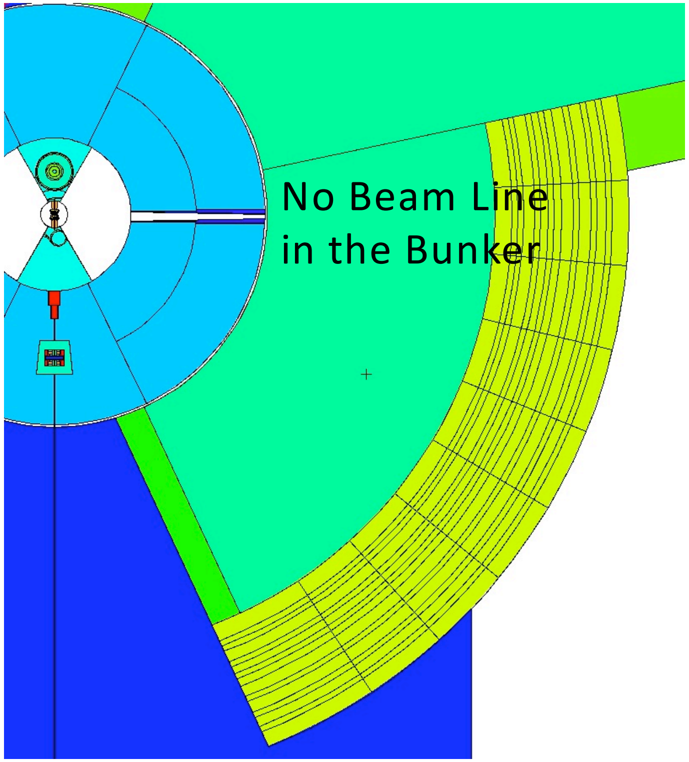


The gamma is responsible of only 7% of the dose rate

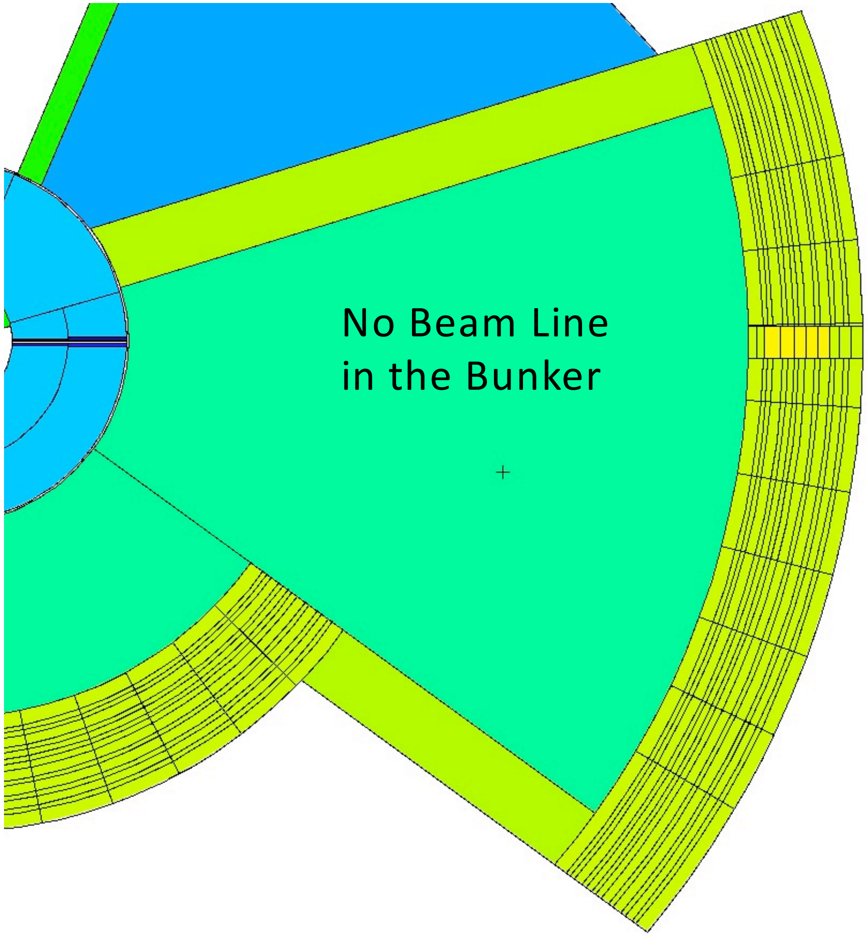
We concentrate on neutron dose rate and add a small systematic correction for gammas

Geometry for wall: 3.5 m Heavy Concrete

Short sector



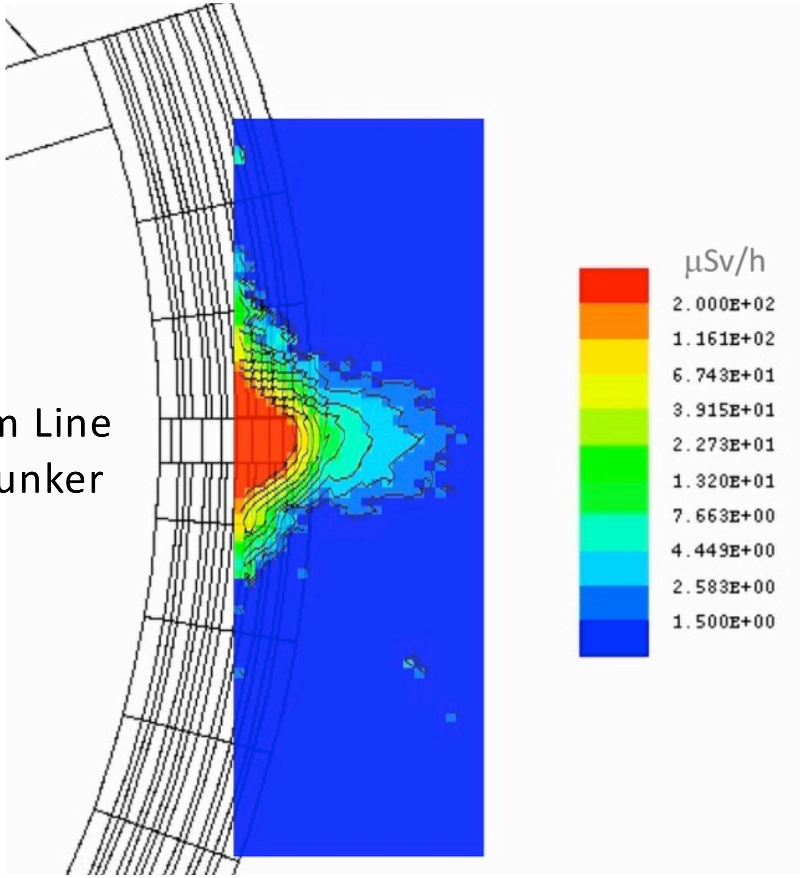
Long sector



Wall dose rate after 3.5 m of heavy concrete. CSPEC beam (long sector)

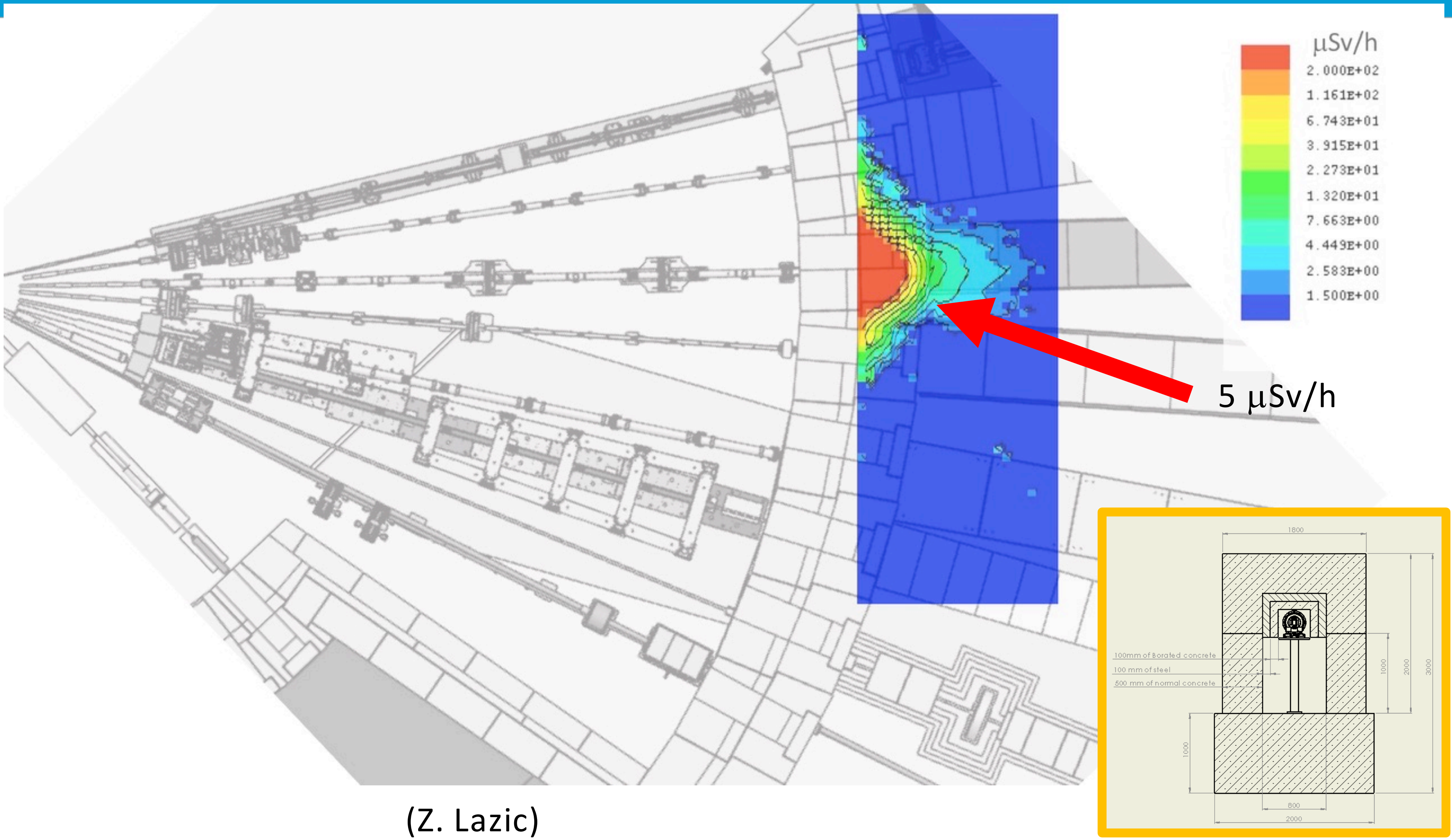
- **Required 3 µSv/h** (calculated 1.5 µSv/h) for **supervised area**
- Calculation done with no beam line in the bunker gives about 5 µSv/h ~1m from axis
- about a factor 10 dose rate reduction by adding guide structures inside the bunker

No Beam Line in the Bunker



The geometry configurations we are using is very conservative

The presence of common shielding outside the bunker will prevent access to the hottest spots

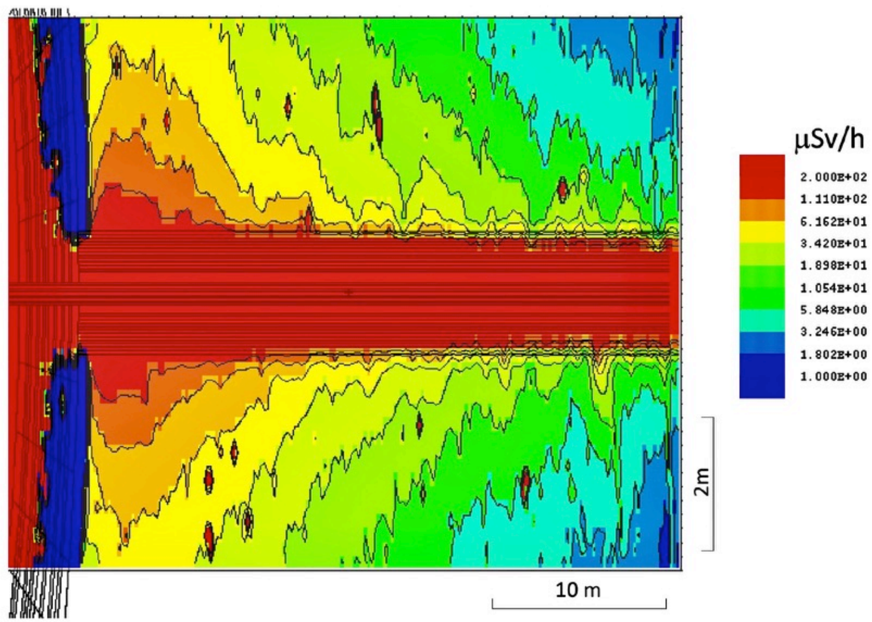


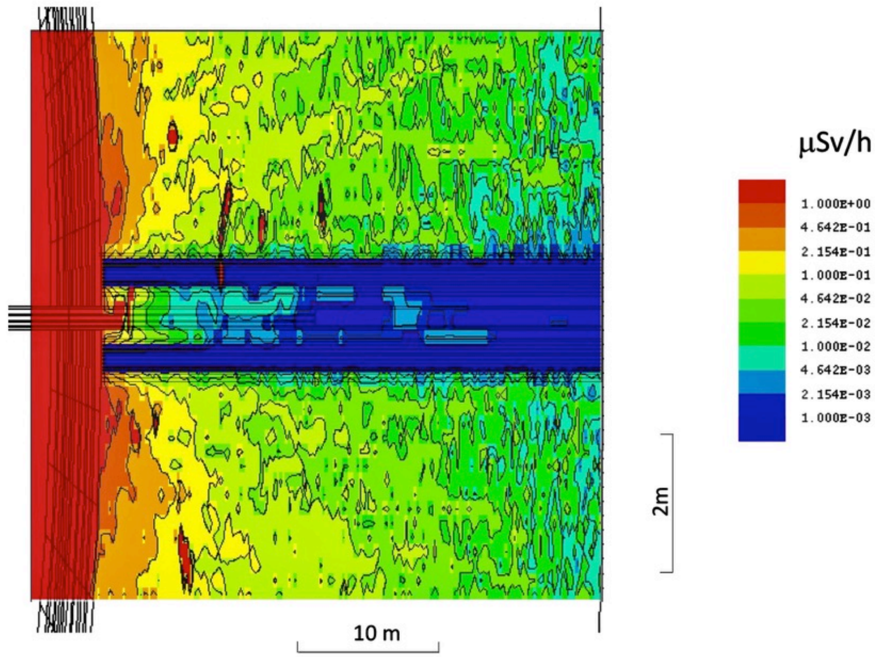
(Z. Lazic)

(Senad Kudumovic)

Note: in a real situation the dose rate at the wall exit is dominated by contribution from the beamline

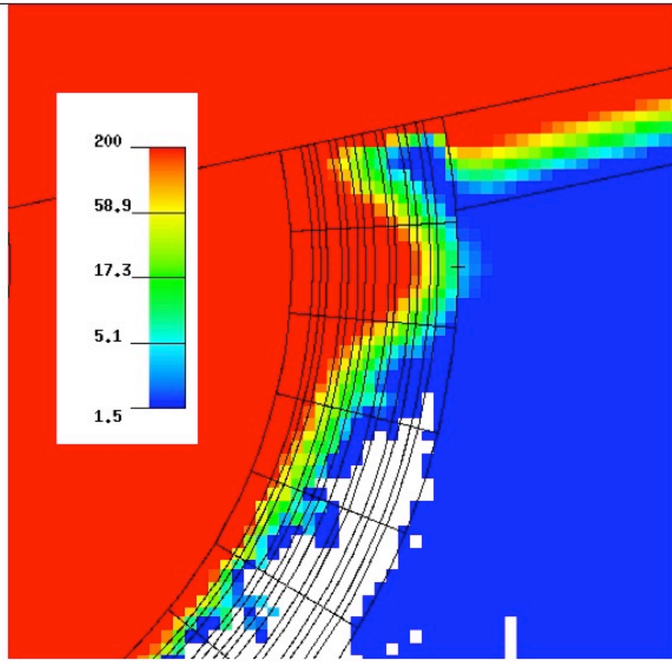
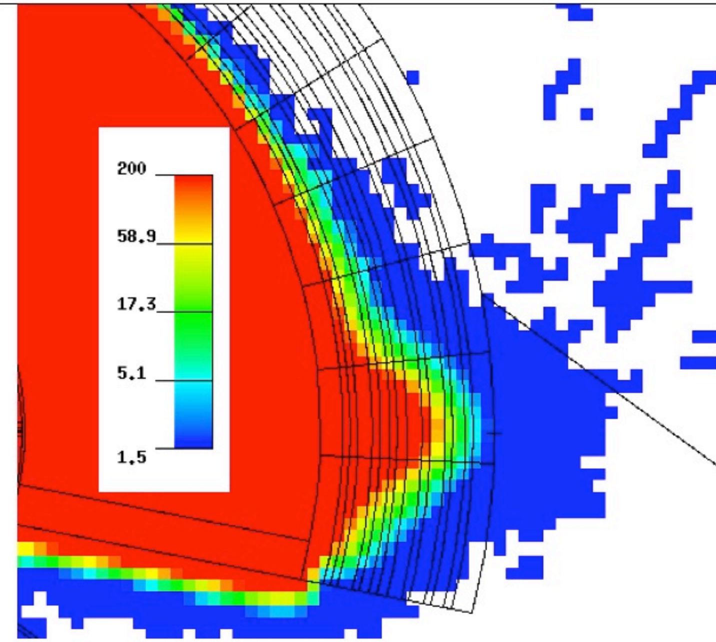
Dose rate (μSv/h) at the exit of the bunker short sector (straight guide, 8 × 10 cm² opening).





Dose rate around the guide and tunnel outside the bunker. The neutron propagation in the beamline is artificially stopped in the bunker wall (of 2.6 m heavy concrete), 2.3 m from the external surface of the wall.

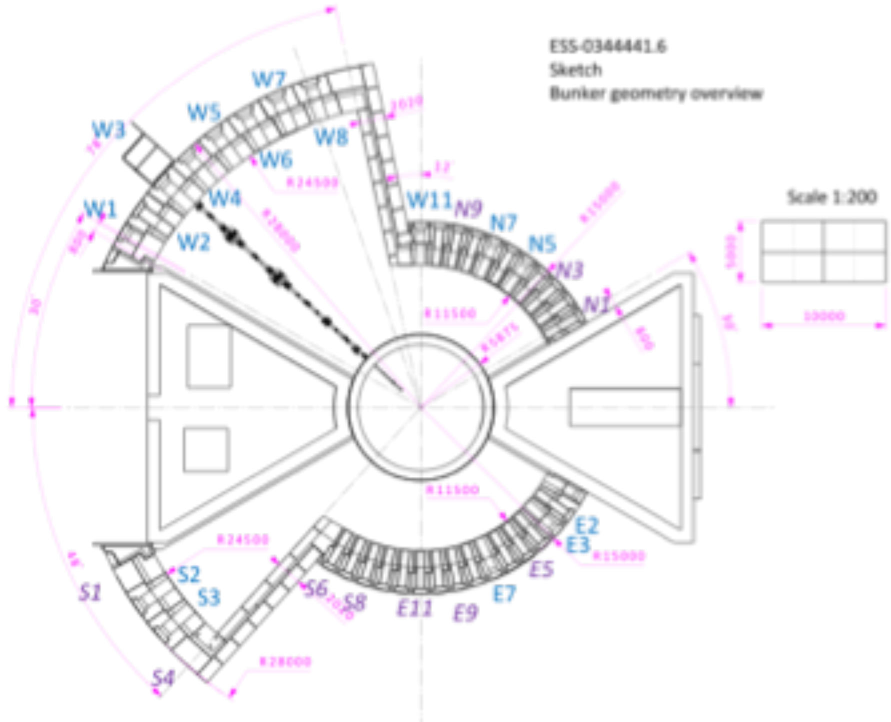
Results short sector:
Test Beam Line vs ESTIA. TBL is worst case

		
Beamline	TBL	ESTIA
0 m from axis	3.3 $\mu Sv/hr$, RE=8%	0.7 $\mu Sv/hr$, RE=7%
0.5 m from axis	2.7 $\mu Sv/hr$, RE=8%	0.6 $\mu Sv/hr$, RE=8%
1 m from axis	1.7 $\mu Sv/hr$, RE=12%	0.3 $\mu Sv/hr$, RE=15%

Test Beam Line is the worst case for the short sector

contents

- ❑ Source term
- ❑ Wall
- ❑ Roof
- ❑ Skyshine
- ❑ Activation
- ❑ conclusions



Criteria for roof

- At the time of designing the roof, it was not clear if the roof will be an unrestricted controlled area, with dose rate limit of 25 μSv/h (calculated 12.5 μSv/h) or a restricted controlled area, with a dose rate limit of 2.5 mSv/h.
- As a general guideline for the roof design we have considered the limit for an unrestricted controlled area.

We have designed the roof for the most conservative possibility

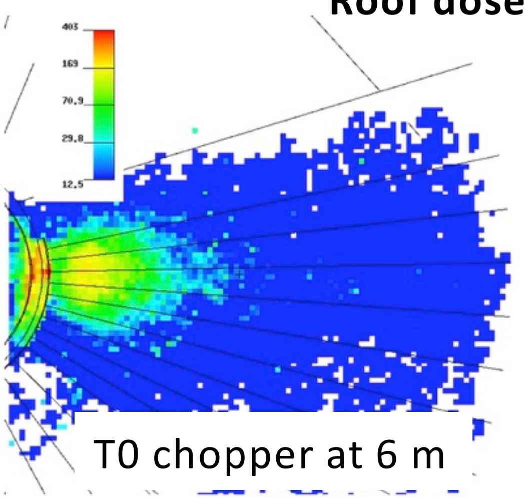
Roof: design strategy

- Determination of the worst case beamline configuration
- Neutronic design for chosen beamline
- Extension to full roof

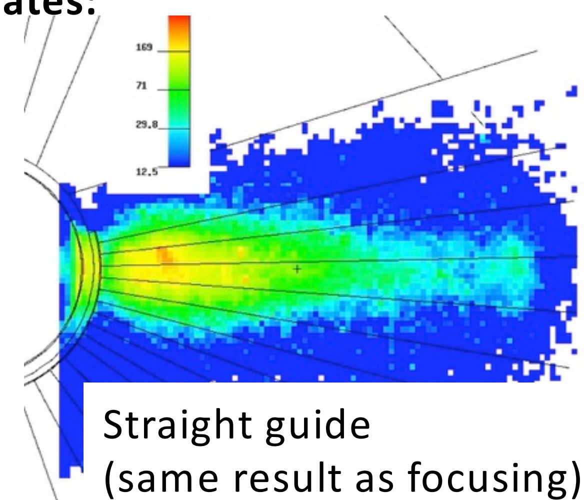
Reference beamline configuration choice

- Different options compared
  - T0 chopper
  - Focusing guide with shutter at the end
  - Straight guide with shutter at the end
  - Straight guide with shutter in the center.

Roof dose rates:

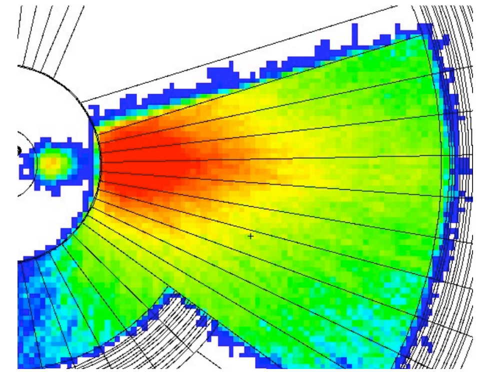


T0 chopper at 6 m

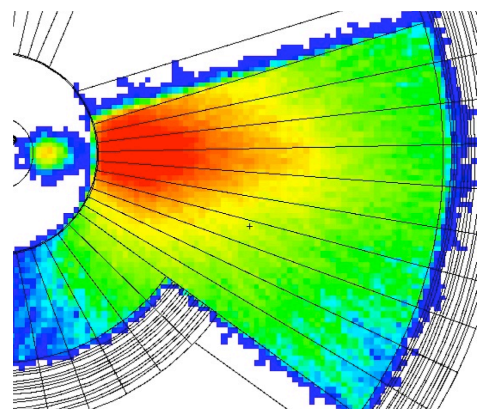


Straight guide
(same result as focusing)

E> 1 MeV Fluxes below roof:



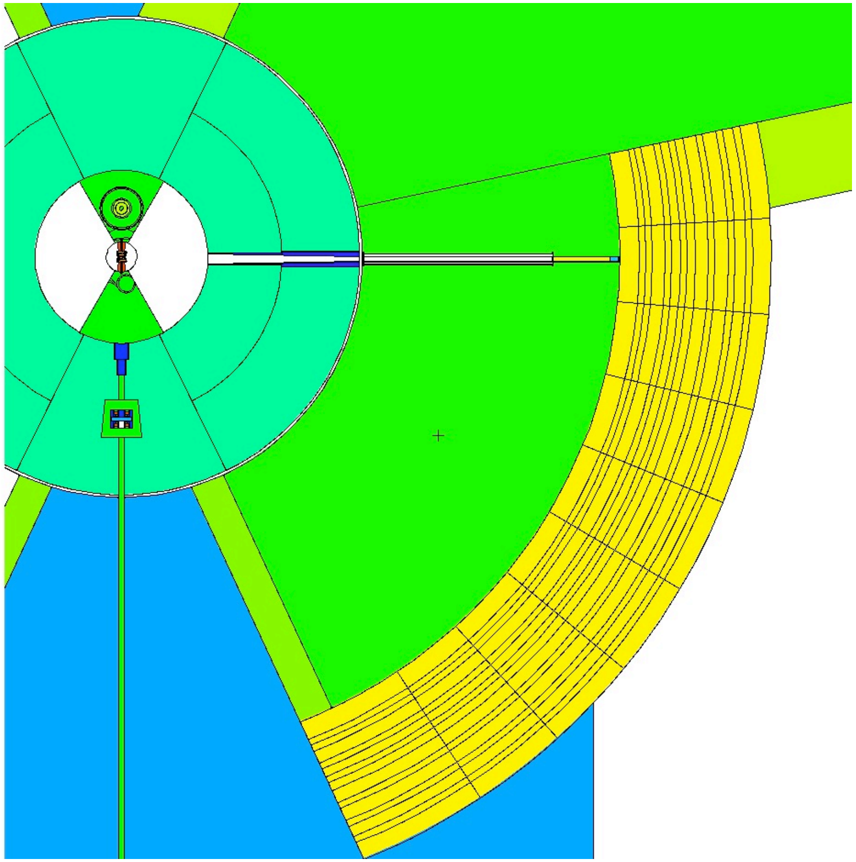
Straight guide, **shutter at end**



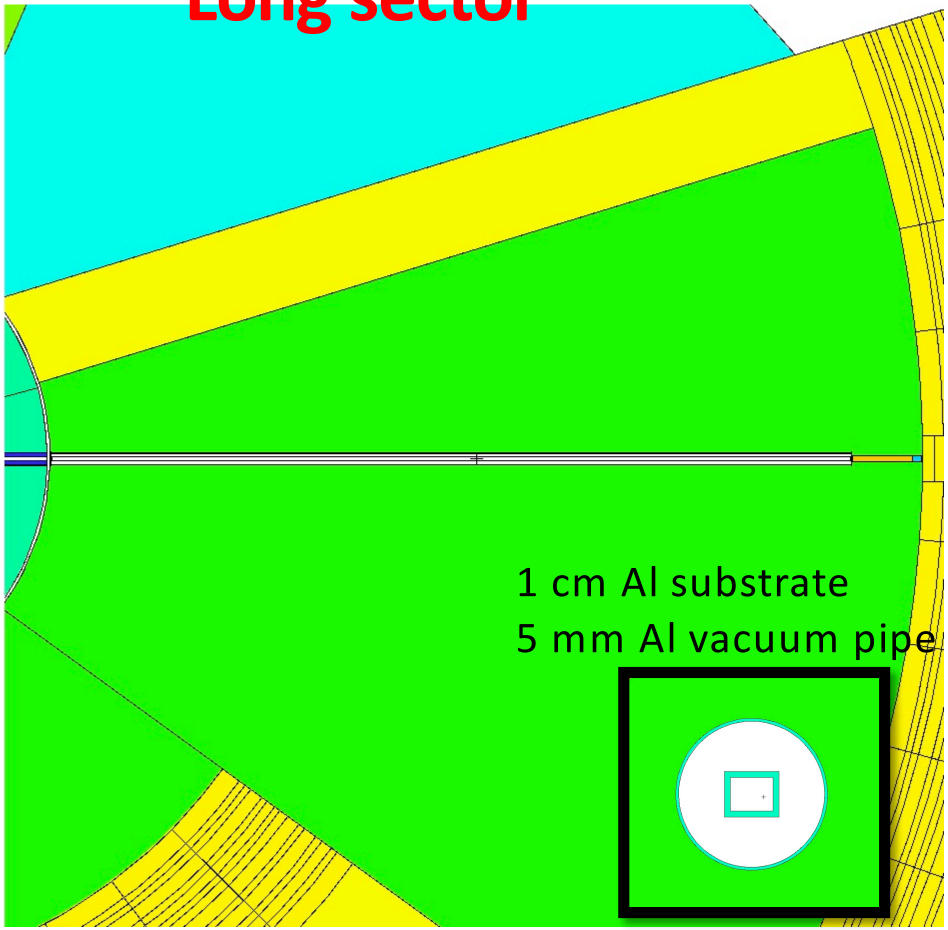
Straight guide, **shutter at center**

Geometry for roof

Short sector



Long sector



Extremely detailed geometry model

Dose rate on the roof depends on the guide opening

CSPEC Guide Opening	Average dose rate above roof [μSv/h]
7 X 5.5 cm^2	1.96
7 X 3 cm^2	0.36
5 X 4 cm^2	0.35
3X3 cm^2	0.082

The dependence of the size of the guide opening to the roof dose rate is not linear and has required a detailed study

Flux correction factors for the long sector and their contribution to the roof dose rate

Using the roof dose rate dependence on the guide opening for CSPEC, we have calculated the dose rate contribution for each beamline

Beam Port	Neutron Instrument	Beam width at monolith (cm)	Beam height at monolith (cm)	Effective aperture size (cm^2)	source size dose correction factor
W1	**NMX**	3.0	3.0	8.9	0.042
W2	**BEER**	3.6	3.8	13.4	0.12
W3	**CSPEC**	7.0	5.5	38.5	1
W4	**BIFROST**	5.3	3.6	19.1	0.17
W5	**MIRACLES**	4.8	5.1	24.7	0.46
W6	**MAGIC**	5.0	3.0	15.1	0.087
W7	**T-REX**	6.7	3.1	20.9	0.15
W8	**HEIMDAL-A**	4.7	3.6	17.1	0.14
	HEIMDAL-B	2.0	2.0	4	0.006
			West (long) sector sum		2.17
S3	**DREAM**	3.4	4.0	13.7	0.13
S2	**ODIN**	3.8	3.5	13.2	0.097
			South (long) sector sum		0.223

EUROPEAN SPALLATION SOURCE

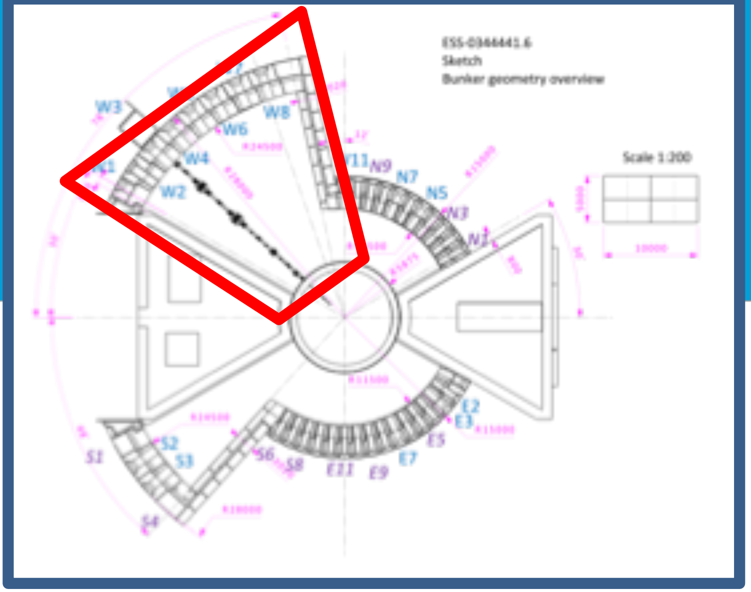
Stepped Roof

- Studying the different dose rate on the roof for different beamline configuration we notice that the neutron dose rate is inhomogeneous in the long sector
- For this reason we decide to design the roof with different steps
- For instance on top of CSPEC there is higher dose so we need thicker roof

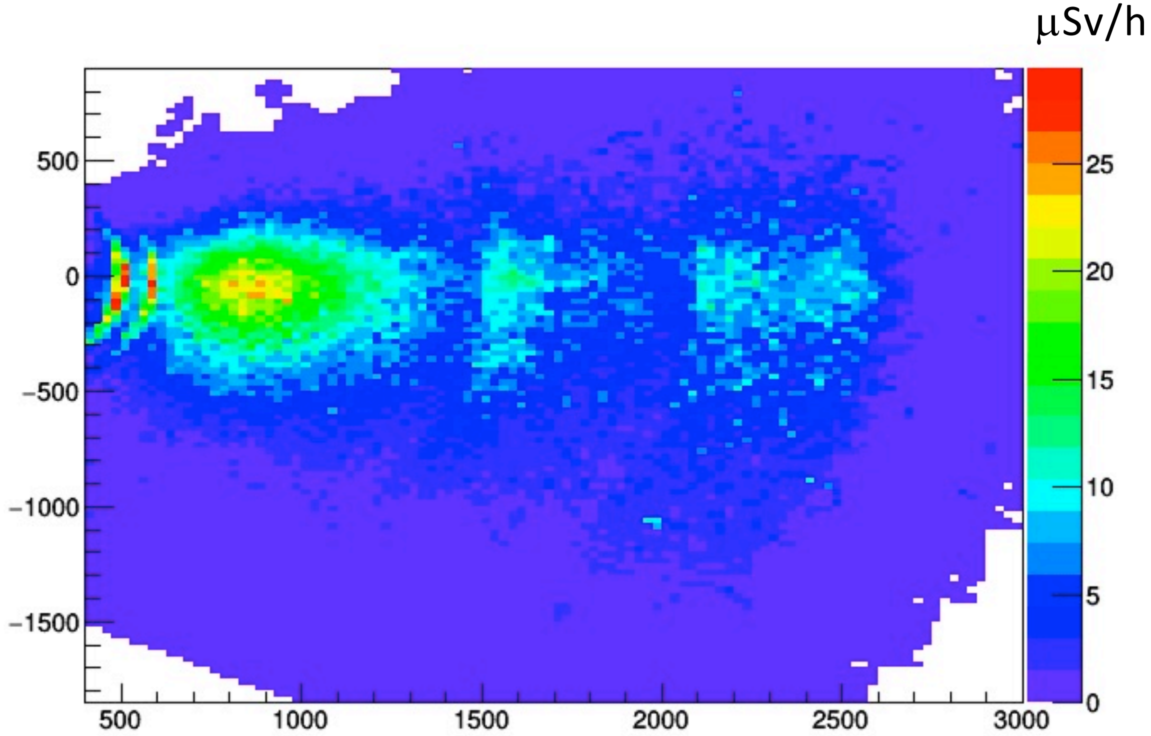
We shield more when we need more shielding

➡ **Cost optimization and improve crane access**

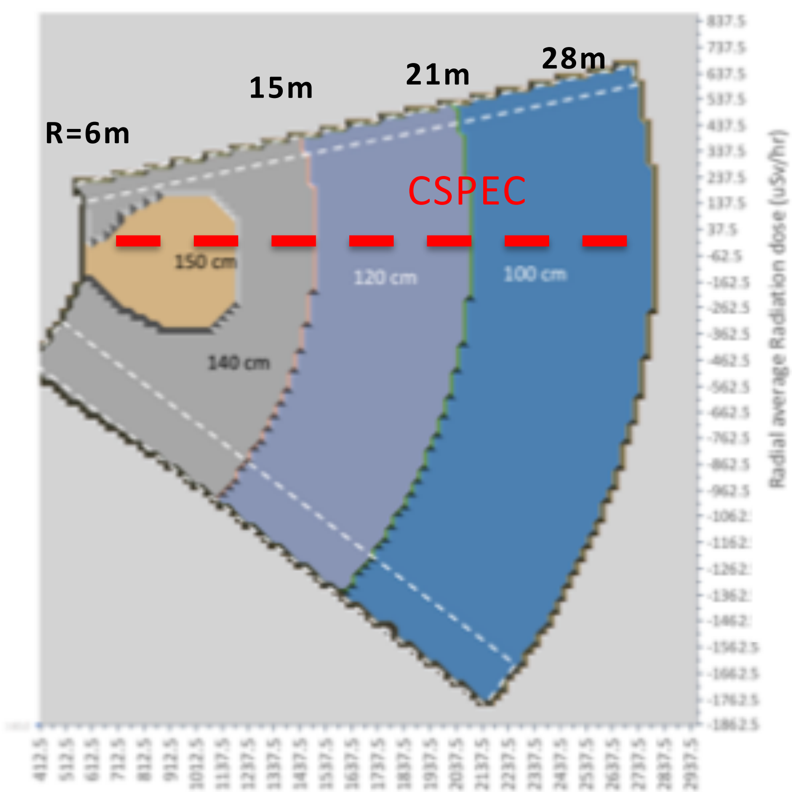
Long sector: West

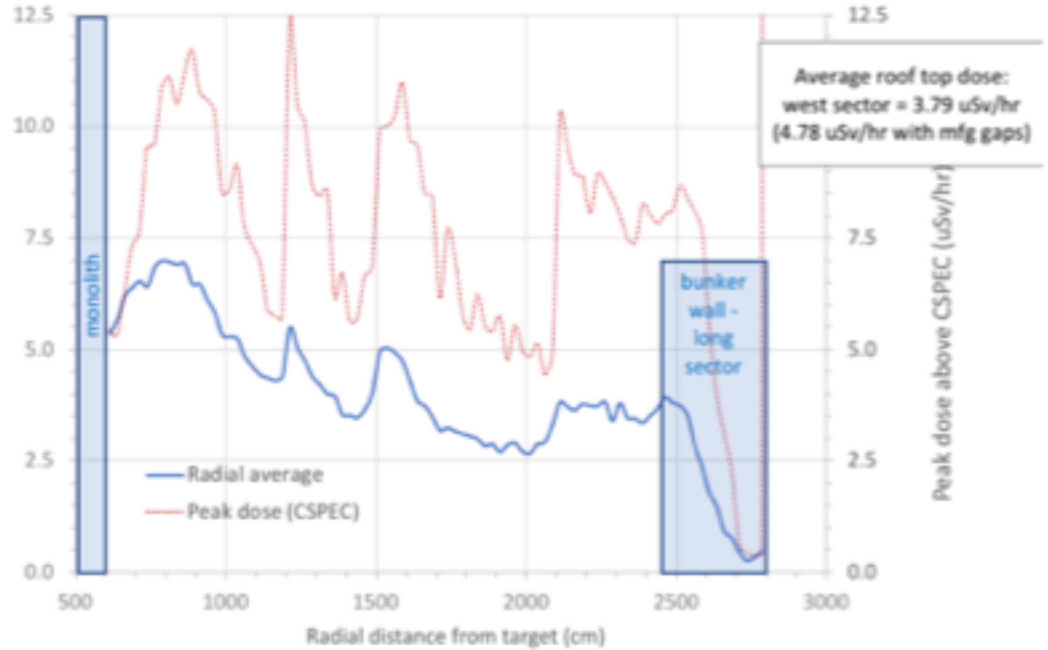


Dose rate map on the top of the West sector stepped roof with the 8 beamports open, using the flux correction factors from previous slide



Three-step roof for the West sector with added step above CSPEC





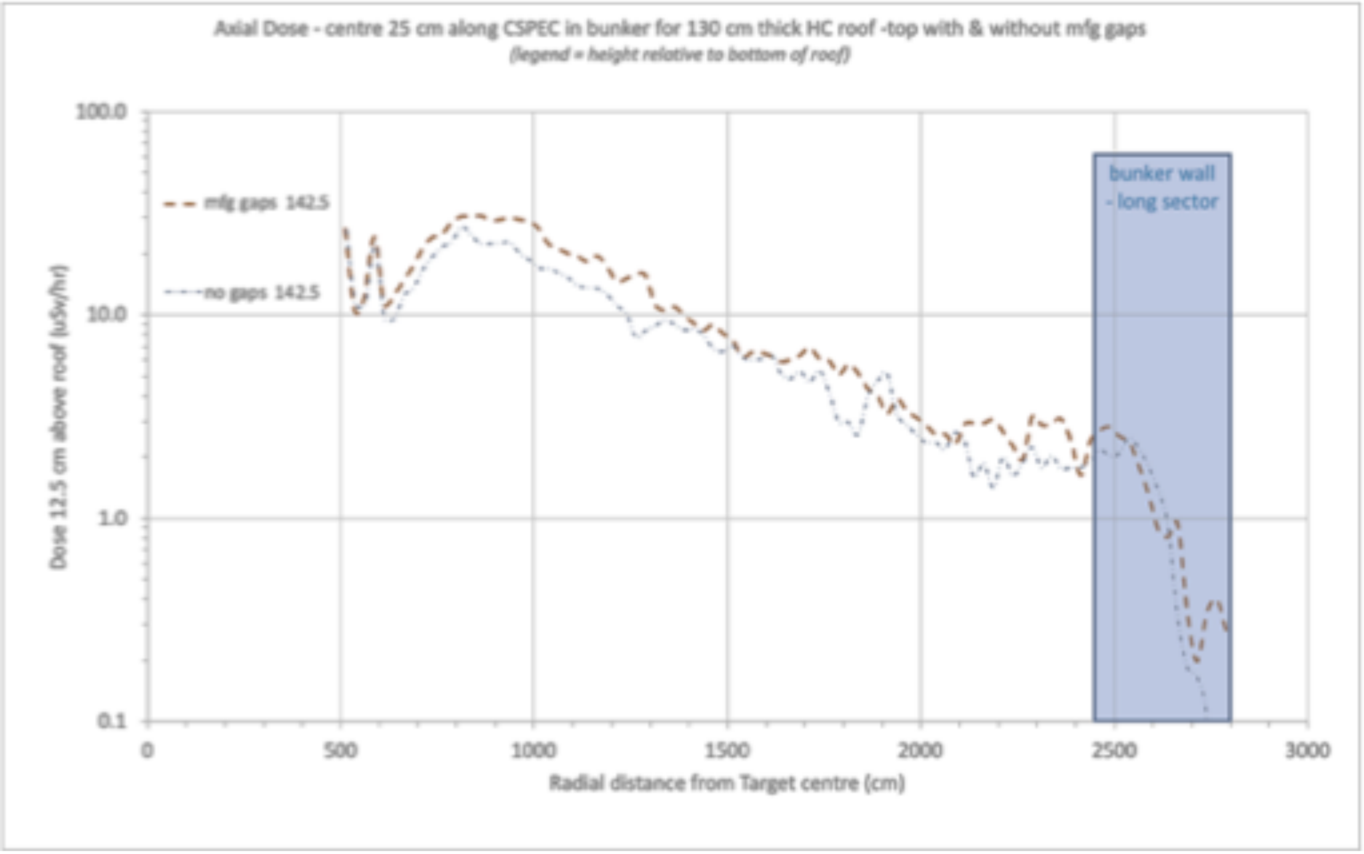
Average radial dose distribution for the entire west sector stepped roof (blue line), and for a line cutting through the peak dose rate, above CSPEC (red line).

Average roof dose is 3.8 µSv/h.

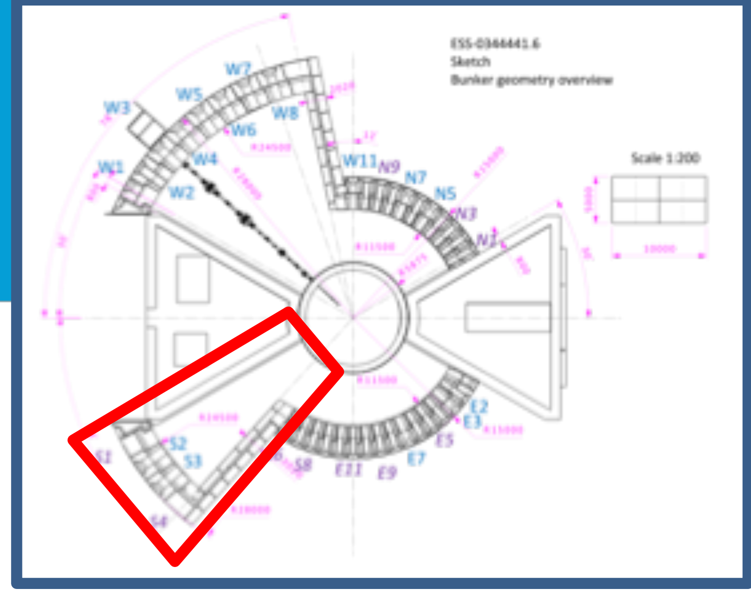
The peak dose above C-SPEC is 12.3 µSv/h around R ~ 12 m.

Effect of manufacturing gaps

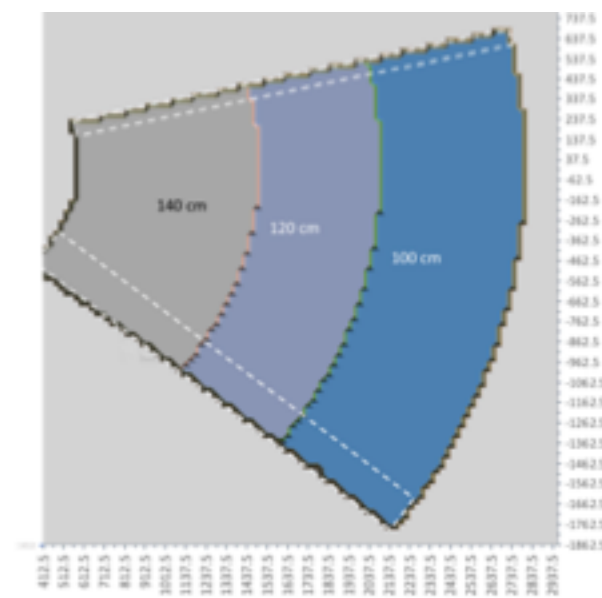
The transmission of radiation dose through the bunker roof increases on average by 26% with 20 mm manufacturing gaps



Long sector: South three-step roof



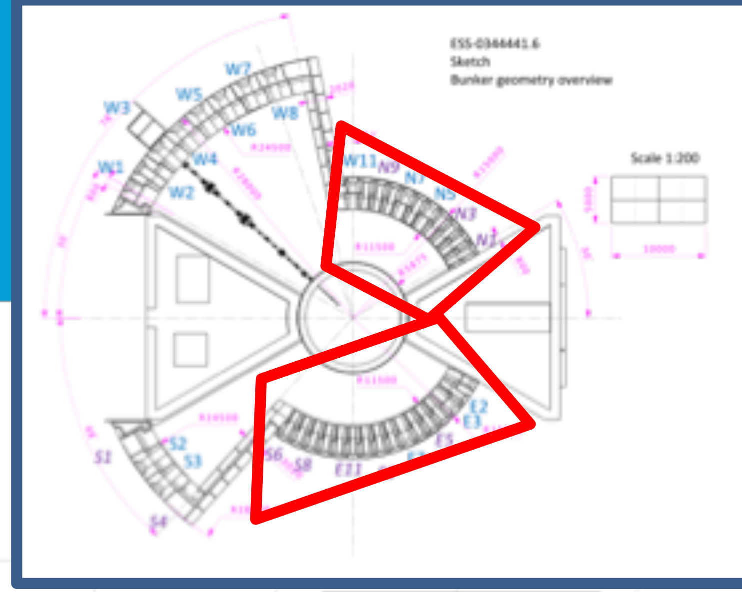
- Based on the results for the West sector.
- the roof top dose in the South with ODIN and DREAM in operation, but no beamline at either S1 or S4, is ~ 1/10th of the average dose for the West Sector.
- Therefore, a three-step roof, will ensure dose levels below those of the west roof



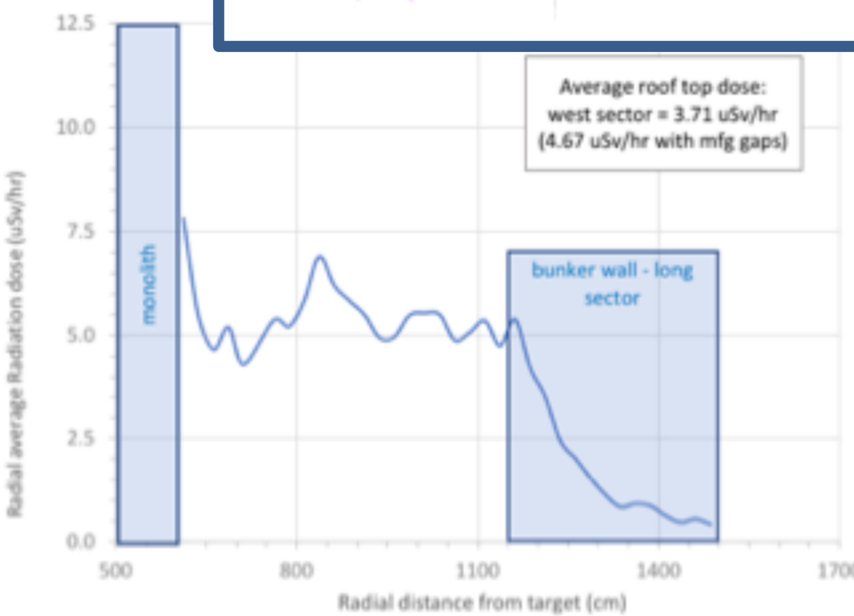
South Sector roof does not need extra shielding like CSPEC

Cost optimization

Short sector (North and East):



- The more important question for the short sector is to estimate how much the total roof dose is likely to increase when the short sector beamlines are all fully operational.
- This would **be beyond full-operational scope of the ESS** (i.e. **26-28 beamlines** in use, including the test beamline), but not beyond possibility.
- The basic principle for the short sector beamlines, in the North and East is that only every second beamline should be used.

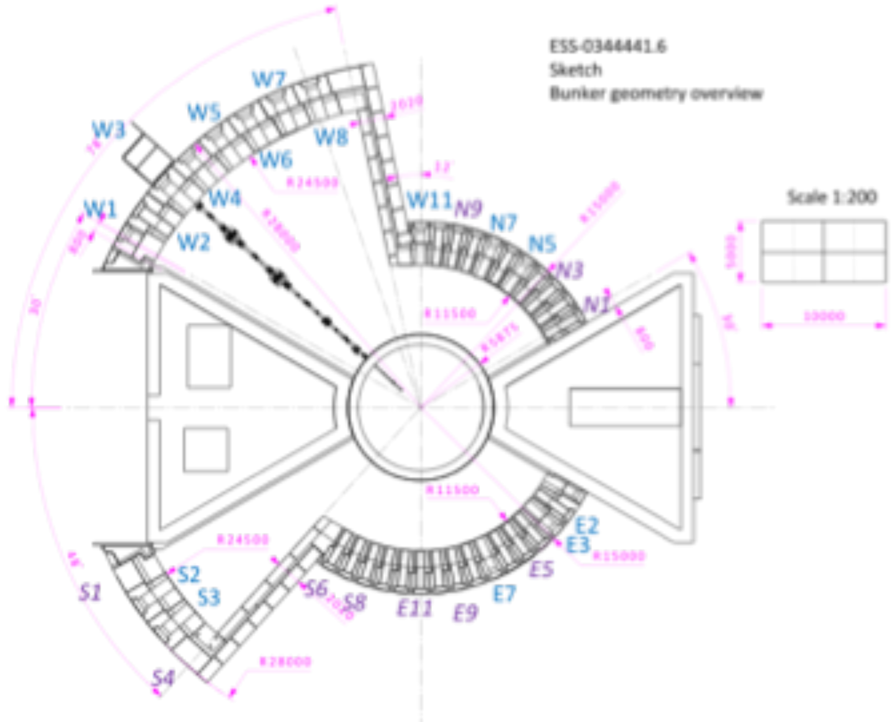


Short Sector does not need steps
1.3 m thick flat roof is sufficient

Average radial dose rate distribution for the full north sector of a **1.3 m thick flat roof**. Average roof dose rate is 3.7 μSv/hr, and peak dose rate is 6.9 μSv/h around R ~ 8.5 metres.

contents

- ❑ Source term
- ❑ Wall
- ❑ Roof
- ❑ Skyshine
- ❑ Activation
- ❑ conclusions



Skyshine requirements

- The allowed dose rate limit in the ESS site offices **100 µSv/y** for non-radiation workers.
- The allowed dose rate limit at the **site boundary is 50 µSv/y**.
- Conservatism factor for calculated skyshine dose by analytical method is 3.
- Hence the total design limit for all contributions (including accelerator, target, instruments and bunker) is
  - **33.3 µSv/y** for B02 (nearest ESS office at 136 m from target center) &
  - **16.7 µSv/y** for R4 (nearest point on the site boundary to the neutron bunker).

Inputs for Sullivan's analytical approach

bunker sector	Number of Instruments (project scope)	Number of Instruments (full potential)	Roof area. A (m^2)	Average simulated dose. H_0 (µSv/h)	Hadron dose equivalent rate $H_0.A$ (Sv/h.m^2)
west (long)	8	8	375	4.8	1800
north + short west	3	6	126	4.7	592
east + short south	3	8	179	4.7	842
south (long)	2	4	175	1.2	211
total	16	26	855		3444

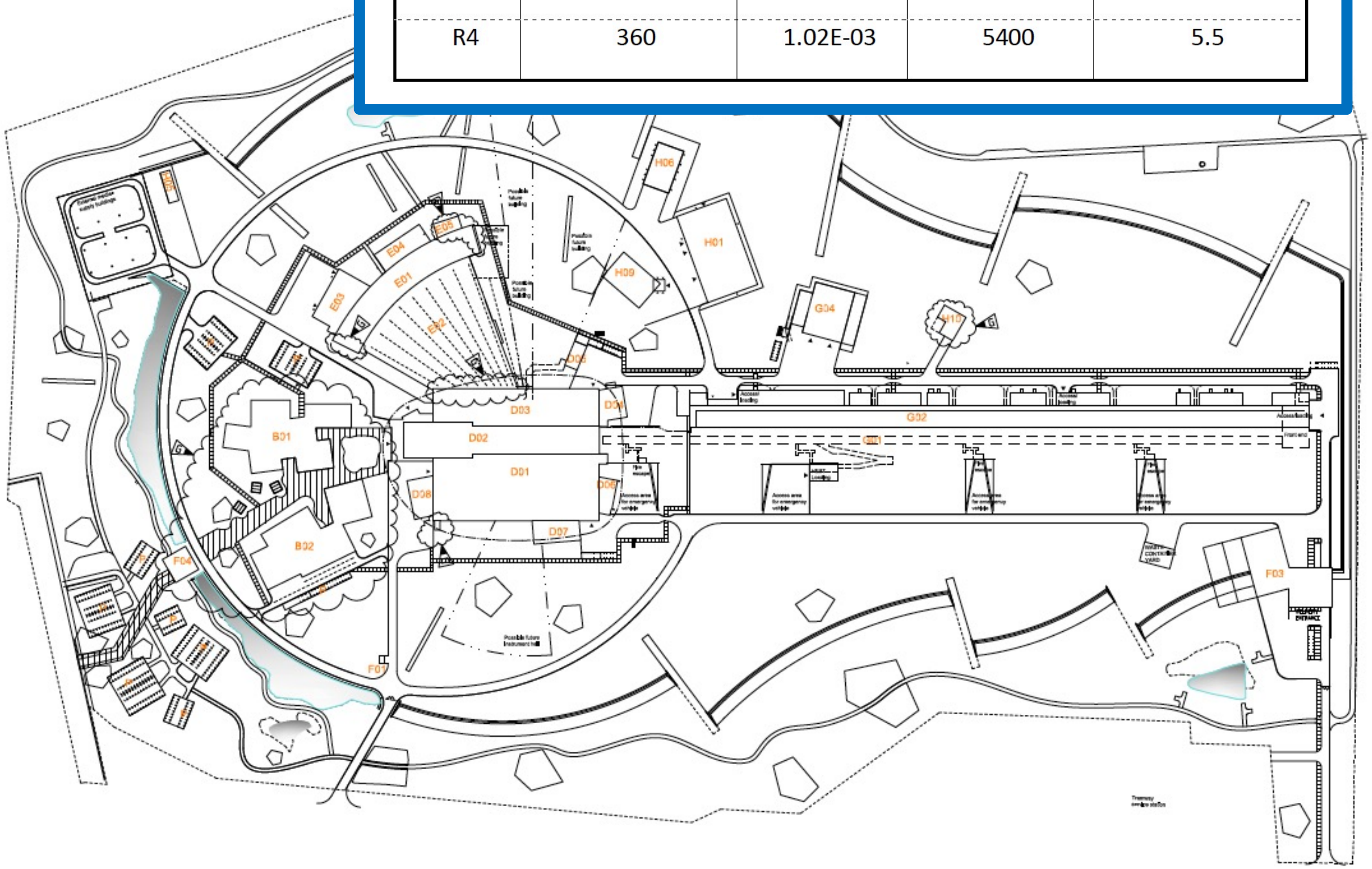
Skyshine dose rate is calculated by following equation

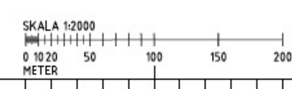
$$H = 7 \times 10^4 \sum (H_0 A)\left(e^{-R/600}/R^2\right) \ \mu Sv/h$$

Where $\sum H_0 A$ is the hadron dose equivalent rate in Sv/hr times surface area.

Skyshine dose rates at nearest point of site office (B02) and nearest point on the site boundary (R4)

location	distance from target centre (m)	skyshine (μSv/h)	occupancy factor (h/y)	annual dose from bunker (μSv/y)
B02	136	1.04E-02	1800	18.7
R4	360	1.02E-03	5400	5.5





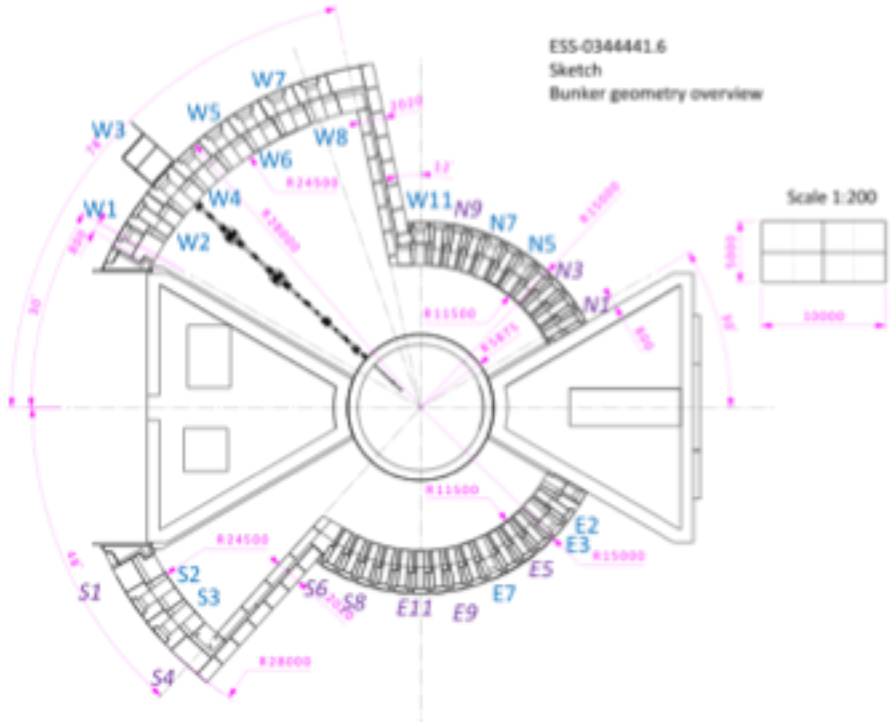
Skyshine results

- Combining the contributions from accelerator, target and instruments with the bunker skyshine dose, we obtain a total calculated dose of 21.5 μSv/y and 6.0 μSv/y for B02 & R4, respectively.

- **We conclude that the bunker contribution to the ESS skyshine dose is well within acceptable limits.**

contents

- ❑ Source term
- ❑ Wall
- ❑ Roof
- ❑ Skyshine
- ❑ Activation
- ❑ conclusions

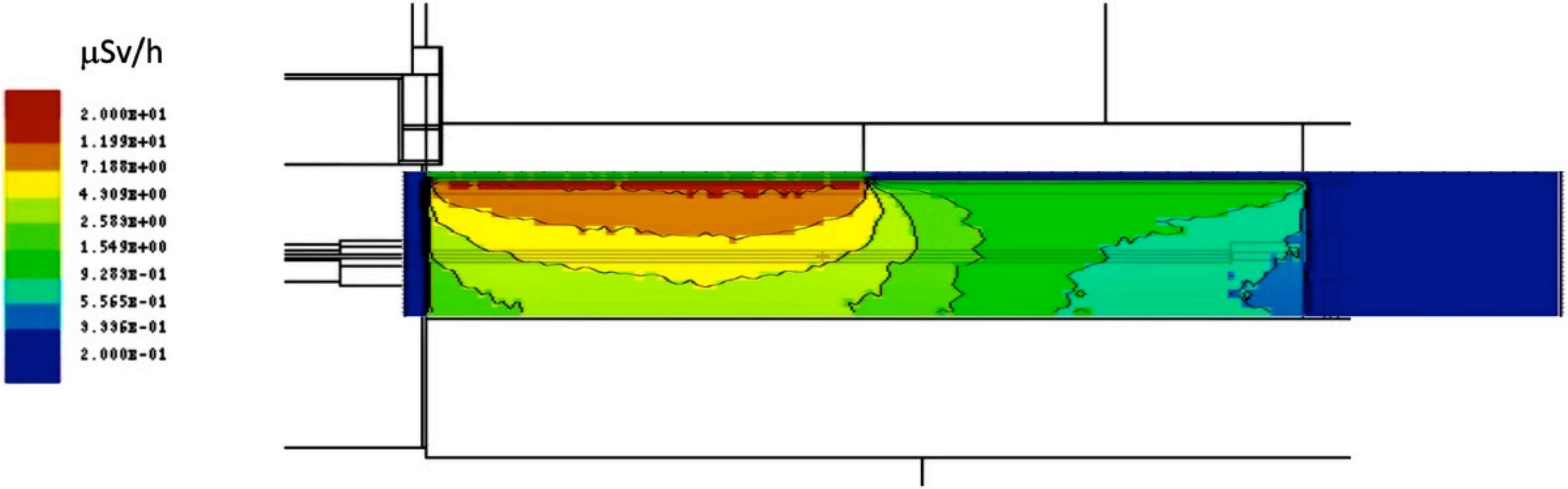


Roof activation long sector (CSPEC beamline)

Gamma dose rate (10 years irradiation, 1 day cooling)

Only activation of roof and wall has been calculated.

Dose rate levels are at the level of 10s of μSv/h, which is acceptable as in most cases work is done remotely



Activation of wall (long sector)

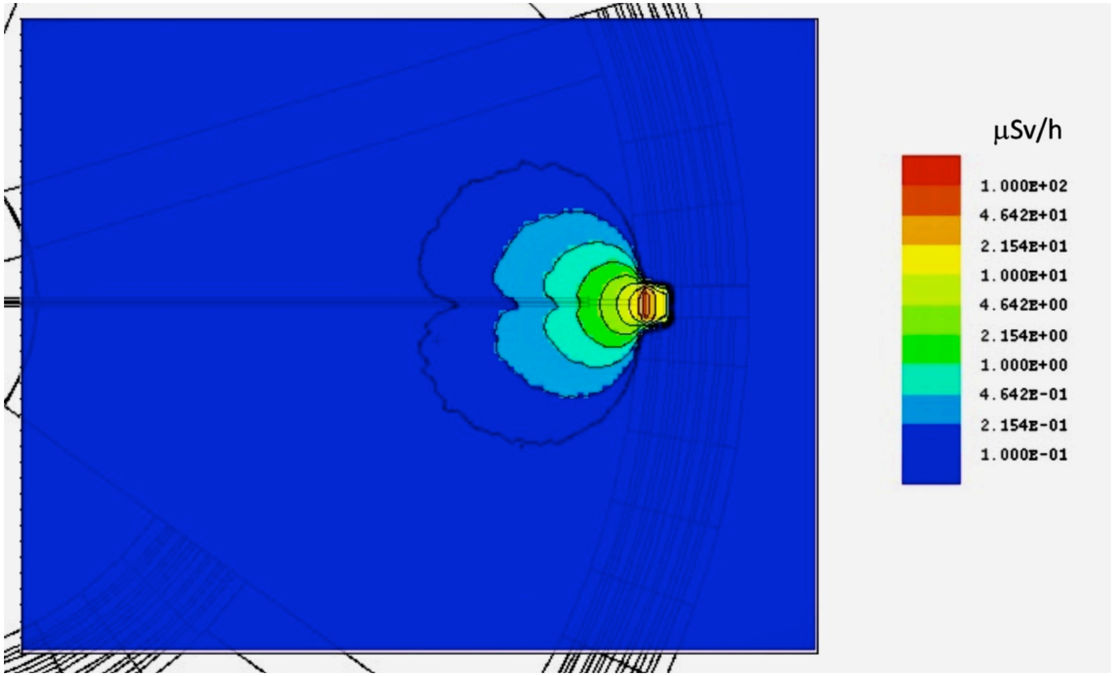
Gamma dose rate (10 years irradiation, 1 day cooling)

With beamline in bunker

with beam opening in bunker (to be calculated) dose rate will be much lower

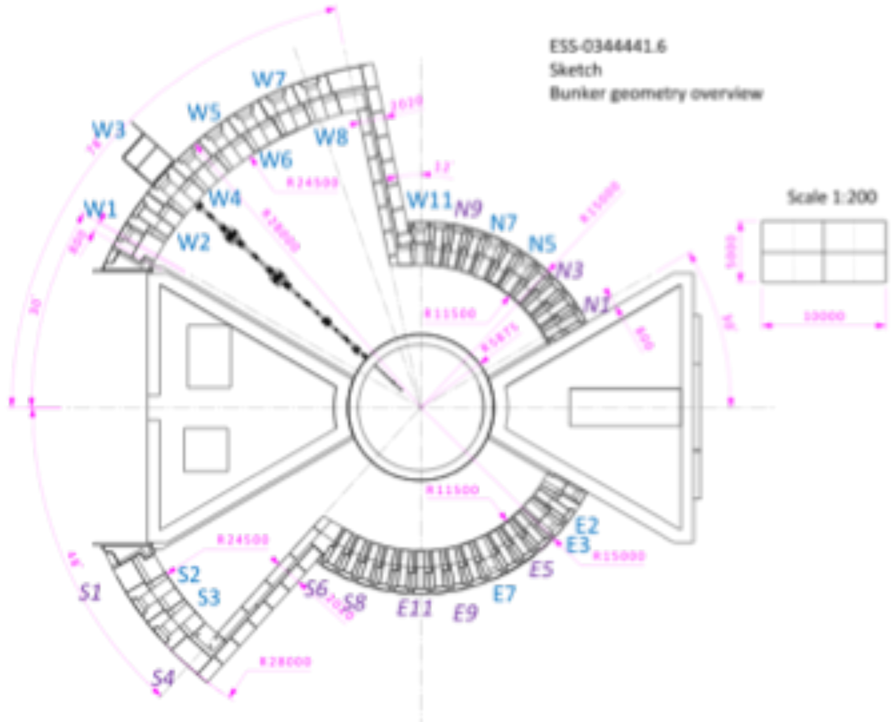
Additional reduction from
- adding boron layer in vacuum pipe (required)
- Adding locally boron layer in wall and roof (possible)

5 µSv/h at 1 m



contents

- ❑ Source term
- ❑ Wall
- ❑ Roof
- ❑ Skyshine
- ❑ Activation
- ❑ Conclusions



Conclusions (1)

- We have redesigned the bunker wall and roof with a comprehensive study taking into account source term, facility configuration, gaps, dose rate and skyshine requirements, and activation.
- The shielding material for wall and roof consists of heavy concrete, of a composition known as magnadense and density of 3.8 tonne/m^3.
- The roof and wall thicknesses are:

	South	West	North	East
wall	3.5 m			
roof	3 step 1.4 m - 6<R<15m 1.2 m - 15<R<21m 1.0 m - 21<R<28m	Same as South, + additional step above CSPEC	Flat 1.3 m	

Conclusions (2)

- The new design will allow the operate the bunker roof as an unrestricted controlled zone for radiation, and satisfies all ESS skyshine requirements.
- We have designed the roof in a stepped configuration for cost optimization, crane access and lowered bunker weight
- The approach we used in all our studies is conservative since we used the hardest spectrum for all the sectors and we also extrapolated beyond scope facility

- Two neutronic reports in preparation for CDR:
  - Source term
  - Neutronic design

- **We are ready for the CDR**

Bunker neutronic team

S. Kennedy

V. Santoro

D. Di Julio

Z. Lazic

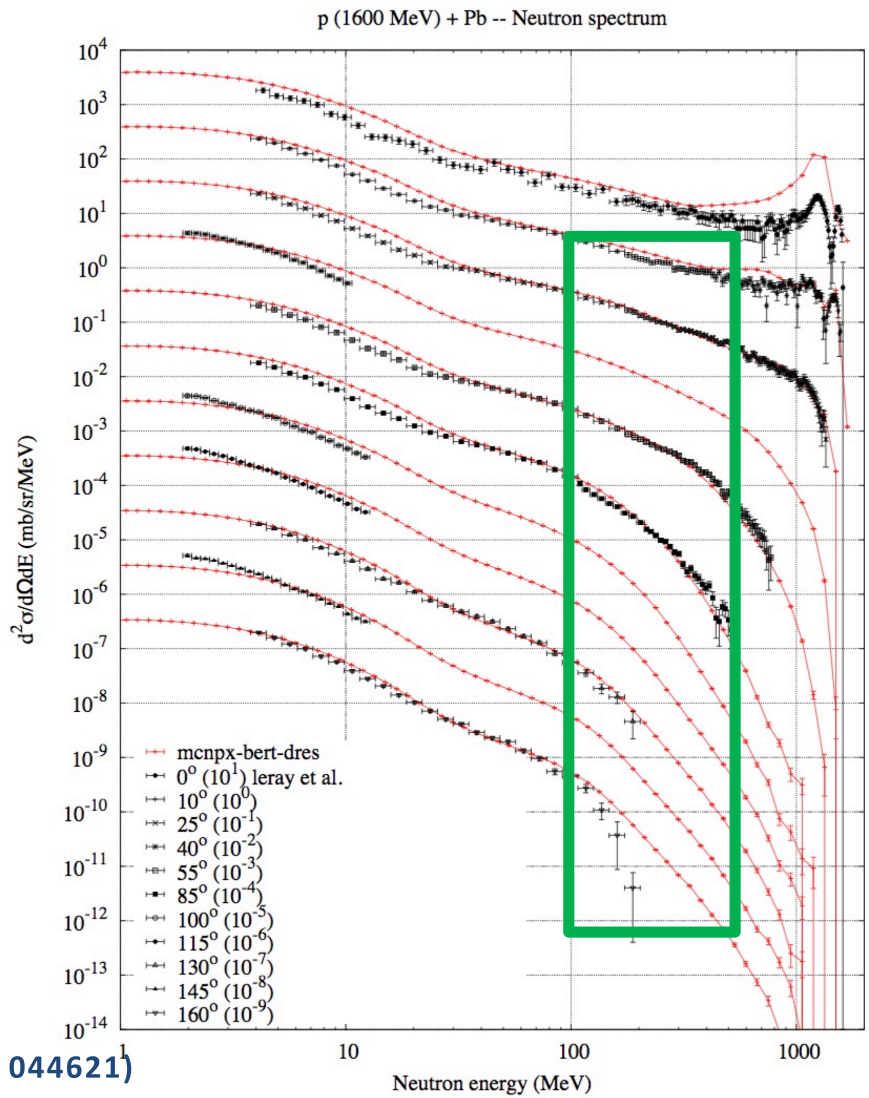
E. Klinkby

P. Bentley

BACKUP SLIDES

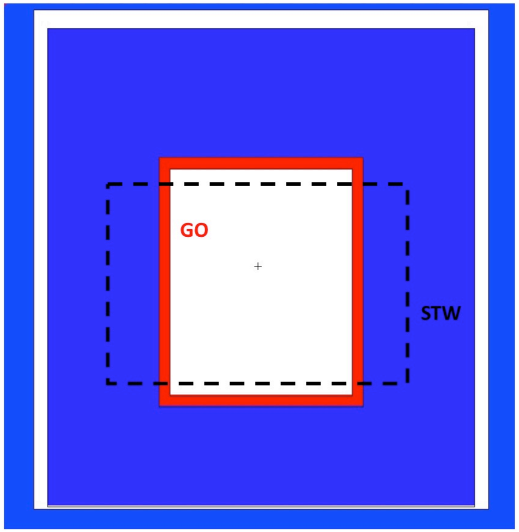
IAEA benchmark, comparison of different spallation models with neutron yield data

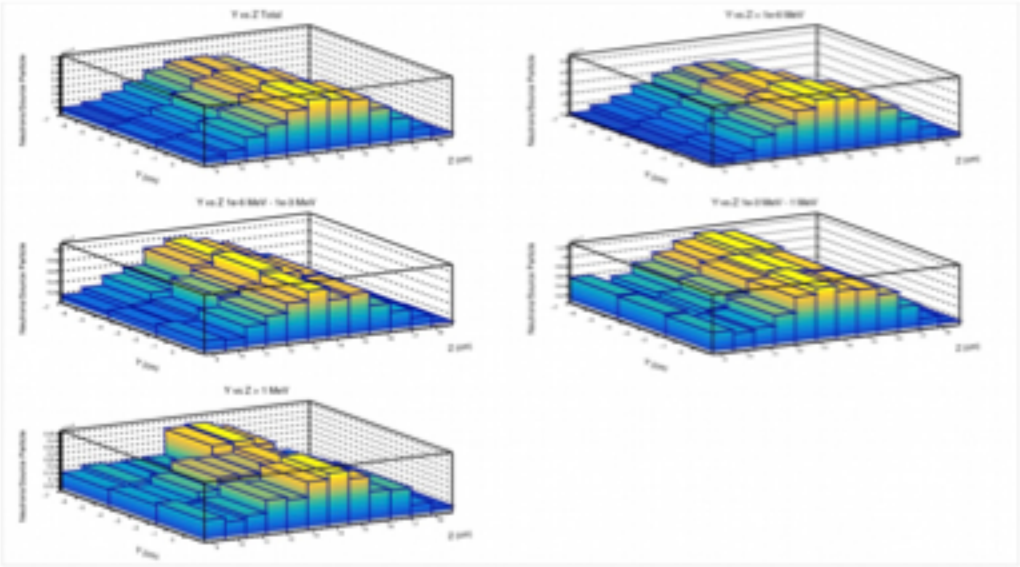
For neutron production the standard Bertini-Dresner model combination reproduces well the data in the energy and angular range relevant to ESS



(PHYSICAL REVIEW C, VOLUME 65, 044621)

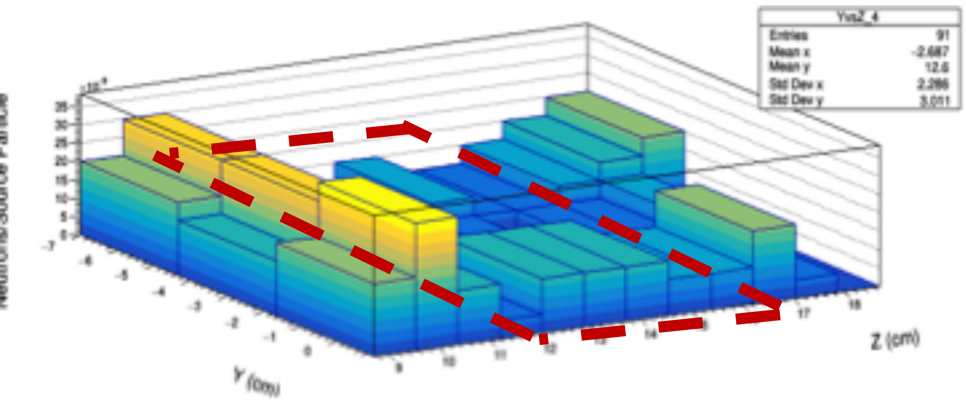
Source term: source term window should match guide opening



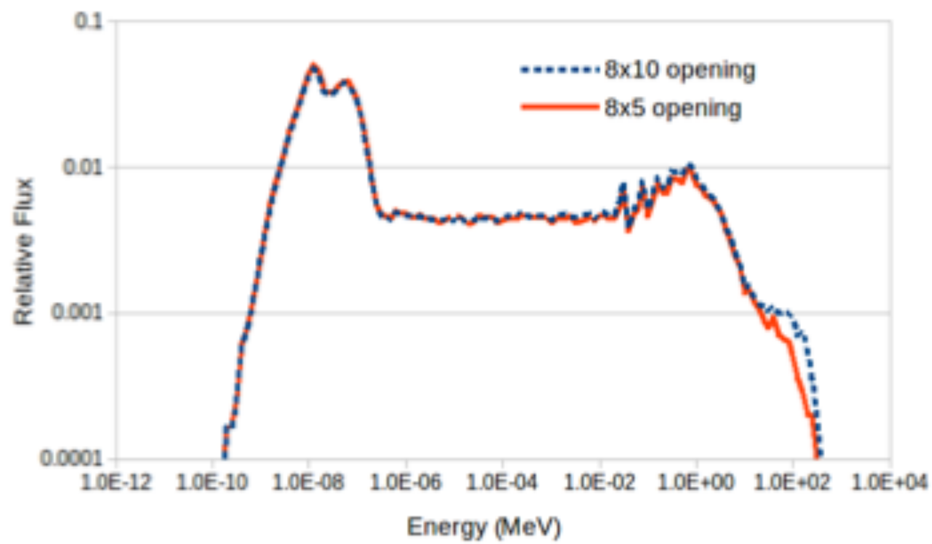


2D distribution of neutrons at 2 m with $\theta < 1°$.

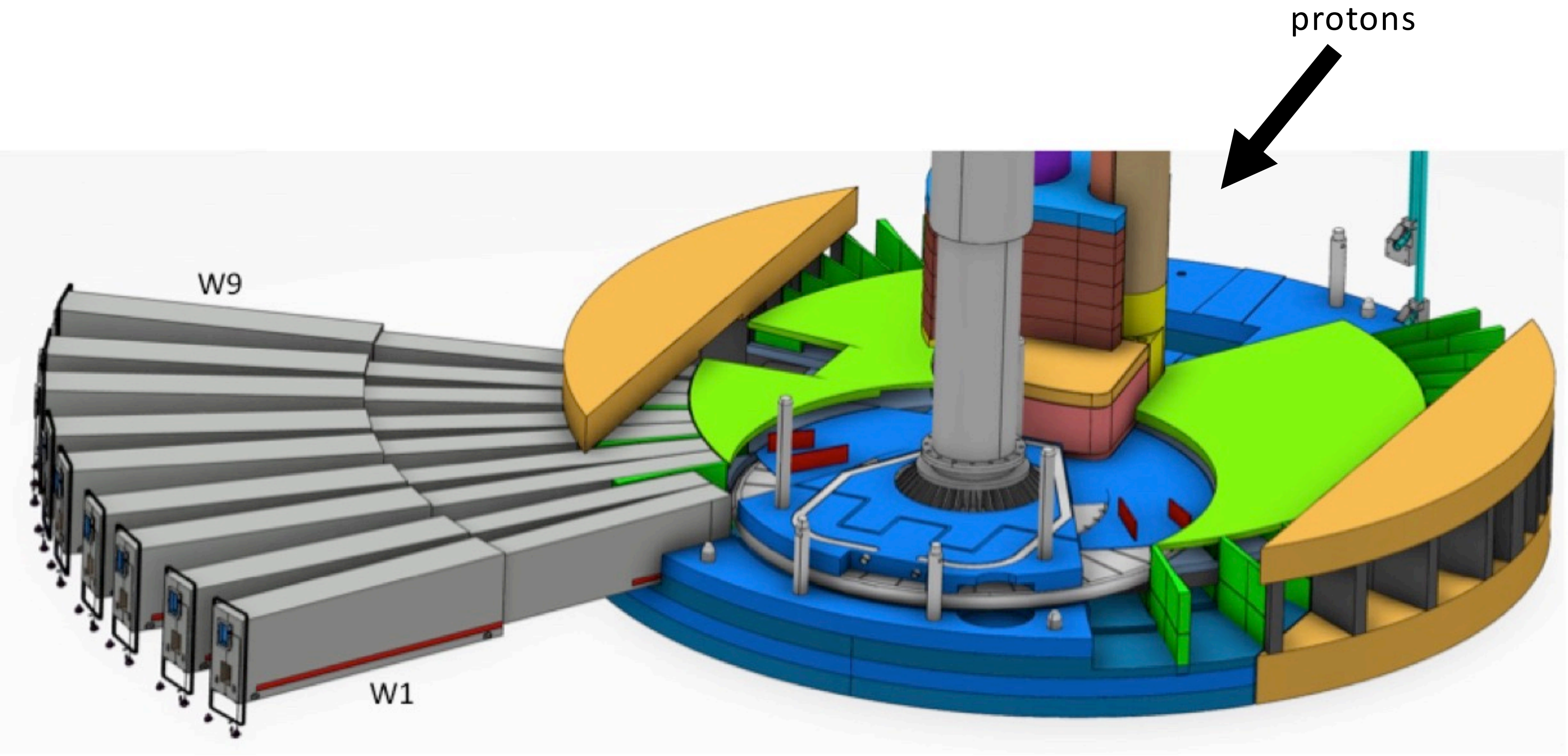
smaller guide openings cut a significant fraction of fast neutrons



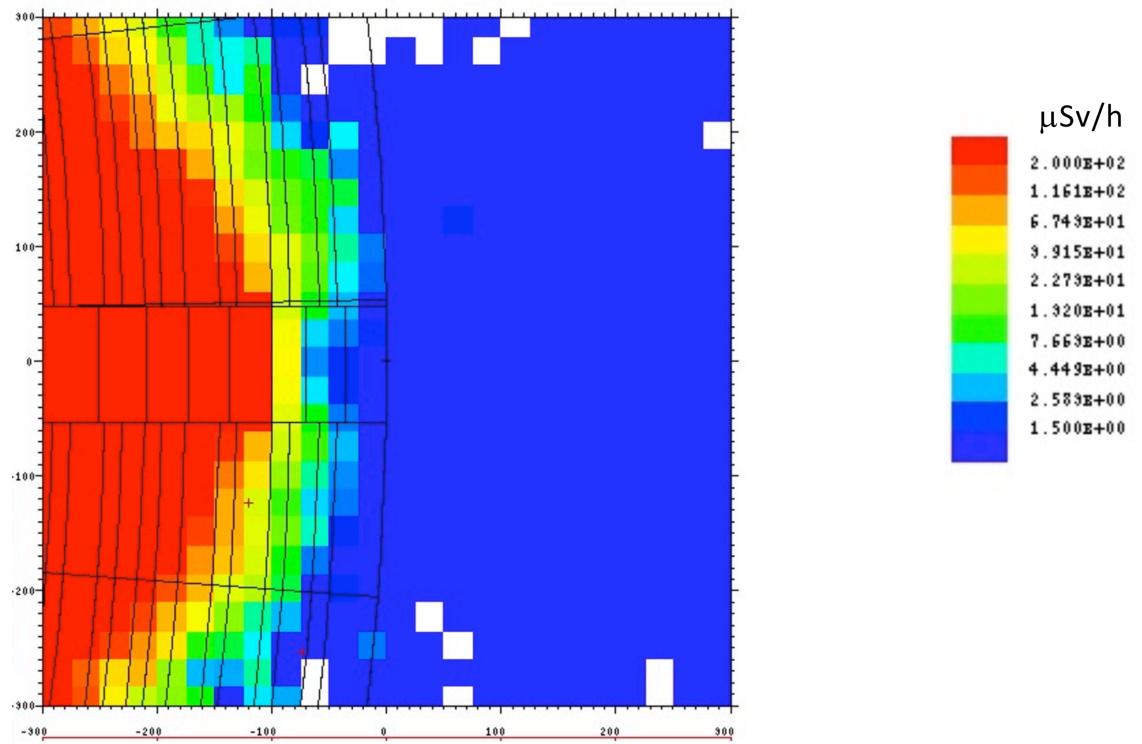
2D distribution is more uniform for a smaller guide opening (CSPEC is 5.5 cm high)



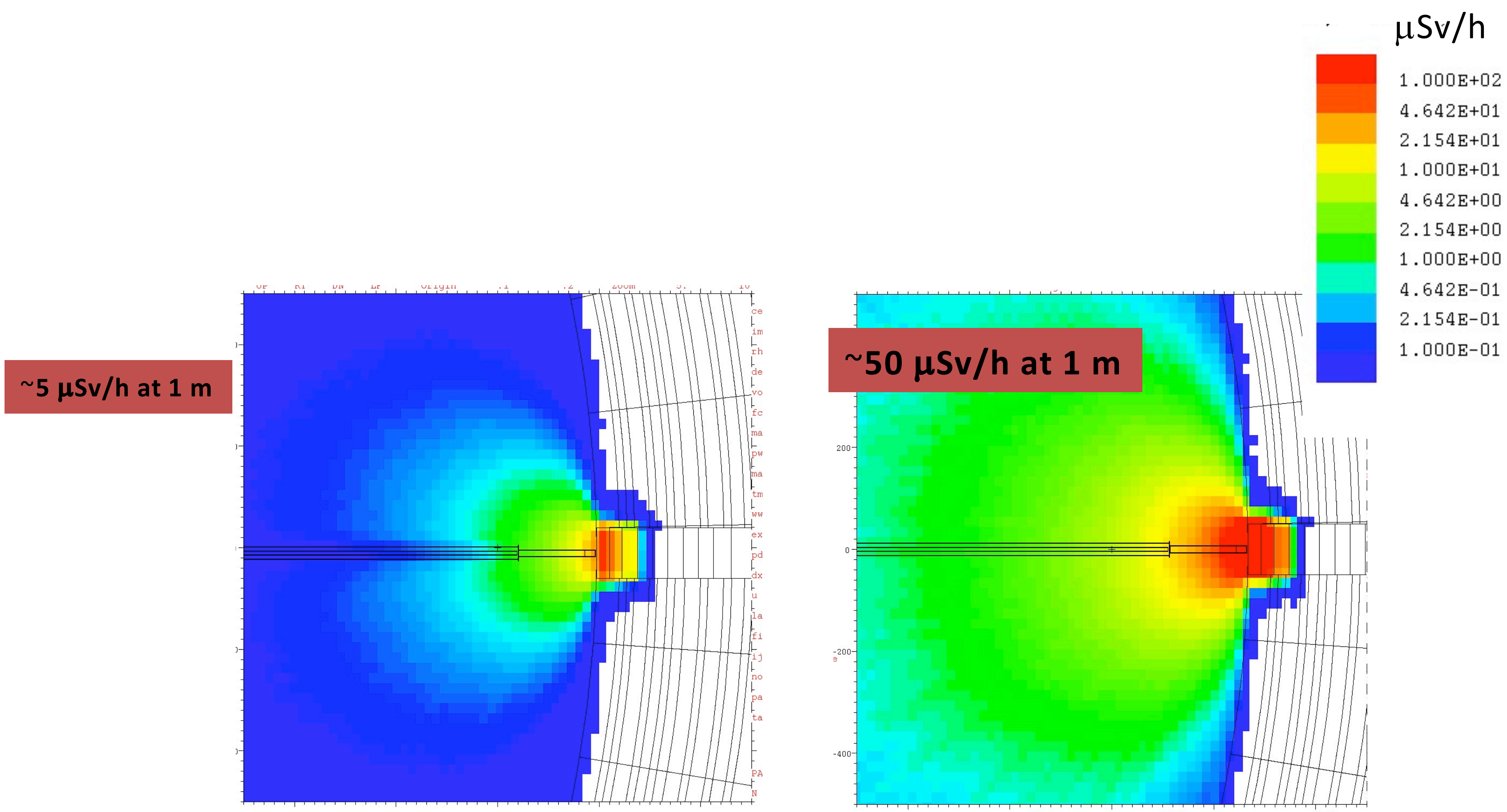
Energy spectra at the 2 m position for an 8 cm x 10 cm opening and a 8 cm x 5 cm opening in the position of CSPEC.


protons
W9
W1

CSPEC wall dose rate with steel insert is below is 0.8 μSv/h

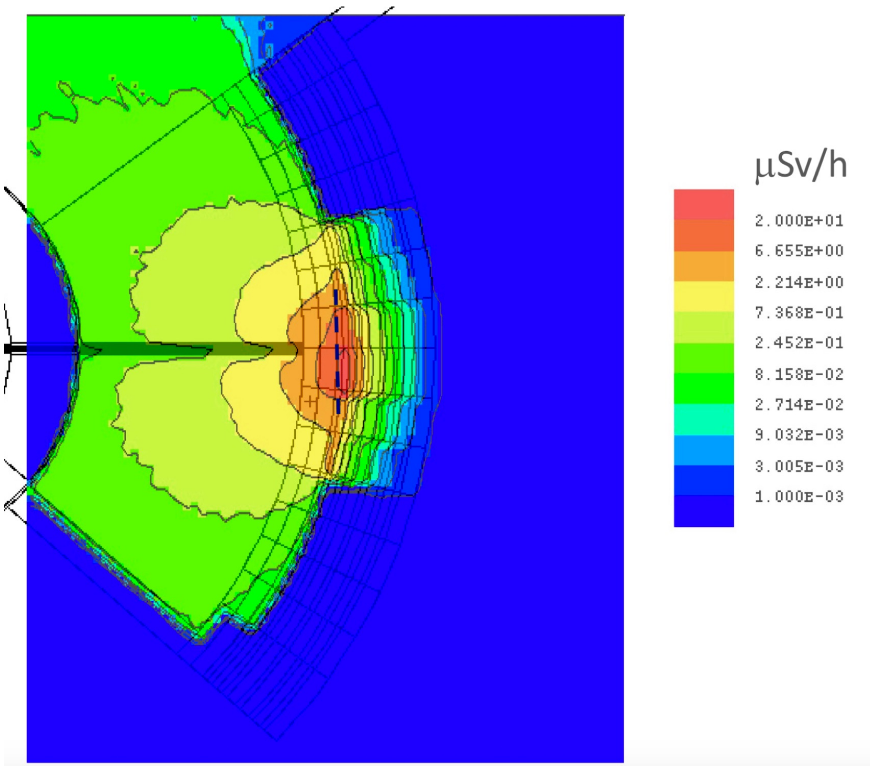


With no beamline in bunker, wall activation is 10 times higher

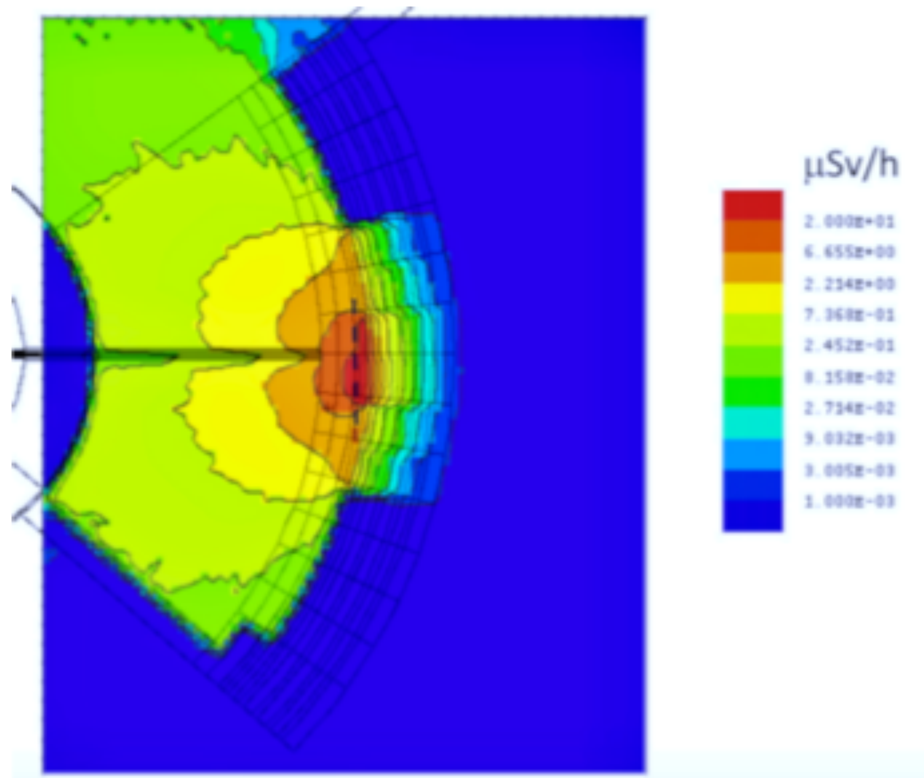


Use of boron absorbing layers can be considered to reduce activation of wall and roof

+ 5 mm mirrobor



No mirrobor



Short sector wall 2.6m HC (3.9 g/cm^3), 10 years operation, 1 day cooling

Importance of high energy neutrons and their proper modeling

Dose rate on roof for only the CSPEC beamline

n < 50 MeV: 0.076 μSv/h

n < 100 MeV: 0.24 μSv/h

n < 200 MeV: 0.74 μSv/h

n < 300 MeV: 1.28 μSv/h

n <500 MeV: 1.71 μSv/h

All neutrons: 1.96 μSv/h

Note: in a real situation the dose rate at the wall exit is dominated by contribution from the beamline

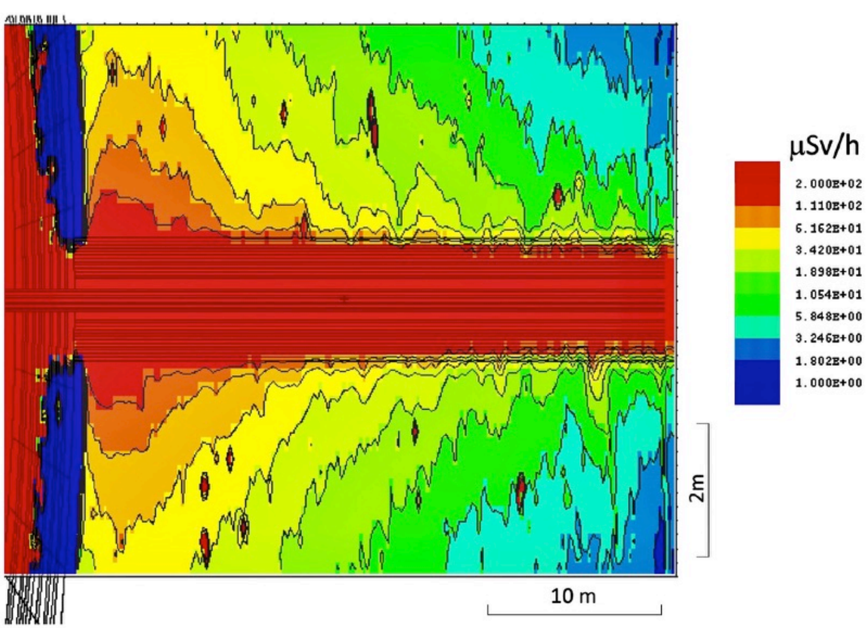


Figure 10 Dose rate (µSv/h) at the exit of the bunker short sector (straight guide, 8 × 10 cm² opening).

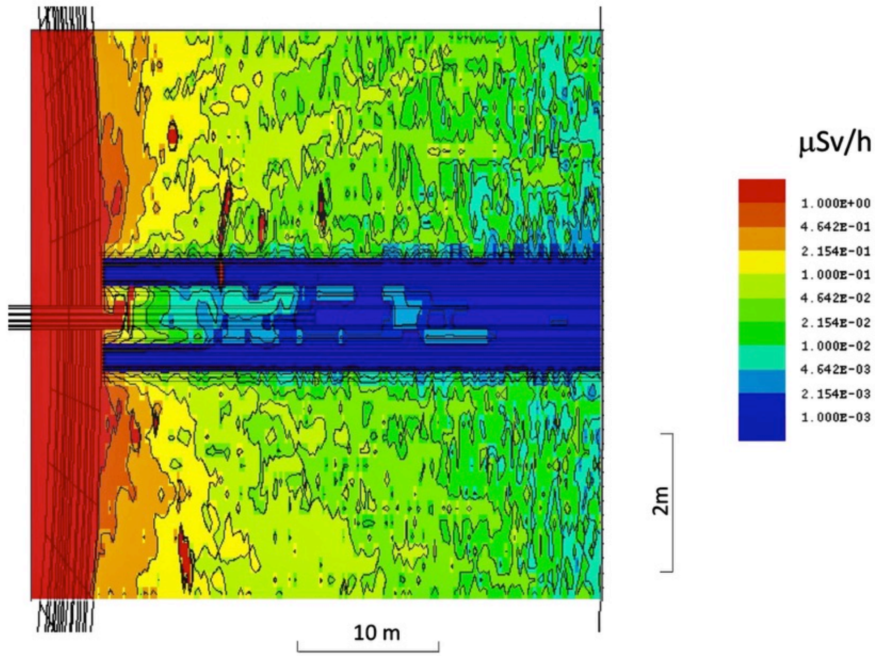


Figure 12. Dose rate around the guide and tunnel outside the bunker. The neutron propagation in the beamline is artificially stopped in the bunker wall (of 2.6 m heavy concrete), 2.3 m from the external surface of the wall.

(calculations done not for the present wall but for 2.6 m, for a 3.5 m wall the relative contribution of the beamline is higher).