BIFROST radiation & conventional risks

iSRR – 5th December 2025

Hall outline

Cave

BW chopper

Shutter

Bunker wall

BW chopper

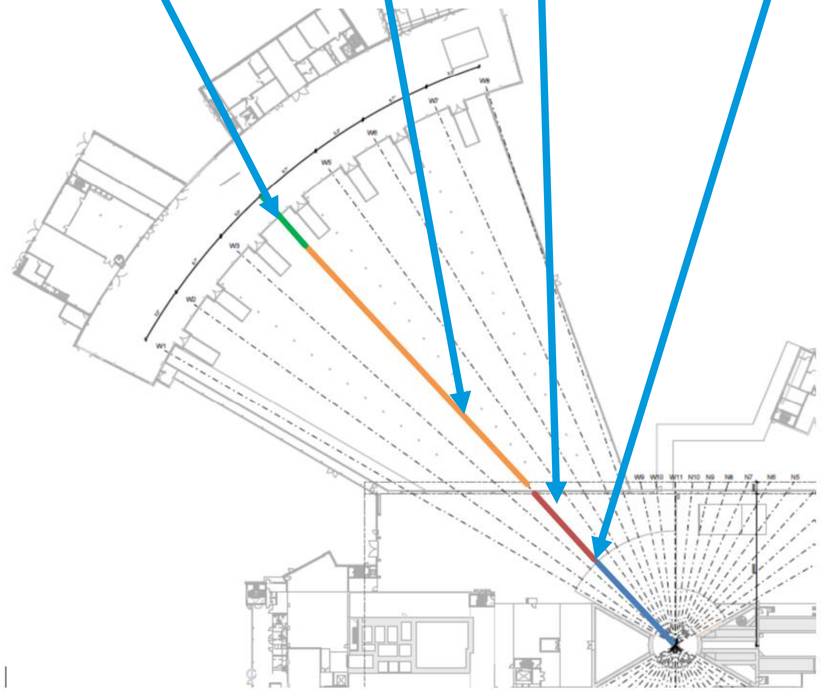
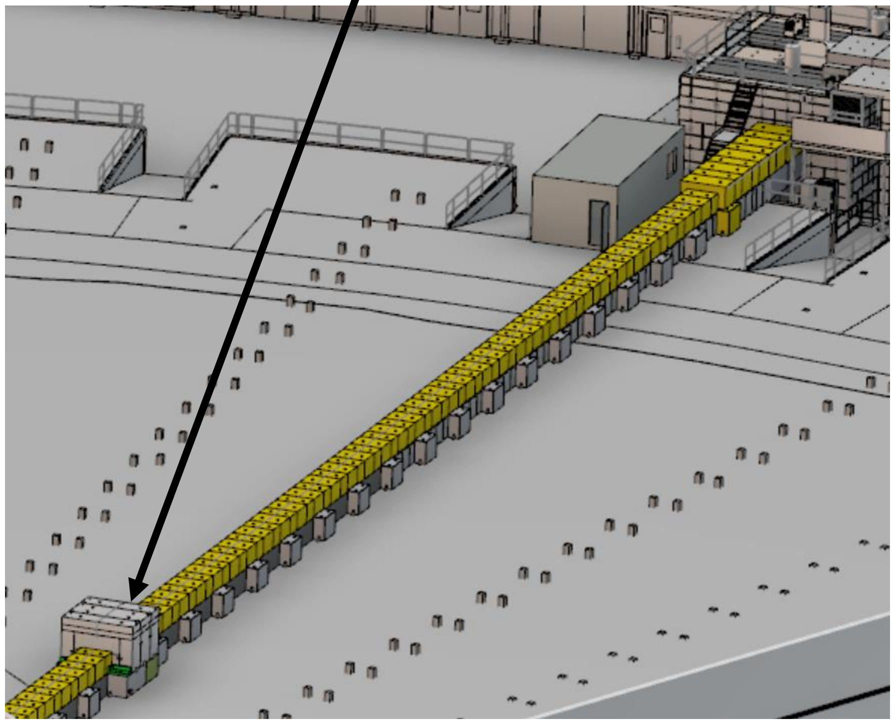


Figure 11 - Outline of the west sector beam-lines, outlining the bunker section (blue), the D03 section (red), the E02 section (orange) and the cave section (green).



- Bunker PSS in effect up to but not including the BW chopper
- BIFROST PSS starts at BW chopper and including chopper pits
- PSS locks on chopper pit
- Cave intrinsically locked (hatch blocks access to keystone)

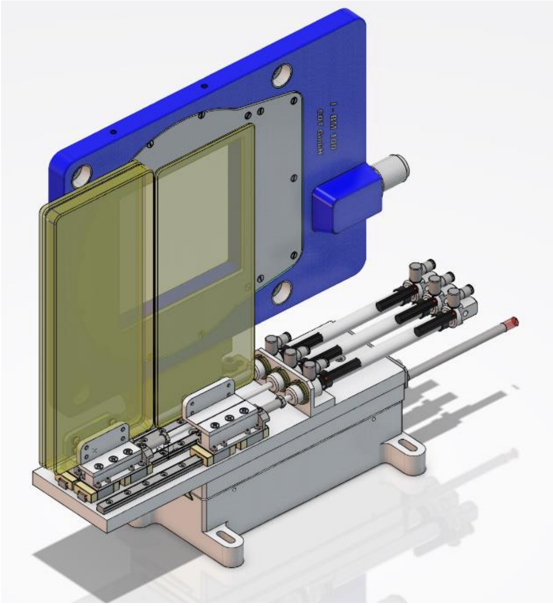
Component reminder

Guide

Chopper

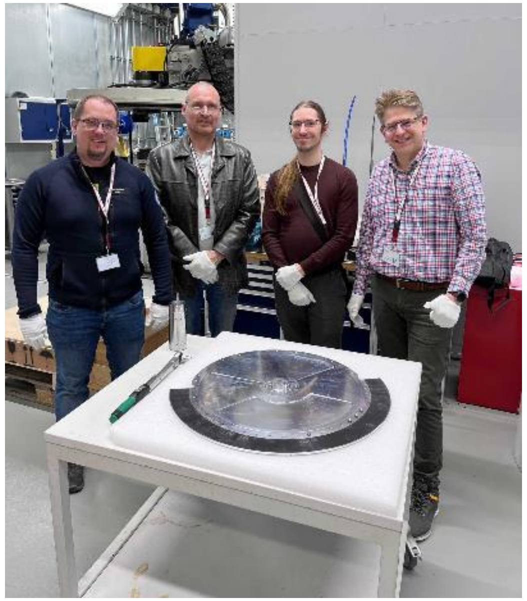
Shutter

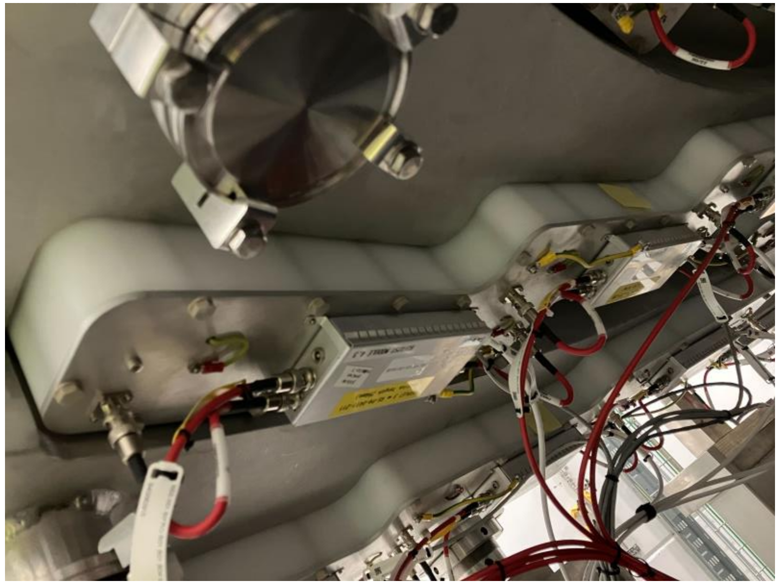
Monitor and attenuators



Component reminder II

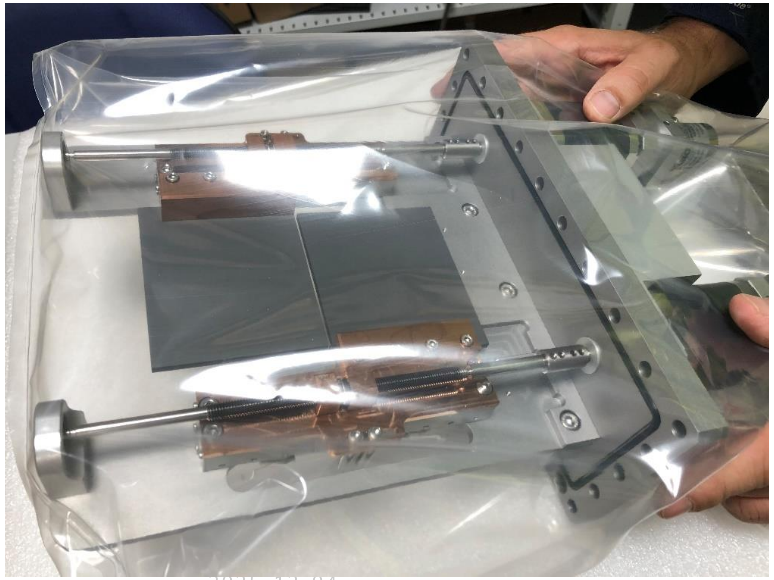
Chopper control & disc





Mounted detector

Divergence jaw



Cadmium in tank

Get lost tube

ESS radiation limits

ESS-0000004 - GSO
ESS-4133053 – ALARA charter
ESS-0239718 – General RP rules

Supervised area (subset of requirements)

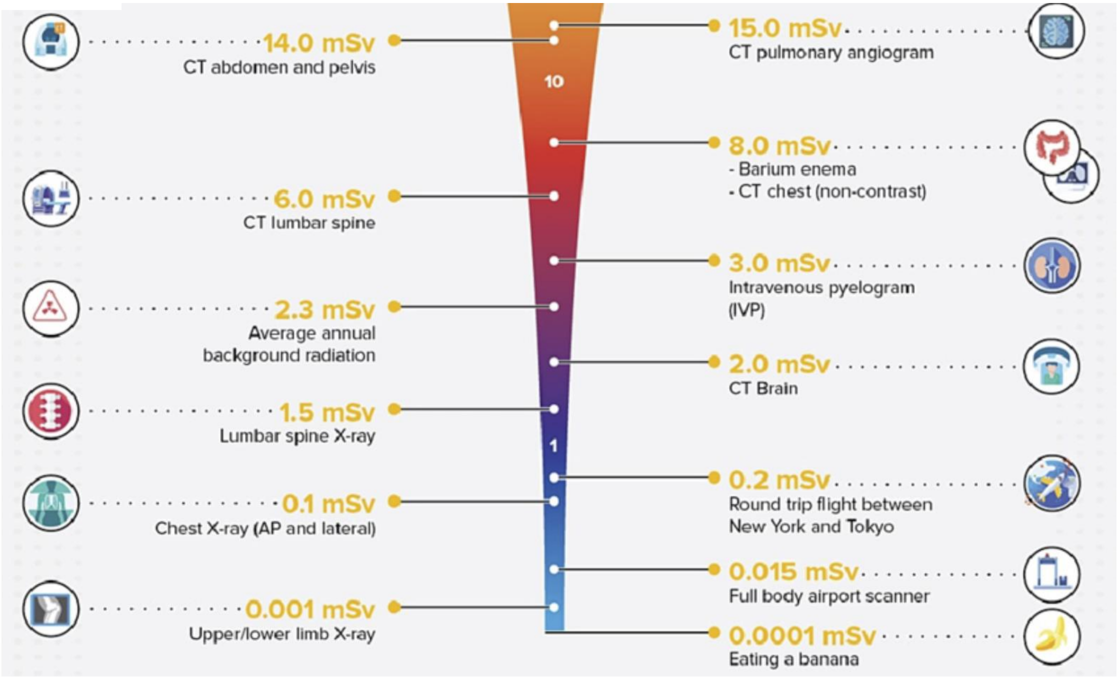
3 The ambient equivalent dose during normal operation and likely accidents (likely to happen yearly) shall be less than 3 μSv in any given hour.

4 Temporary hotspots should not exceed a dose rate of 15 μSv/h.

Controlled area (subset of requirements)

- Less than 25 uSv in any given hour

Operating conditions and likelihood (per year) of initiating event	Exposed worker with radiation safety task	Exposed worker without radiation safety task	Non-exposed worker
Normal operation, H1	Dose limit 20 mSv/year Dose constraints (*) 2 mSv/year		Dose limit 1 mSv/year Dose constraints (*) 0.1 mSv/year
Anticipated events, H2 $F \geq 10^{-2}$	Design criteria 20 mSv/event	Plan protective action based on realistic estimation for typical cases and applying ALARA via a respective ESS committee and an established ESS guideline [6]	
Unanticipated events, H3 $10^{-4} \leq F < 10^{-2}$	Design criteria 20 mSv/event		
Improbable events, H4A $10^{-6} \leq F < 10^{-4}$	Design criteria 20 mSv/event		



Radiation sources on BIFROST

<u>Sources of radiation on BIFROST:</u>

- Fast neutrons from moderator
- Thermal neutrons within guide
- Gammas from neutrons absorbed in guide coating (high energy)
- Gammas from neutrons absorbed in boron (low energy)
- Thermal neutrons scattered in air (almost like a gas)
- Prompt gammas from aluminum
- Gammas from target

<u>Activation (much lower radiation levels):</u>

- Copper in pulse shaping chopper
- Aluminium and vanadium (short lived) (both sample environment and guide and chopper housings)
- Problematic samples (La, Ir, Mn, Tb, Cu) – halflife of days to months
- Very long lived activation has low radiation levels, samples like Co, posing no immediate hazard but a pain in the neck for users
- Activity scales with sample mass

Beamline radiation risks up to BW chopper – prompt radiation

Mode	Cause / Initiating Event	Person Affected	Hazard	Radiation Level exceeds	Source of Hazard	Sub Mode / Task	Likelihood per year (From H Category) ESS-0000004	Target Risk (From ESS Target Risk for Rad Haz) ESS-0000004	Actions to Mitigate Risk (Risk Controls)
Proton beam On	Person outside guide shielding. Proton beam On	Exposed worker without radiation safety task	Prompt ionising radiation	2mSv/year	Radiation from prompt activation gammas	N/A	H1 1	≤ 1 X 10 -2	Guide shielding to achieve radiation levels with beam on or off equal or less than 3 microSv/hour in contact. RAD Work Permit.
Neutron beam On	Intrusion to the guide shielding downstream shutter during beam on shutter open.	Worker	Prompt ionising radiation	10mSv/event	Ionising radiation	N/A	H3 1 X 10 -4	≤ 1 X 10 -4	a) Shielding and barriers to prevent access to cave. Signage. b) PSS activated with proton beam on target and instrument shutter open. c) Locking of shielding blocks by safety interlock system. d) Warnings (sign or alert) implemented outside Guide shielding to alert persons of potential risk.
Proton beam on/ Neutron beam off	Intrusion to the guide shielding (downstream the shutter up to the chopper pit) proton beam operation-Instrument shutter is closed	Worker	Prompt ionising radiation	10mSv/event	Ionising radiation	N/A	H3 1 X 10 -4	≤ 1 X 10 -4	a) See ESS-3999144 - Conventional and Radiological Hazard Analysis and Risk Assessment of NSS Bunker Area b) Shielding and barriers to prevent access to cave. Signage. c) Bunker PSS activated with proton beam on target d) Locking of shielding blocks by safety interlock system. d) Warnings (sign or alert) implemented outside Guide shielding to alert persons of potential risk.

- For bunker radiological risks and mitigations, see ESS-3999144
- Many variants of the same intrusion hazards: Guide shielding protects from all neutron and prompt radiation, area controlled by bunker PSS and block locking, procedure and signs

Beamline radiation risks up to BW chopper – beamline activation

- For bunker radiological risks and mitigations, see ESS-3999144
- Beamline activation hazards, mitigated by prompt radiation shielding, RP procedure and PSS interlock (bunker PSS)

Mode	Cause / Initiating Event	Person Affected	Hazard	Radiation Level exceeds	Source of Hazard	Sub Mode / Task	Likelihood per year (From H Category) ESS-0000004	Target Risk (From ESS Target Risk for Rad Haz) ESS-0000004	Actions to Mitigate Risk (Risk Controls)
Proton beam Off	Person outside guide shielding. Activated components within guide shielding.	Exposed worker without radiation safety task	Activation	2mSv/year	Activation from components.	N/A	H1 1	≤ 1 X 10 -2	Guide shielding to achieve radiation levels with beam on or off equal or less than 3 microSv/hour in contact. RAD Work Permit.
Proton beam Off	Person outside guide shielding. Activated components within guide shielding.	Non-exposed worker	Activation	0.1mSv/year	Activation from components.	N/A	H1 1	≤ 1 X 10 -2	Guide shielding to achieve radiation levels with beam on or off equal or less than 3 microSv/hour in contact. RAD Work Permit.
Proton beam Off	Person inside guide shielding: Maintenance of components.	Exposed worker without radiation safety task	Activation	2mSv/year	Activation from components.	N/A	H1 1	≤ 1 X 10 -2	Work order procedure (radiation check, time and distance) to ensure staff do not receive a high dose. RP Work permit must be accepted by RP.
Proton beam Off	Person inside guide shielding: Maintenance of components.	Non-exposed worker	Activation	0.1mSv/year	Activation from components.	N/A	H1 1	≤ 1 X 10 -2	Work order procedure (radiation check, time and distance) to ensure staff do not receive a high dose. RP Work permit must be accepted by RP.
Proton beam Off	Access to guide shielding when access has not been granted.	Worker	Activation	1mSv/event	Activation from components.	N/A	H3 1 X 10 -3	≤ 1 X 10 -2	a) Only allow shielding dismantling procedure with RP work permit and supervision. b) PSS interlock module for guide shielding. C) Signage at pit opening.

Beamline radiation risks at BW chopper – all

- Minor air contamination risks mitigated by RP procedure (use dosimeter during all maintenance) These are monitor gas, shutter lead impurities, lead and aluminium.
- Chopper pit – similar to guide and shutter. Activation, prompt radiation. Mitigated by guide shielding design, access procedure and PSS
- Thermal shutter closed gives access to cave – shutter failure mitigated by links to radiation monitors

Mode	Cause / Initiating Event	Person Affected	Hazard	Radiation Level exceeds	Source of Hazard	Sub Mode / Task	Likelihood per year (From H Category) ESS-0000004	Target Risk (From ESS Target Risk for Rad Haz) ESS-0000004	Actions to Mitigate Risk (Risk Controls)
Neutron beam On	Intrusion to the Chopper in the BW Pit during beam on , shutter open.	Worker	Prompt ionising radiation	10mSv/event	Ionising radiation	N/A	H3 1 X 10 -4	≤ 1 X 10 -4	a) Shielding and barriers to prevent access to cave. Signage. b) Shielding configuration controlled by RP and supported by the safety interlock system.
Neutron beam Off	Person is in the BW pit and the shutter opens inadvertently	Worker	Prompt ionising radiation	10mSv/event	Ionising radiation	N/A	H3 1 X 10 -3	≤ 1 X 10 -4	a) Safety interlock system preventing inadvertent requests for opening the heavy shutter. b) Monitoring heavy shutter by safety interlock system and interlock with proton beam during access modes.
Neutron beam Off	A person is in the BW pit or guideline from the chopper pit up to the cave and failure in the shutter.	Worker	Prompt ionising radiation	2mSv/year	Neutron Beam	N/A	H3 1 X 10 -4	≤ 1 X 10 -2	Radiation monitor down the stream heavy shutter with link to PSS. PSS signage activated when Heavy Shutter opening is detected.
Neutron beam Off	Shutter fails in absorbing neutrons or gammas	Worker	Prompt ionising radiation	100mSv/event	Ionisation radiation	N/A	H3 1 X 10 -3	≤ 1 X 10 -2	a) PSS interface with radiation monitors (safety interlock system) b) RP Survey in the guide area and chopper pit by RP before access to the guide area.

Verification of mitigation - beamline

- Responsibility of RP and PSS
- Judging from our simulations, the gaps in the neutron guide are the key hotspots: Neutron absorbers (shutter, chopper) aluminium windows, air scattering of neutrons
- Use neutron dosimeter near the shielding doglegs

At 20 W: Shielded dose increase outside is below 0.00001 uSv/h – check that there is no measurable increase at 20 W (if so, something is very wrong)

If allowed: Open guide shielding after shutter and verify gamma dose at 20 W.

At 200 kW: increase is around 0.06 usv/h – measureable and hotspots can be identified.

Radiation risks - cave

- All radiation risks outside cave, from prompt and activation, are mitigated in the same way as for the beamline: By appropriate shielding (see later slides for the Hx events driving the shielding design)

Mode	Cause / Initiating Event	Person Affected	Hazard	Radiation Level exceeds	Source of Hazard	Sub Mode / Task	Likelihood per year (From H Category) ESS-0000004	Target Risk (From ESS Target Risk for Rad Haz) ESS-000000	Actions to Mitigate Risk (Risk Controls)
Neutron beam On	Person on the cave roof. Ionising radiation (regions with higher than 3 uSv/hr)	Worker	Prompt ionising radiation	0.1mSv/event	Ionising radiation	N/A	H2 1 X 10 -1	≤ 1 X 10 -2	a) Shielding. b) Blue controlled area, RAD work permit required to access the roof.

Roof could be blue controlled area at 5 MW (see later slide)

Mode	Cause / Initiating Event	Person Affected	Hazard	Radiation Level exceeds	Source of Hazard	Sub Mode / Task	Likelihood per year	Target Risk	Actions to Mitigate Risk (Risk Controls)
Neutron beam Off	Access when we have high activation material inside the cave	Worker	Activation	1mSv/event	Activated components	N/A	H3 1 X 10 -4	≤ 1 X 10 -4	a) Work order procedure (radiation check, time, and distance) to ensure staff does not receive a high dose.) b) RP Work permit must be accepted by RP. c) RP check of the cave for maintenance. d) Use of personal EPDs to alert people if they are near radiation sources. e) Use Radiation monitor output in the sample area to grant access to personnel when it is safe. f) Signage at the cave entrance and locally at high radiation areas (sample env.) g) RP access veto by removing the RP access veto key and locking the cave access door and cave roof hatch by the safety interlock system.

Access to activated components (see later slide)

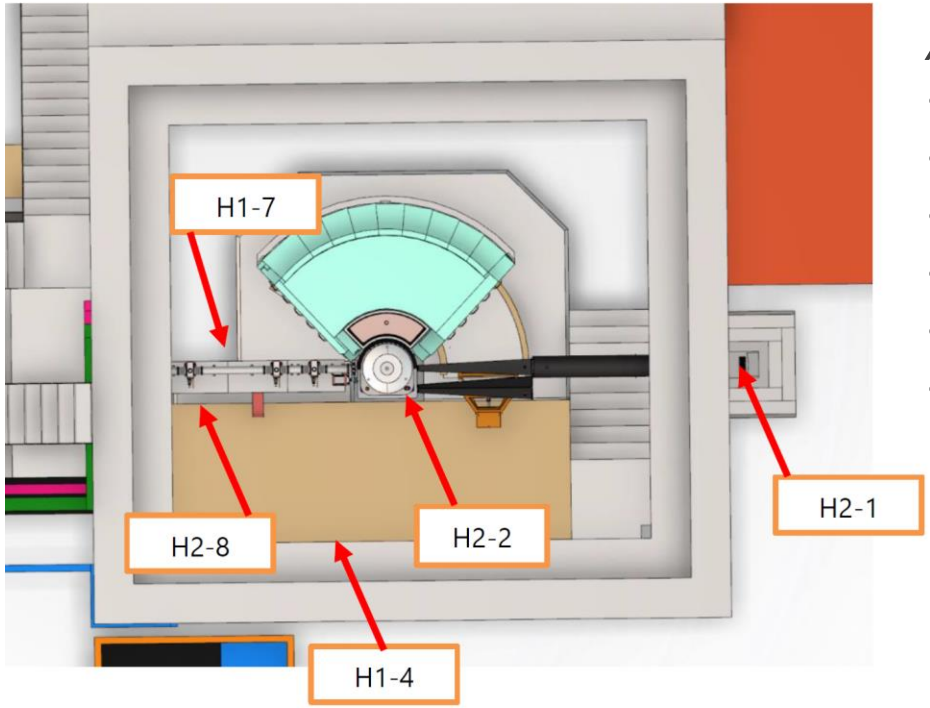
Mode	Cause / Initiating Event	Person Affected	Hazard	Radiation Level exceeds	Source of Hazard	Sub Mode / Task	Likelihood per year	Target Risk	Actions to Mitigate Risk (Risk Controls)
Neutron beam On	Intrusion to the cave via doors during beam on, shutter open.	Worker	Prompt ionising radiation	100mSv/event	Ionisation radiation	N/A	H2 1 X 10 -2	≤ 1 X 10 -6	a) Warnings (PSS LED signaling panels) implemented outside cave access door to alert persons of potential risk. b) Locking of cave access door by safety interlock system. c) Monitoring cave access door by safety interlock system and interlock with heavy shutter and proton beam.

Access to cave (PSS): Prevents person from being in the cave when shutter opens, from entering the cave when it is open, and warns a person if a shutter inadvertently opens while in the cave

Cave shielding

Maximum flux Operational Beam (MOB): Full flux wavelength band centered on 3 Å, PSC parked open, other choppers operational, 5 MW: **Flux: $1.6*10^{10}$ n/s/cm^2. Neutron current: $5x10^{10}$ n/s.**

Accidentally Unchopped Beam (AUB): All choppers accidentally parked in open position, 5 MW: **Flux: $4*10^{10}$ n/s/cm^2. Neutron current: $1.25*10^{11}$ n/s.**



e 5 - BIFROST cave interior, the arrows point to the location of the event in question.

All Hx scenarios less severe than the following 6:

- **H2-1:** AUB on beam stop
- **H2-2:** MOB on Cd sheet
- **H2-3:** MOB on 100 % incoherent scatterer
- **H2-8:** MOB on closed divergence jaws
- **H1-7:** MOB guide gammas
- **H1-4:** MOB Bragg peak (neutron beam) hitting cave from within

Verification of mitigation - cave

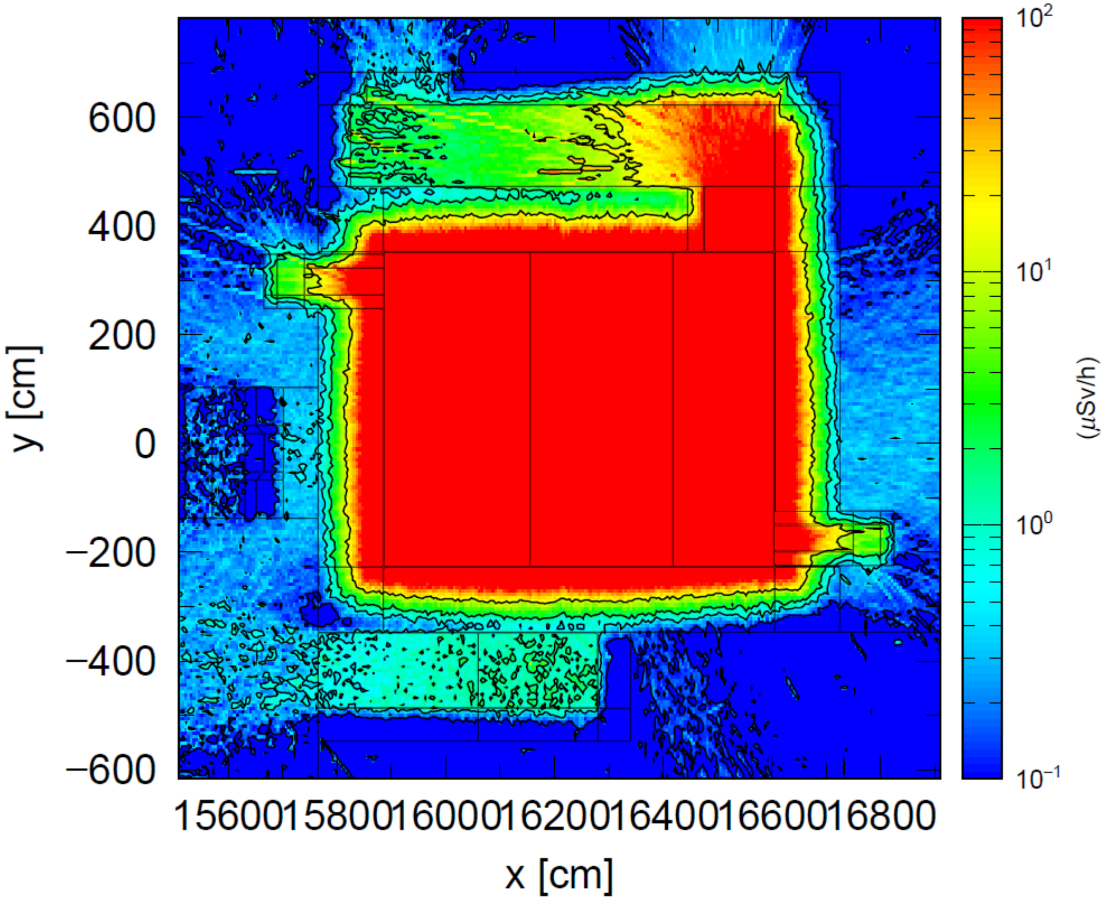
- Responsibility of RP and PSS
- Use neutron dosimeter near the shielding doglegs, feedthroughs and roof.

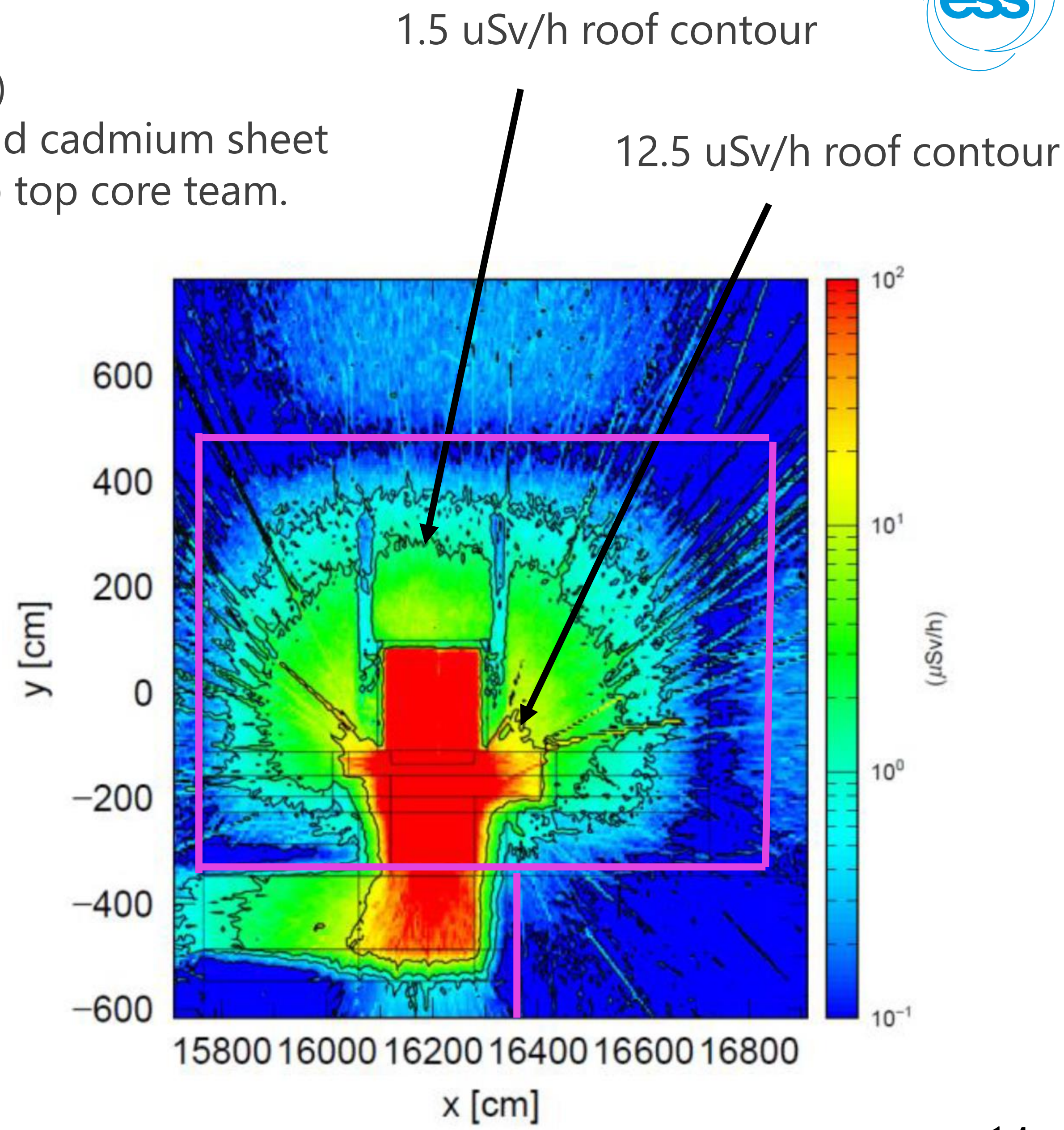
At 20 W: Use in-cave dosimeters to verify gamma dose when placing cadmium in the beam – benchmark against simulation
At 200 kW: Measure neutron dose at feedthroughs, use in-cave monitoring to measure cadmium gamma dose

At 200 kW, all 6 Hx scenarios can be investigated, and hotspots and/or problems identified at the measurement limit. Gives time to act, before going to 2 MW.

Chicanes

- Chicanes work – element of safety (not needed though)
- Roof has to be classified as blue eventually, at 5 MW and cadmium sheet in the beam – we may be able to avoid that but not up top core team.





2025-12-04

Feedthroughs

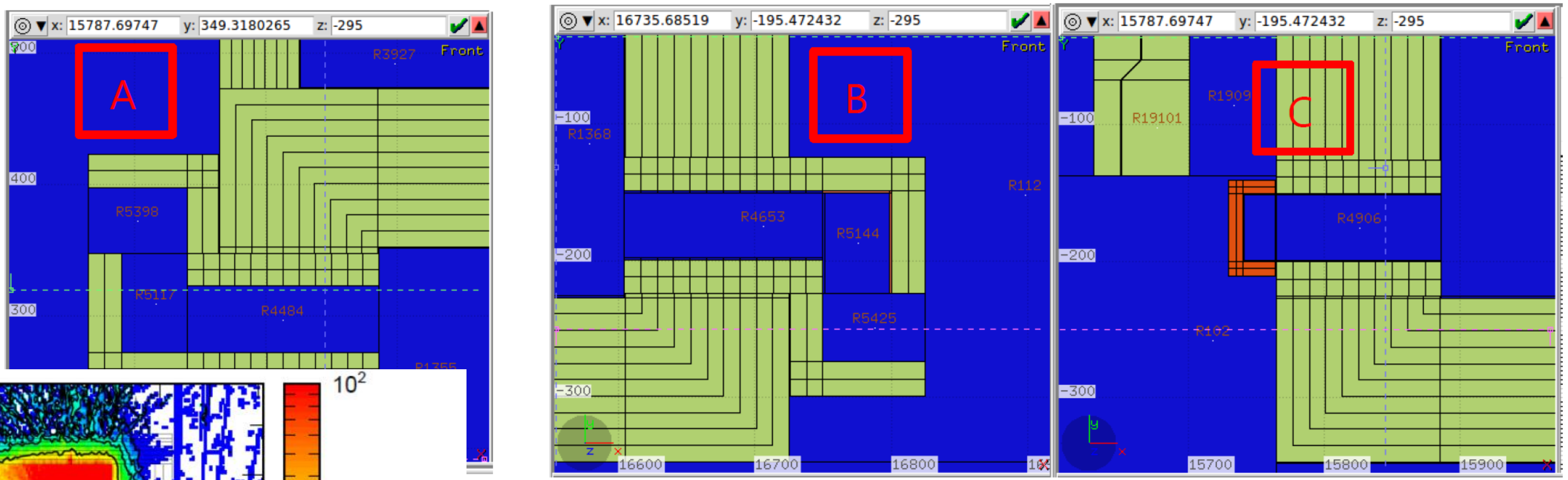


Figure 27: Cable tracing at E01 floor level

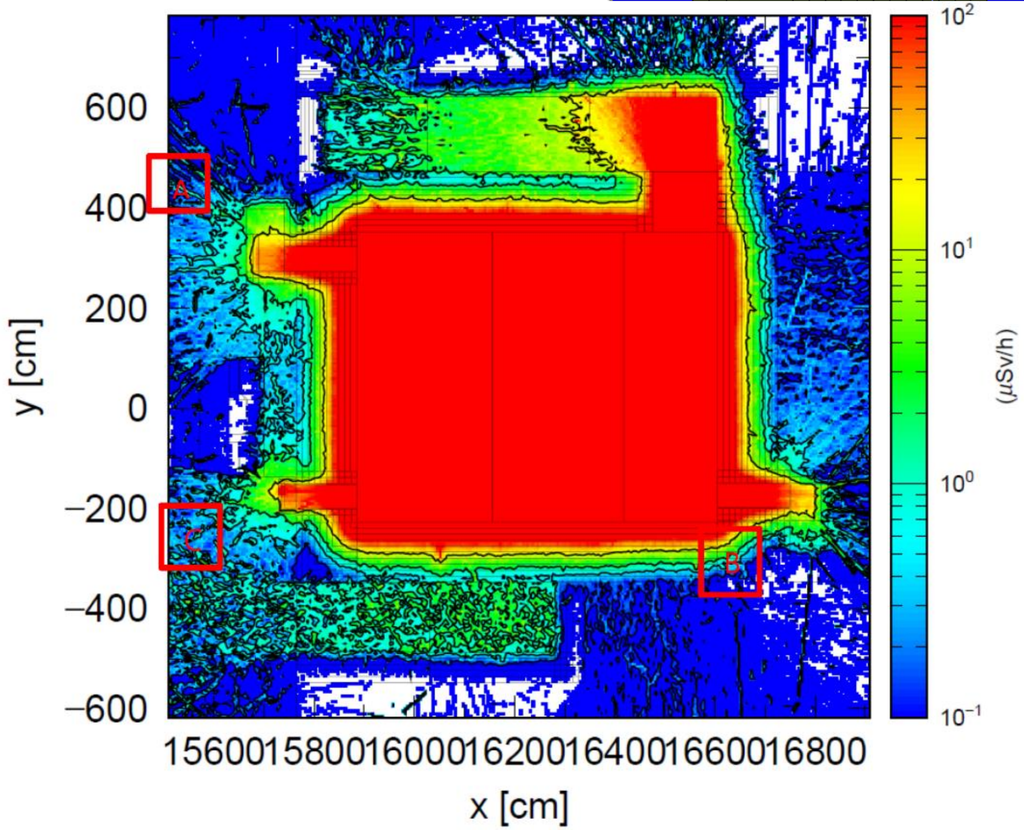
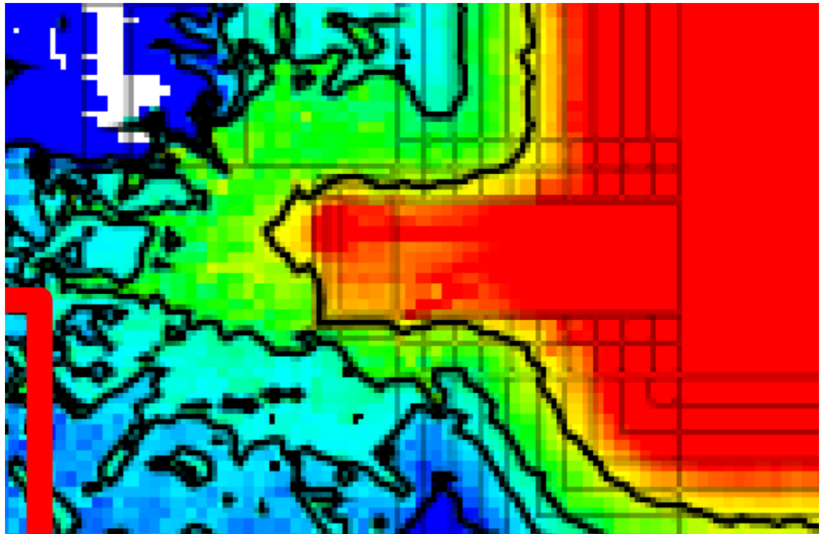


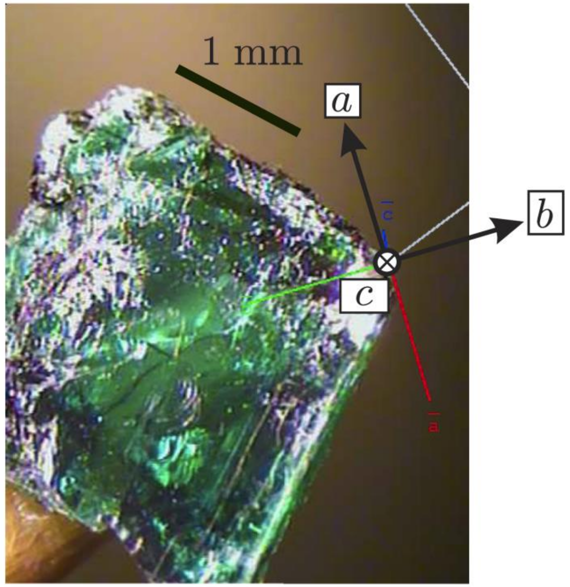
Figure 32: Dose rate in the cable chicanes. Overall.

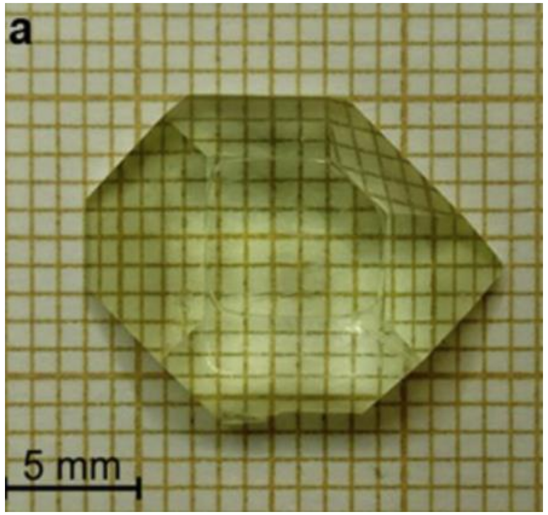
Shicanes and lead blocks work, but borated lining necessary to prevent neutron leakage (with D2O block on sample



Samples and sample sticks

- Most samples are de-facto solid rocks (size between 1x1x1 mm^3 and 10 x 10 x 10 mm^3)
- Rare cases: Powders, contained in sealed cans, manipulated off the instrument area.
- Samples mounted on small holders, made by the user with an M4-M8 thread



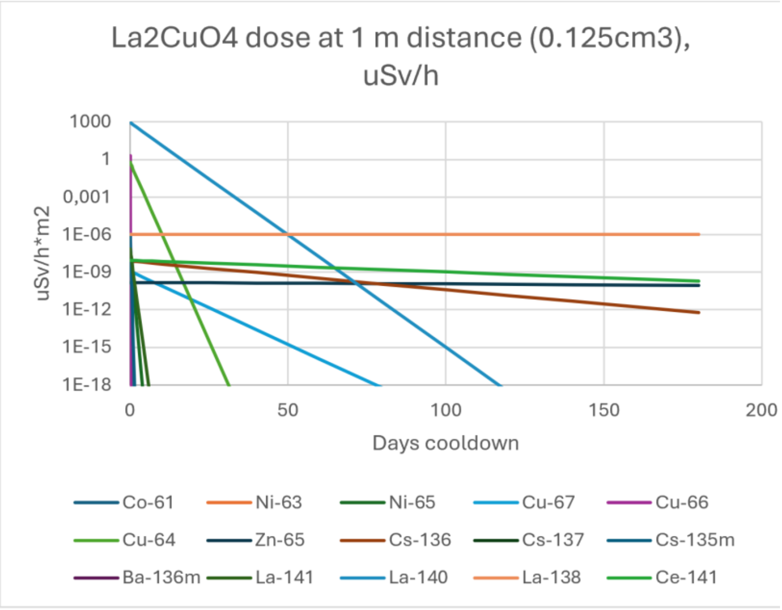


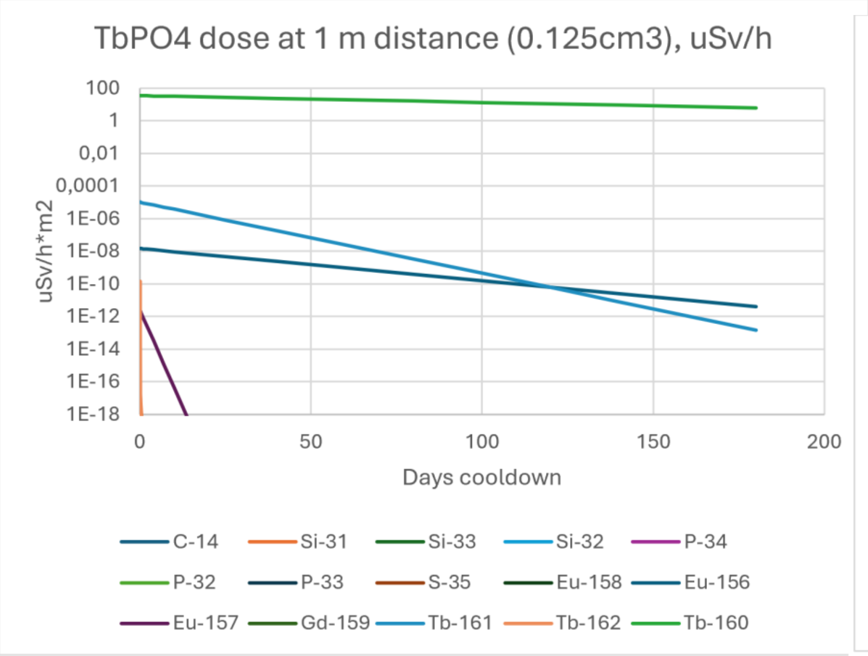
Activation levels

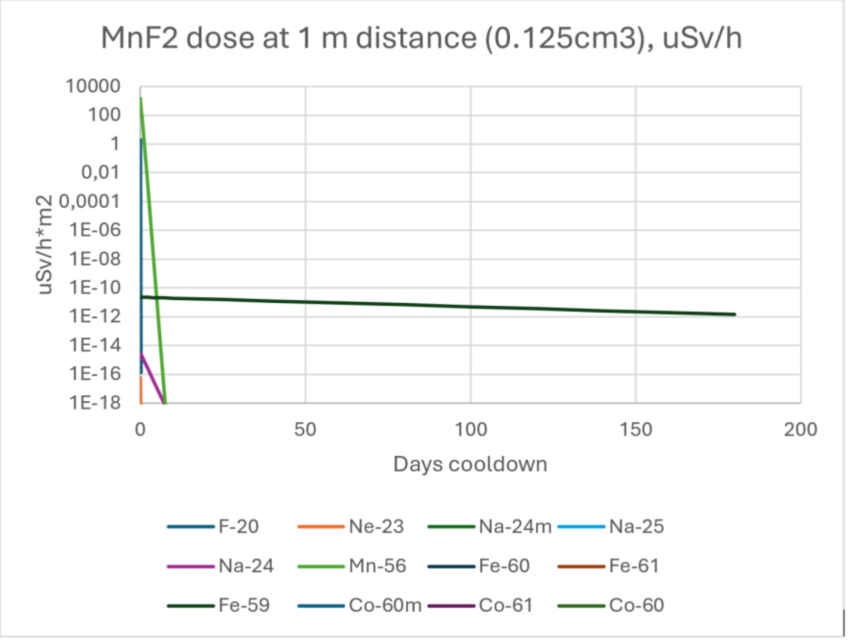
- Aluminum and vanadium activation will be high (100s of uSv/h) at 2 MW and short lived. Require monitoring before entering the cave

- Simulated activation of typical problem samples at 5 MW: Maximum 2 mSv/h. Similar to ILL, we have more flux, but smaller samples.

- We will make designated shielded areas for sample sticks and sample environment, iterating with RP. However, activated samples are a facility wide issue, outside the scope of the core team.

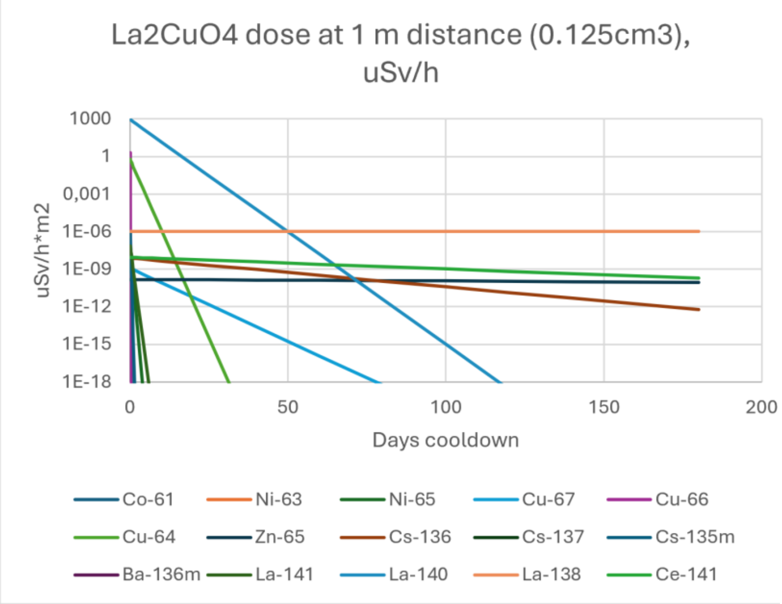


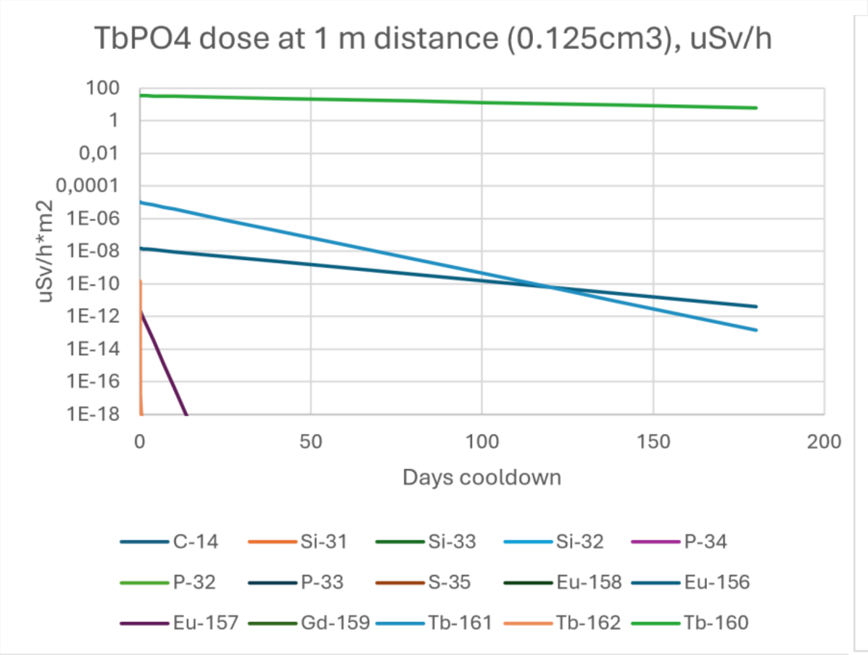


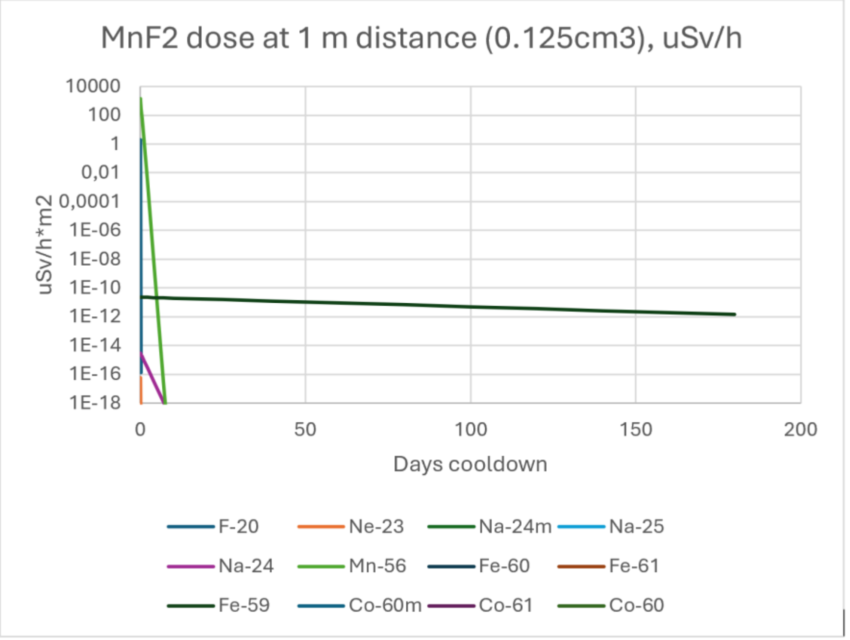


Activation levels

- During all experiments, the substance being irradiated is known well in advance
- Plan experiments to allow cool off
- RP knows about lanthanum-like cases well in advance
- Always check dose rate level before entering the cave
- Always use hand held dosimeter to check sample activation
- Always notify RP about high levels
- Every cryostat can be craned off remotely.







Conventional risks

ESS Rules for Coordination of Electrical Safety:
ESS-0328120

61 conventional hazards, of category C or higher:

16 C+ electrical hazards, highlights below:

- **Exposed electrical conductors in the kW range (cables/coils)**

  Single fatilty (D), mitigation: ESS rules for electrical installations, only trained personnel allowed to do maintenance
- **Exposed electrical conductors in choppers**

  power consumption limited, injury (C)

  Mitigation similar
- **Potential difference due to improper grounding**

  level C, rule mitigation
- **Monitor arcing (C)** – rule mitigation
- **Monitor arcing causing fire** (all power supplies limited to less than 24 W)

Guidelines for design and implementation
of electrical installations, earthing, bonding and
zone division of systems within ESS neutron instruments.:
ESS-1570773

Electric schematics
ESS-4869077
ESS-4962674
ESS-434700
ESS-4961410
ESS-4962673
ESS-4961411
ESS-4961412
ESS-4961407
ESS-4961408
ESS-4961409
ESS-4359331
ESS-5067137

Conventional risks – Mechanical I

<u>29 C+mechanical hazards, highlights below:</u>

- ***12 suspended loads**: Shielding blocks, CHIMs,* Injury or single fatilty (D), mitigation: Fencing off lifts, trained personal only lifting equipment designed or rigging

Only ESS-trained staff that follow ESS guidelines should be used	ESS Rigging team	Rigging handbook ESS-0402063

- ***2 Projectile hazards level C:*** PSC Chopper disc failure – no access while chopper runs
  Chopper designed to withstand breakage
- ***1 High pressure hazard level (C):*** Accidentally pressurized chopper system
  Prevent access and cover windows
- ***1 motorized component hazard (E)*** (forklift collapsing cave): Mitigated by structure
- **10 unprotected heights hazards:**
  Fall fatality (D) – mitigated by rails
  Cave open causing a pit: Rules for dismantling cave
  Tools falling: Kickplates and ESS rules preventing tools to fall

Chopper System Hazard Identification:
ESS-3212988
ESS-3856486
ESS-3212989

Rails designed according to SS-EN ISO 14122-3

Conventional risks

61 conventional hazards, of category C or higher:

1 chemical hazard (level C): Flammable material starting a fire. Low probability – rule mitigation

8 Behavioural hazards:

- *Forklift driving into hutch – mitigated by hutch placement and maximum speed*
- *E01 craning things into people on cave roof – mitigated by training (x2)*
- *Falling down stairs (x2)*
- *Hanging part collides with person inside the cave (x2)*
- *Rigging team drops heavy load onto cave (10 Tons) (E) – mitigated by rigging procedure*

Conventional risks – Chemical I

61 conventional hazards, of category C or higher:

4 chemical hazard (level C):

- *Flammable material starting a fire (C)*. Low probability – rule mitigation
- *Technician inhales cadmium dust (C) (x2)*. Improbable, mitigated by rules
- Toxic sample (mitigated by rules – single crystal)

8 Behavioural hazards (7C and one E):

- *Forklift driving into hutch – mitigated by hutch placement and maximum speed*
- *E01 craning things into people on cave roof – mitigated by training (x2)*
- *Falling down stairs (x2)*
- *Hanging part collides with person inside the cave (x2)*
- *Rigging team drops heavy load onto cave (10 Tons) (E)*

Conventional risks – sample environment focus

1 magnetic field hazard (level D):

- *Pacemaker near magnetic field would be life threatening.*

  Signs always (they should not be in the hall)

  Lights when field is on

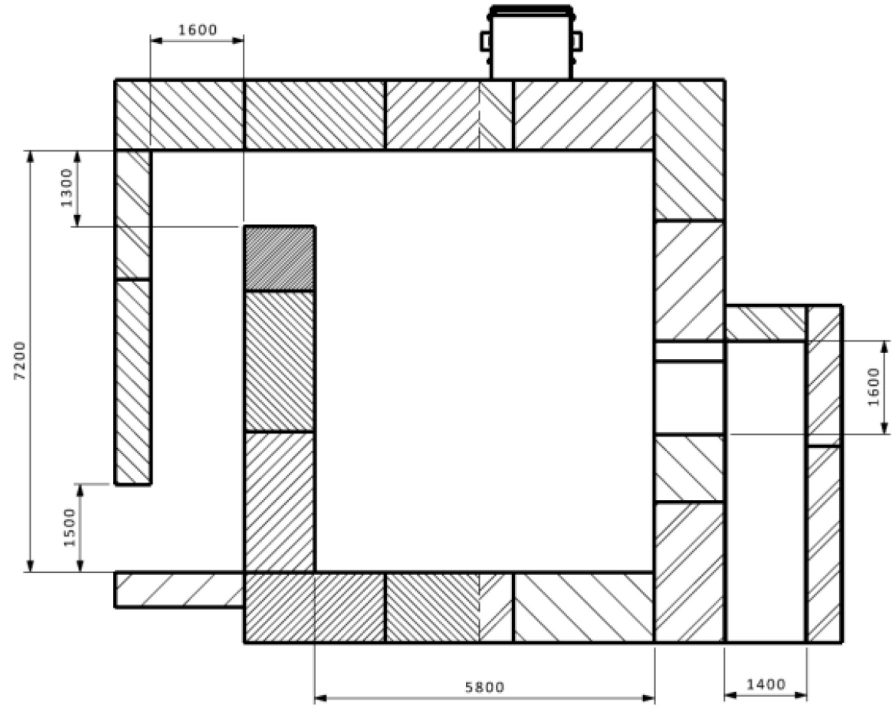
Cryogenic hazards:

- *Frostbite (level B): mitigated by gloves*
- *Cryogen splash on eyes (C) – mitigated by visir*

ODH sample environment - 1

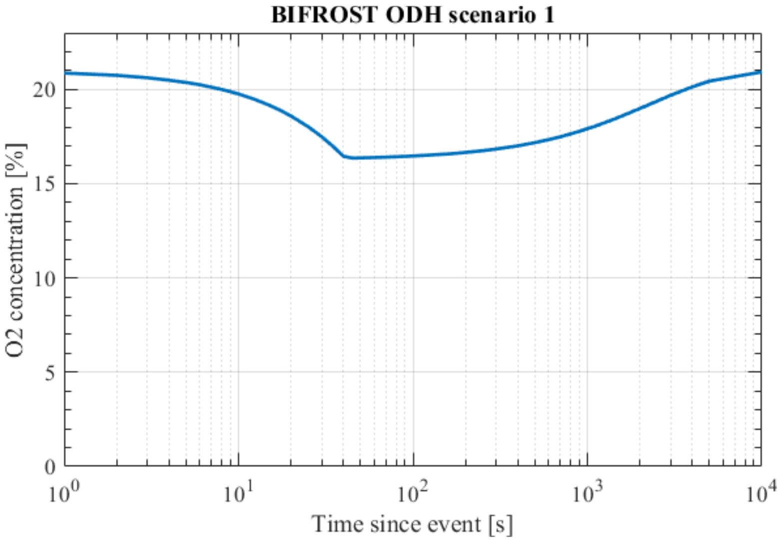
Main ODH points

- *Large cave around 200 m3*
- *Labyrinths giving rise to ventilation*
- *No dewars in cave*
- *Slow evaporation*
- *Likely quench release 40 m3 of gas in a minute*
- *Highly unlikely rupture release 80 m3 of gas quickly*
- *In the ODH analysis, we assume minimum ventilation, which is clearly not accurate but conservative*



ODH sample environment – 1 (ESS-5527298)

Quench (once pr year)



Rupture (once every 50 years)

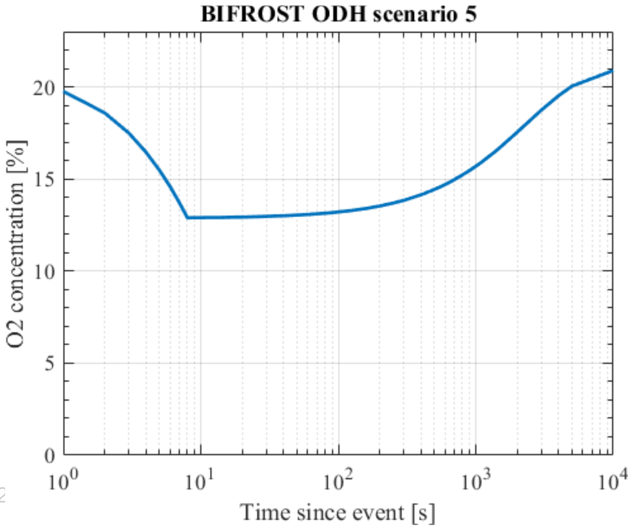


Table 4 – ODH fatality rate (FERMILAB's model)

Formula	Definitions
$\phi = P_i F_i$	ϕ = the ODH fatality rate (per hour)
	Pi = the expected failure rate of the "most credible scenario" (per hour)
	Fi = the probability of a fatality due to "most credible scenario"

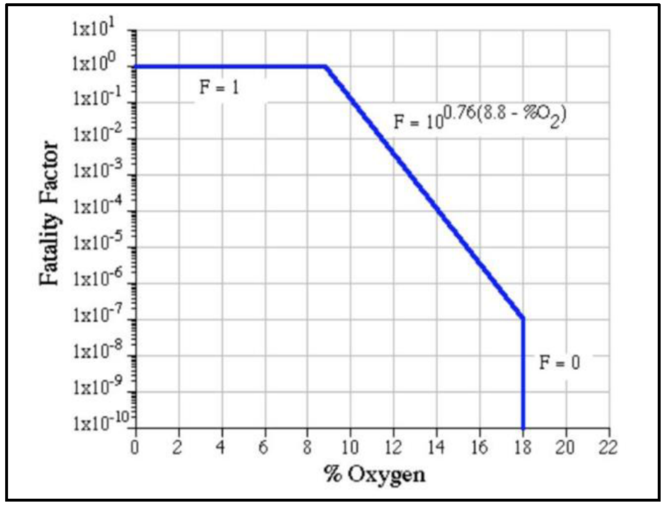
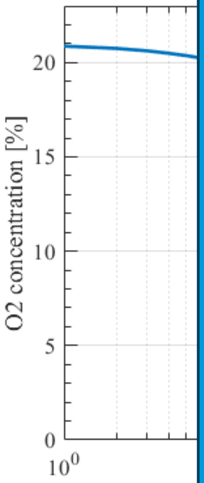


Figure 2: Fatality probability as a function of the lowest oxygen concentration (partial pressure)

ODH - 1

Quench (once pr year)



Ruptu

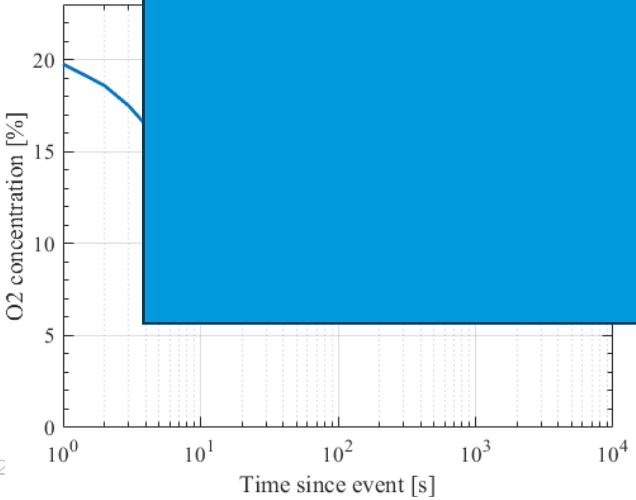


Table 5-1: Summary of ODH class and control measures for BIFROST cave

Room ID	Room name	ODH classification	Loss of containment
E01.W4	BIFROST Cave	0	Nitrogen
		0	Helium

* Although ODH classification from the calculations is 0, these scenarios have been re-evaluated based on the lowest oxygen concentration levels reached and timing of ODH scenario.

Classification 0, but we have an active ODH monitor in the cave regardless – we therefore exceed the ESS requirements for ODH safety mitigation

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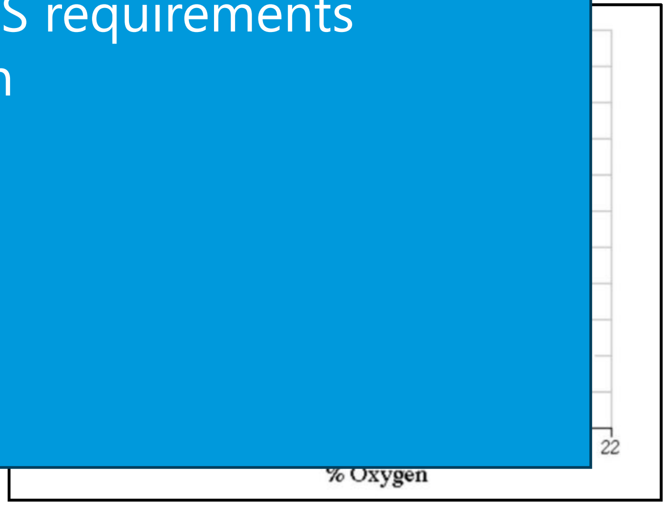

Figure 2: Fatality probability as a function of the lowest oxygen concentration (partial pressure)

Future experiment risks

Sample environment risks, not currently realized, but some day present on the beamline, in the form of temporary setups

- *Pulsed magnetic fields – capacitor banks being discharged*
- *Laser light (IR)*
- *Pressure cells (gas + liquid medium)*
- *Electrical fields (8 kV) – setup within a sample stick*

At 5 MW, we will have shorter experiments and longer sample cool-off times

continuously work to improve efficiency of activation risk mitigation