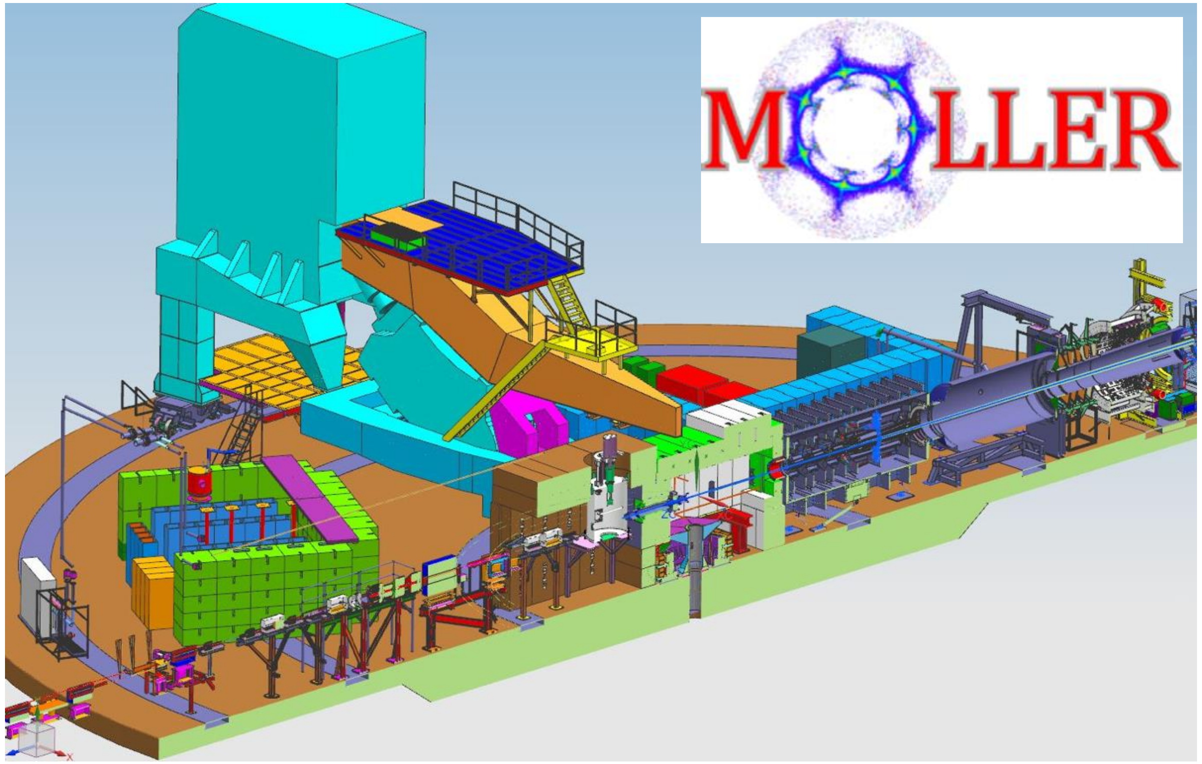
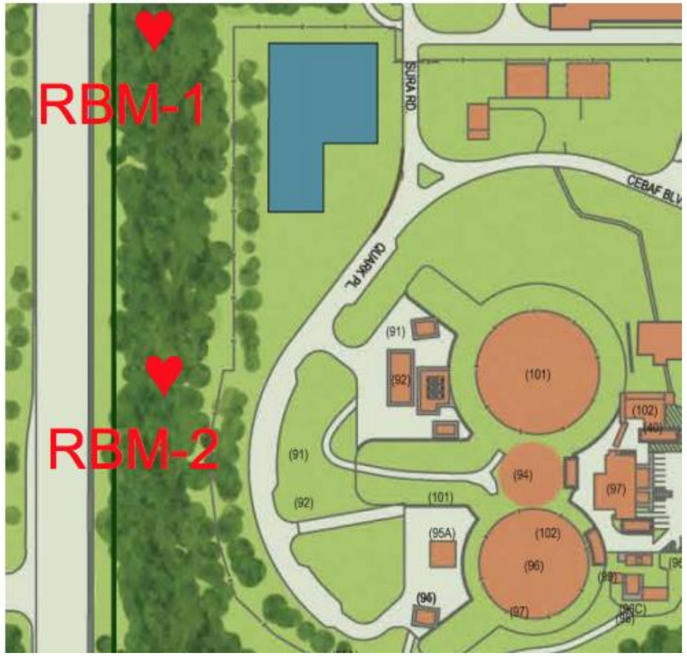
Radiation and shielding

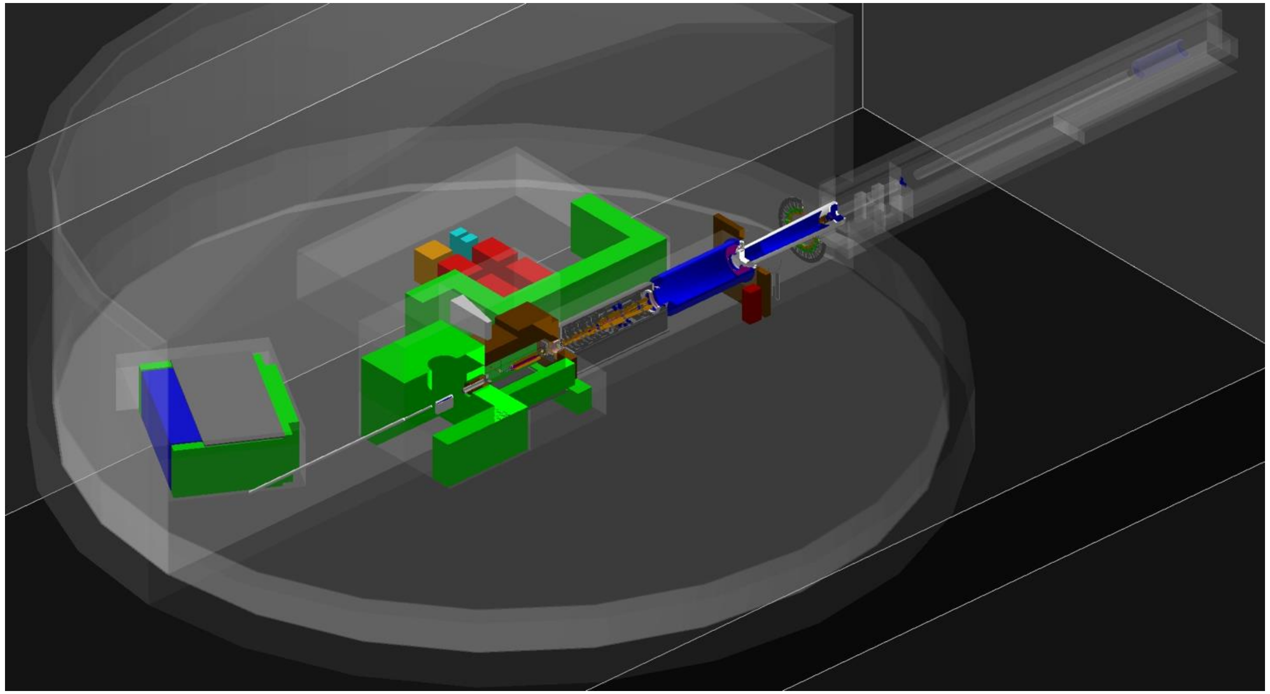


- Ciprian Gal
- July 29-31 2025

Introduction

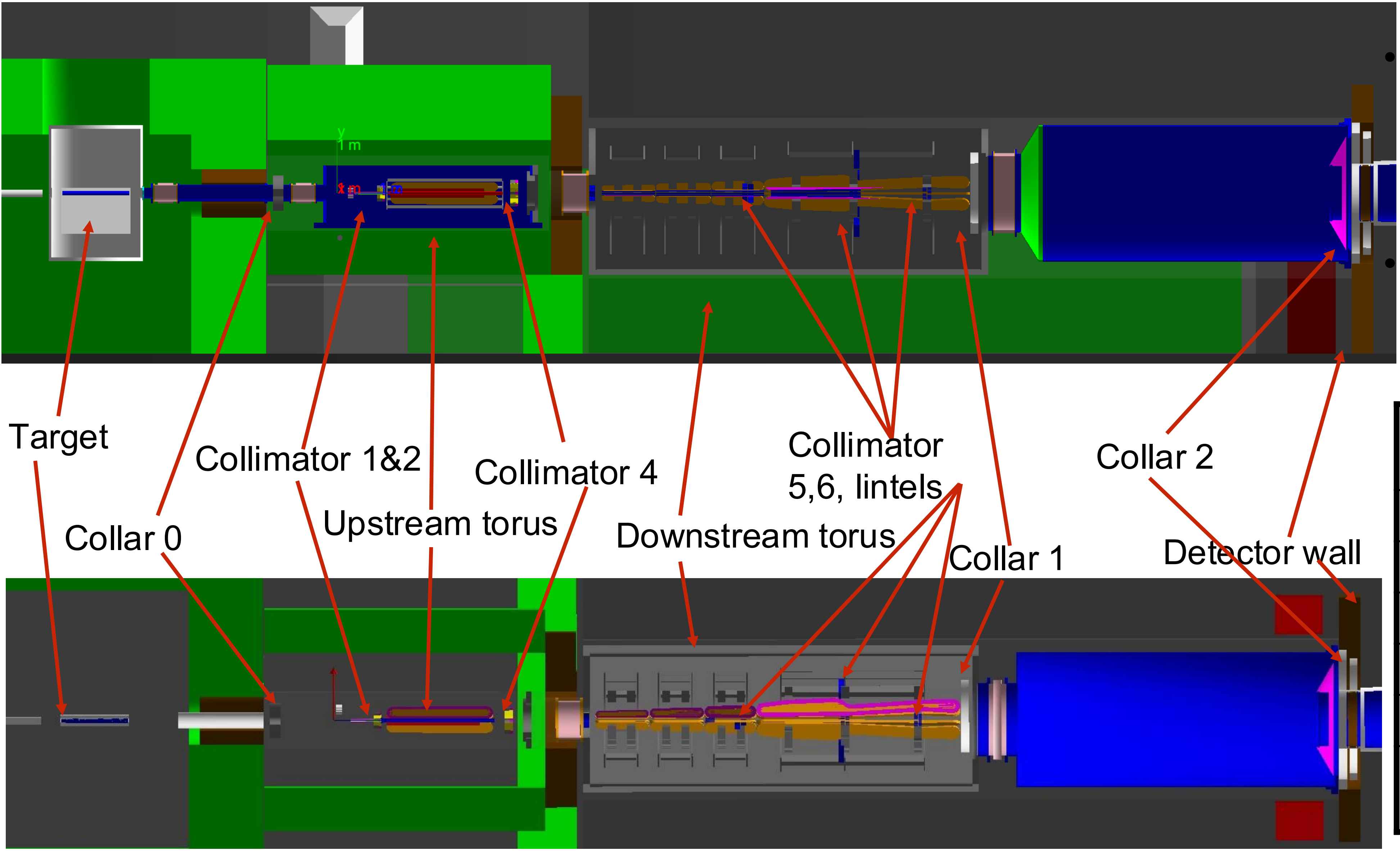


- Radiation measurements outside hall:
  - used for personnel protection
  - boundary dose limit imposed by DOE/Lab is 100/10 mrem per calendar year
- Estimation done with G4 and FLUKA
- Goal is to minimize the dose as much as reasonably possible below the lab limit



- Radiation measurements inside hall:
  - used for equipment protection
  - needed to be able to make effective use of beam time
  - can be additional background
- Estimations done with G4 looking at prompt radiation rates

Shielding design approach

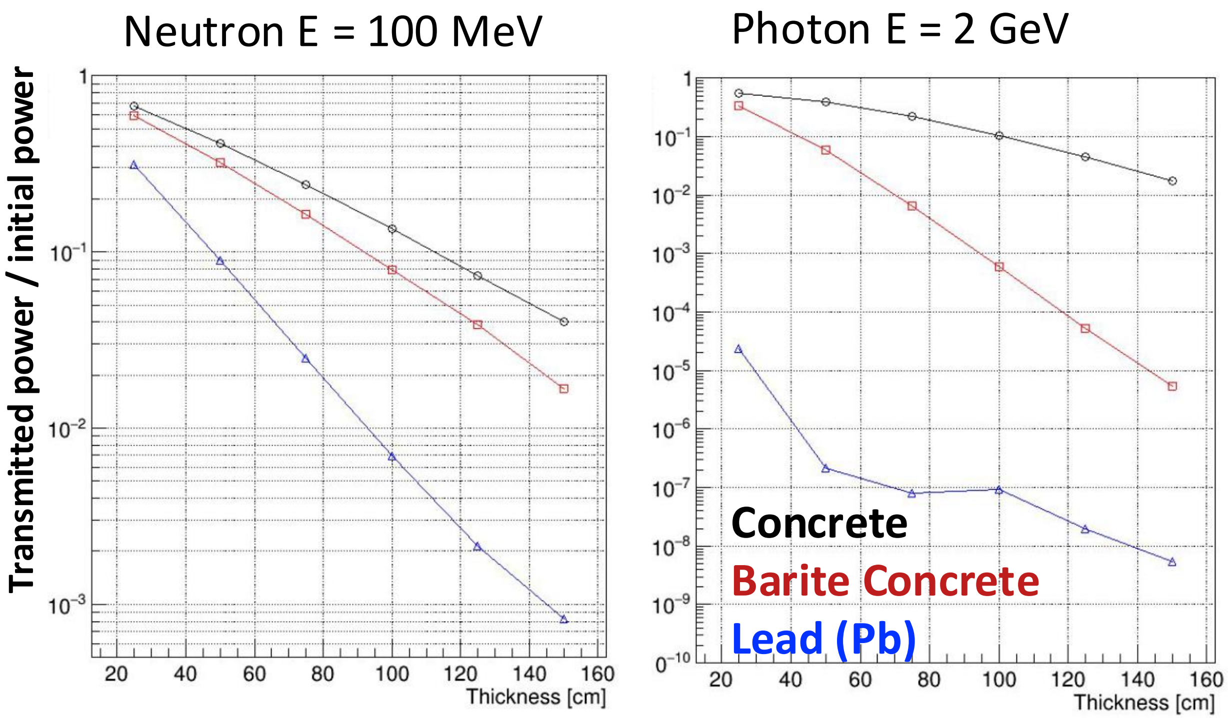


- The shielding model in the simulation incorporates only the details relevant to radiation calculations
- Shielding is located around the components that absorb a significant amount of power

Component	Power @65uA, 1.25m Tgt
Target	3100 W
Collar 0	275 W
Collimator 1	3700 W
Collimator 2	950 W
Collimator 4	60 W
Coll 5,6, Lintel	<55 W

Upstream torus Downstream torus

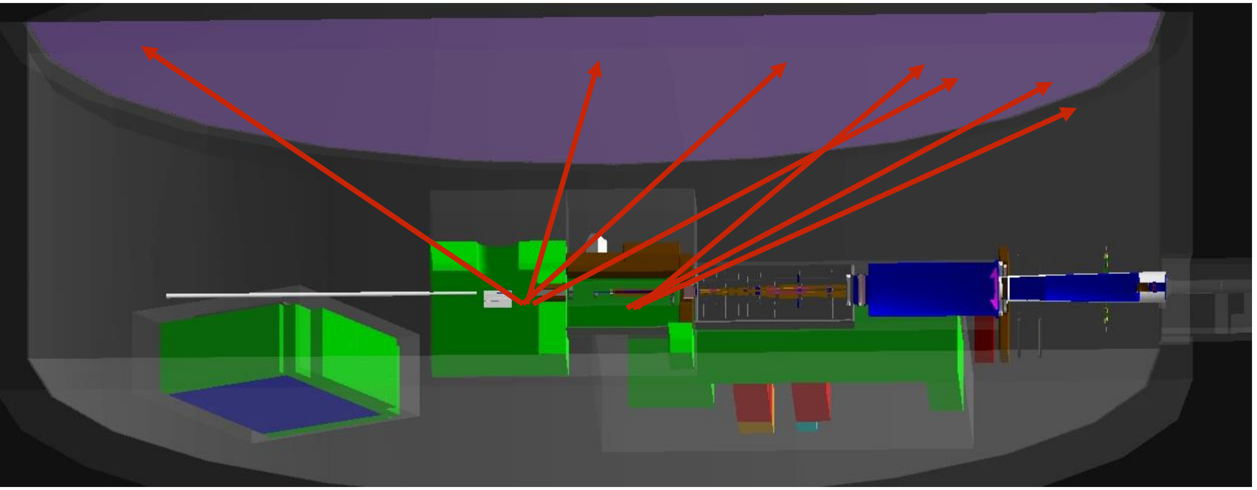
Simulations: Materials



- Concrete is based on the NIST material (O 0.53, Al 0.03, Si 0.34) with a density of 2.3 g/cc
- Barite Concrete is a custom material (water 0.06, barite 0.86, cement 0.08) with a density of 3.36 g/cc
  - Barite is mostly made out of $BaSO_4$ (0.83), CaO (0.05), H_2O (0.04)

- For the shielding we mostly make use of standard NIST materials however there are regions where standard concrete is not sufficient
- Barite concrete is used in regions that see high flux of incoming radiation or where we need more moderation than would be provided by regular concrete
- We performed Geant4 transmission studies to see the impact of different materials on electromagnetic and hadronic radiation
- We can see that the increased density of barite allows it to outperform regular concrete at all thicknesses in both radiation types

Simulations: Boundary dose (G4)

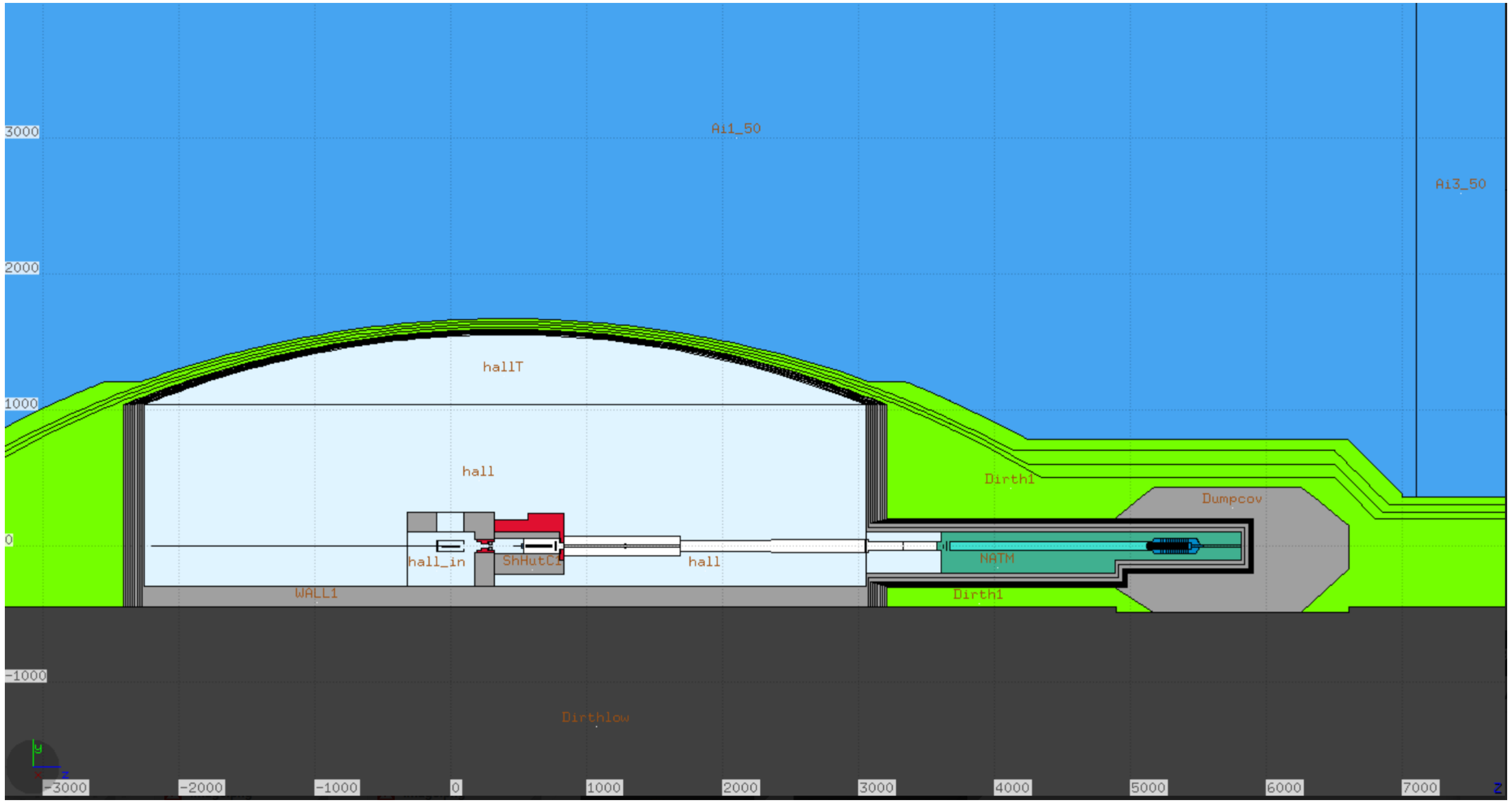


	current	Running time	charge on target
MOLLER	65uA	<16.8 wks/year	660 C
PREX1	>50 uA	~8 wks	82 C

	mW/uA	boundry/yr
PREX1	2.4	**1.34 mrem**
MOLLER	1.4	**5.6 mrem**

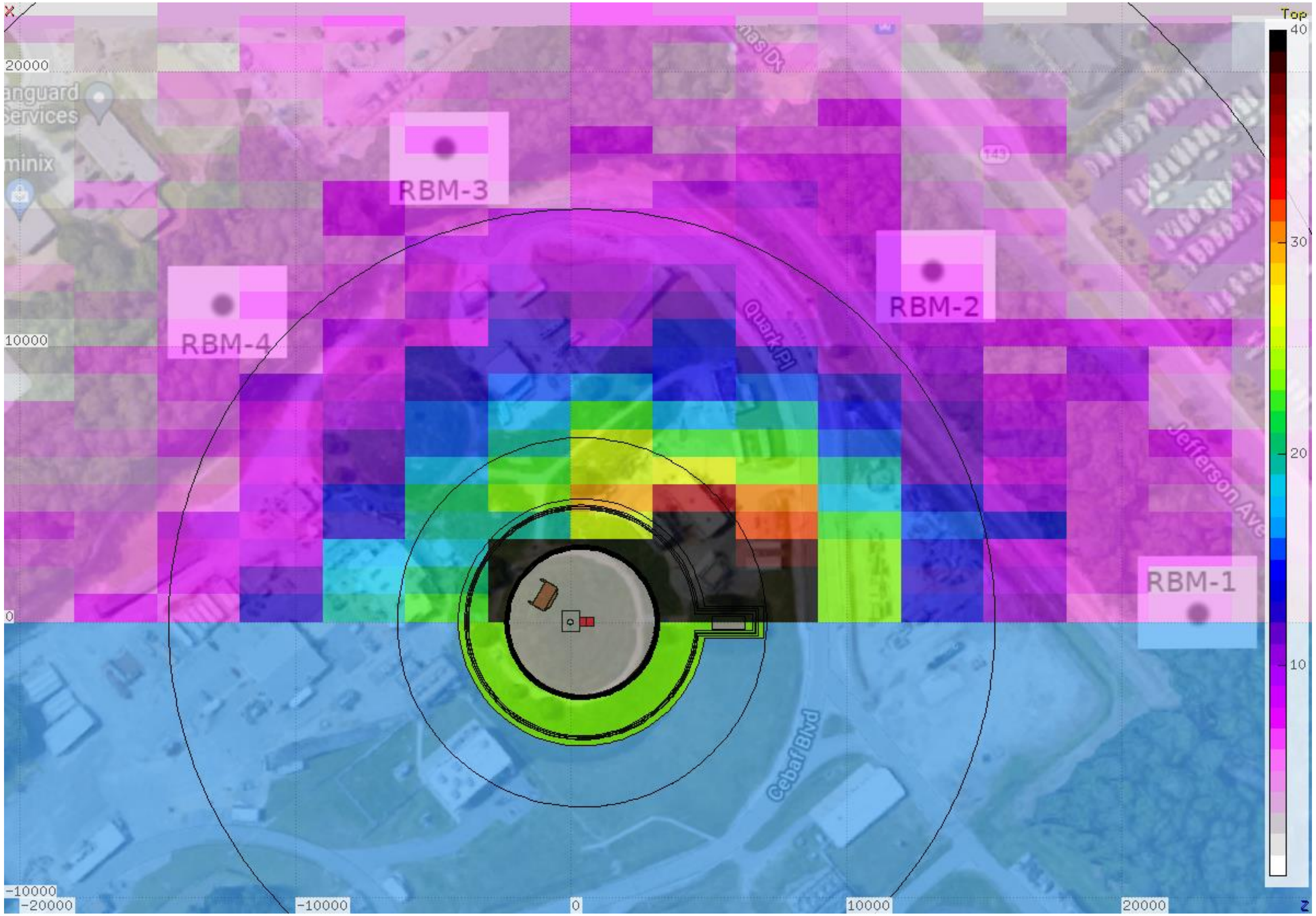
- Procedure was successfully employed during the PREX-2/CREX runs at the lab and it's useful for shielding design
- We evaluate the dose on the boundary by looking at high energy (E>30 MeV) neutrons reaching the roof of the hall
  - This has been shown by RadCon to be a good proxy
- We benchmark this proxy by simulating experimental configurations that produced significant (measurable) boundary dose
- We compare the HE neutron integrated power of previous experiment to different MOLLER configurations
- Areas of focus are the regions where high energy deposition happens
- The target (collimator 1) is a source for ~ 30(60)% of the high energy neutrons
- **Our projection indicates that the current shielding will allow MOLLER to remain under the JLab limit**

Simulations: Boundary dose (FLUKA)



- A configuration that contains the major shielding components around the target and collimator 1 as well as hall walls, overburden, and air was implemented in FLUKA by Lorenzo Zana (RadCon)
- This simulation setup allows for direct determinations of mrem dose at the boundary monitor locations by making use of biasing boundaries
  - While no magnetic fields were applied in this simulation they would not impact the rates of high energy neutrons escaping the hall so we believe the results are accurate

Simulations: FLUKA results



- The radiation map for 2820 PAC hours (117.5 PAC days) at 65 uA shows similar results to what we obtained from our G4 simulation
  - The value are averaged between 0 to 10 m in height (the radiation profile will probably be lower at ground level compared to 10m in height); the monitors are about 2m off the ground
- **These result show that MOLLER is expected to be well within the lab limit**
- **FLUKA sim cross-checked to PREX-1, HAPPEX-H boundary measurements**

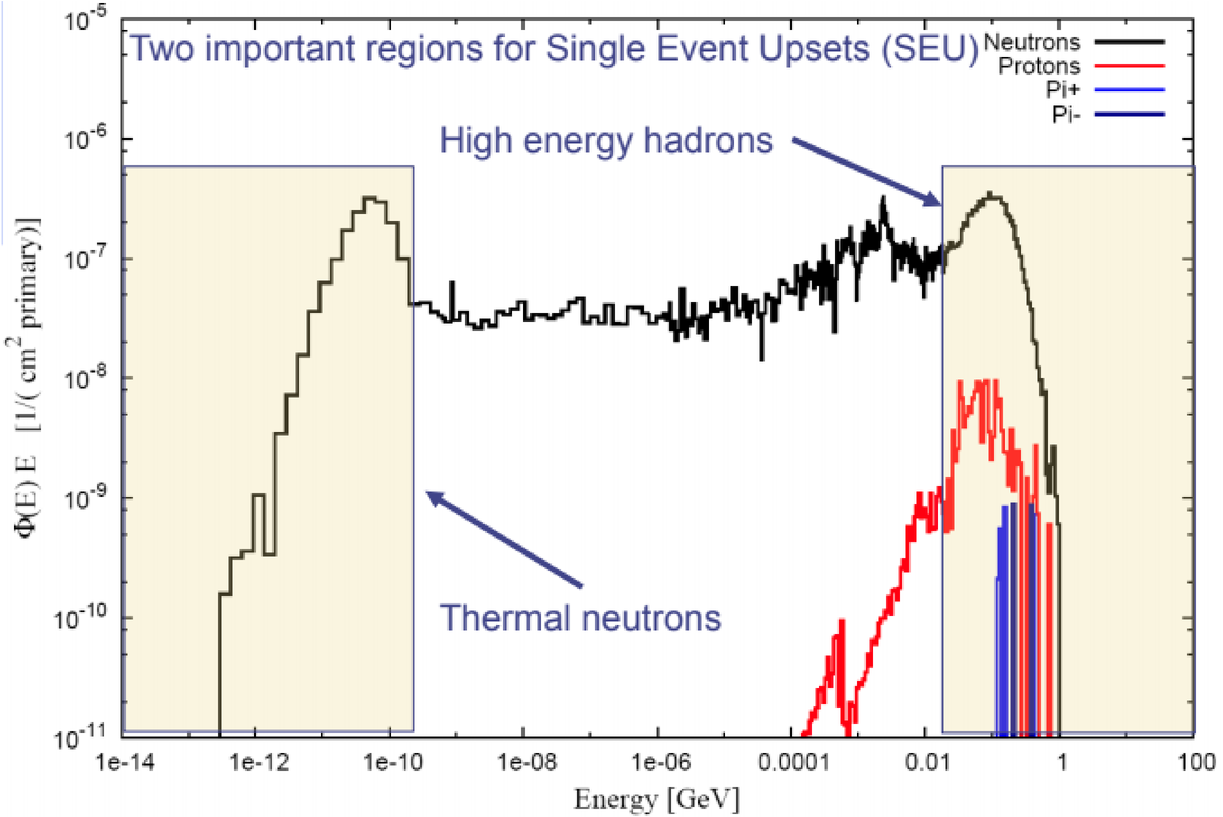
Monitor	Calculated Dose (mrem/2820h)
RBM-1	4.8 ± 1.2
RBM-2	4.9 ± 0.8
RBM-3	6.3 ± 1.1
RBM-4	4.3 ± 0.8

Electronics damage

Category		Effect
Single Event effect (Random in time)	**Single Event Upset (SEU)**	Memory bit flip (soft error) Temporary functional failure
	Single Event Latchup (SEL)	Abnormally high current state Permanent/destructive if not protected
Cumulative effects (Long term)	**Total Ionizing Dose (TID)**	Charge build-up in oxide Threshold shift & increased leakage current Ultimately destructive
	Displacement damage	Atomic displacements Degradation over time Ultimately desctructive

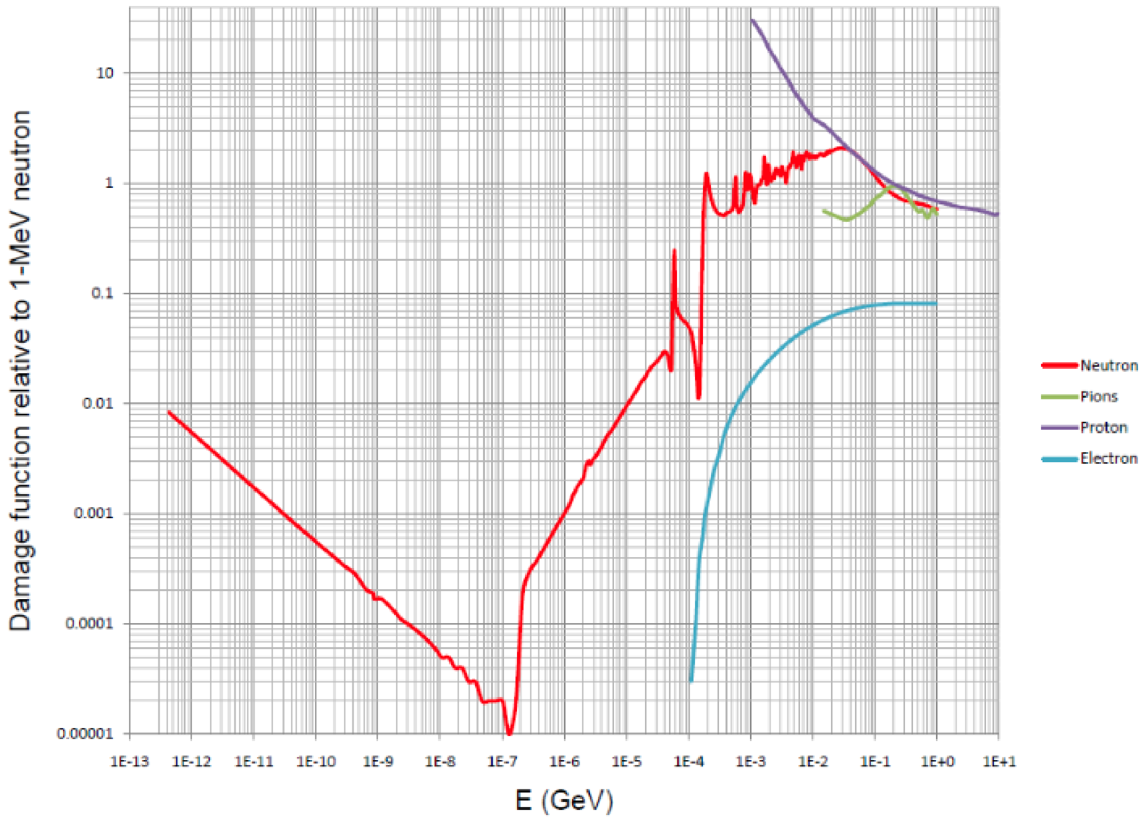
Electronics damage

Single event upsets



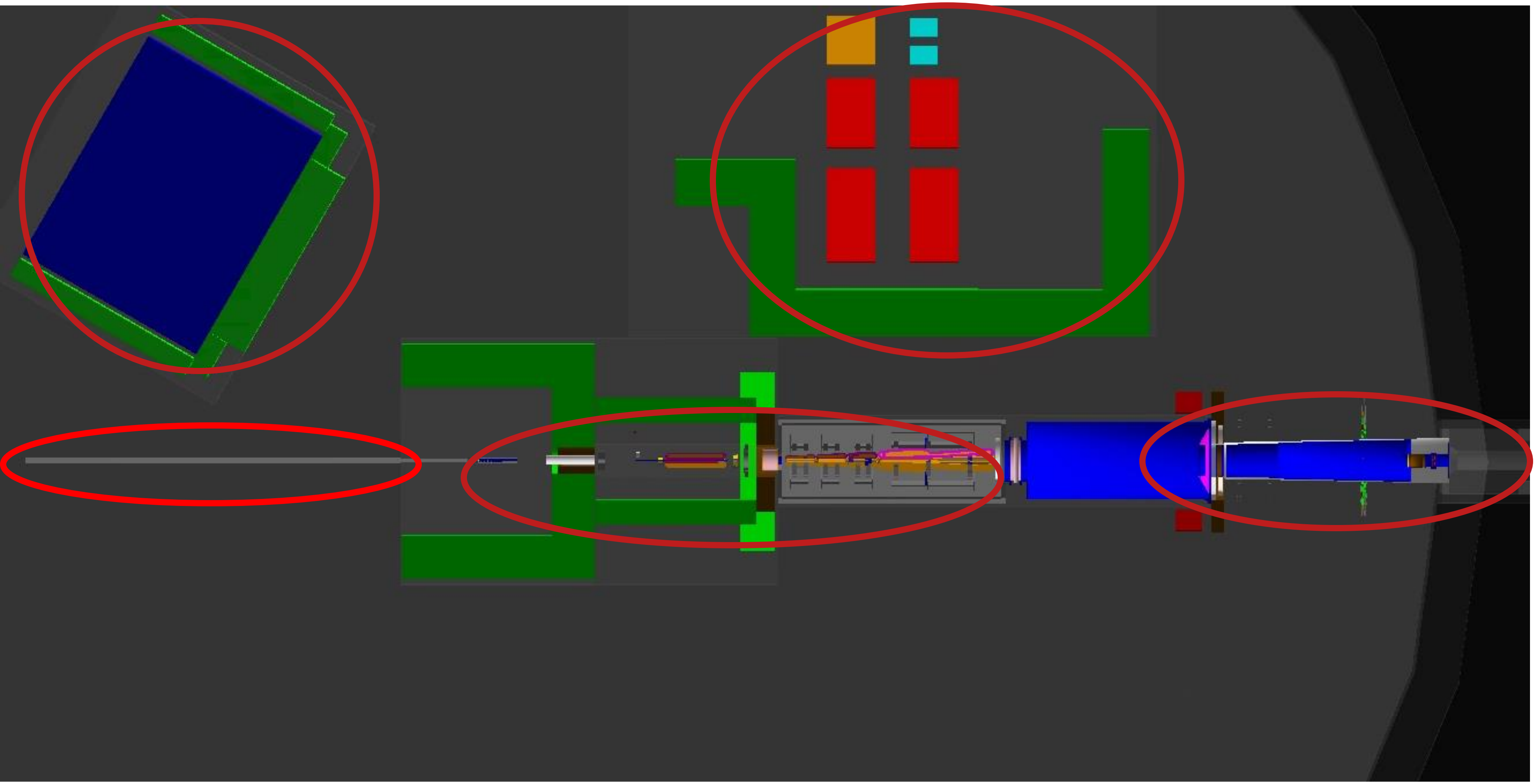
- We evaluate both the low energy (thermal) neutrons and the high energy hadron flux at locations where we have electronics
- We compare to fluxes simulated for experimental setups that ran successfully before at JLab

Permanent damage



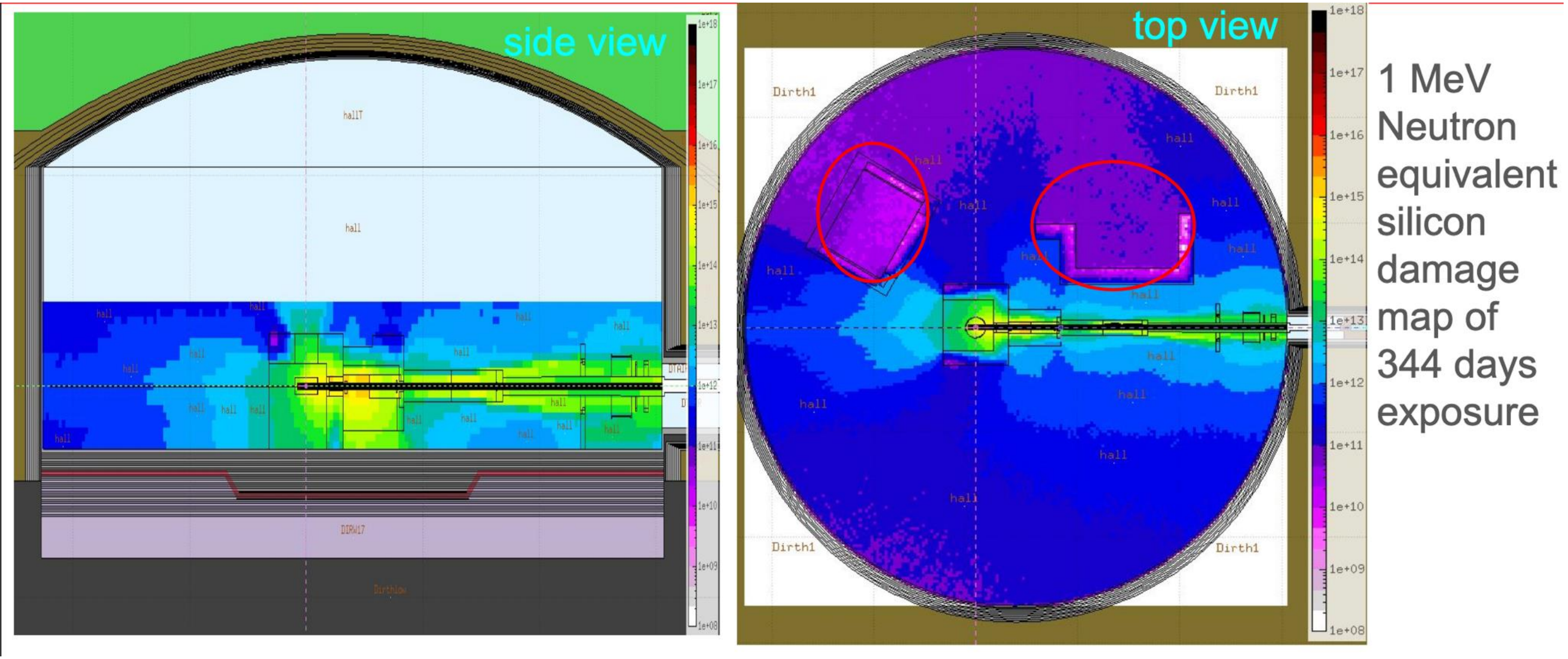
- We evaluate the entire spectrum for neutrons, pions, protons and electrons and use the FLUKA damage functions to convert them into 1-MeV neutron equivalent damage
- Typical commercial semiconductor electronics will show signs of damage at ~1E13 1-MeV n/cm^2
- We additionally calculate the power deposition to get TID

Simulations: Electronics damage areas of interest



- In G4 we focus on three types of calculations
- 1MeV neutron equivalent calculations take into account e,p,pi, neutrons for cumulative damage
- Low energy & high energy neutron fluxes as an indicator for SEU
- Total Ionizing Dose calculations in particular locations based on specific materials
- All simulations showed at least a factor of 10 safety margin compared to published breakdown limits or previous experiments

FLUKA activation studies

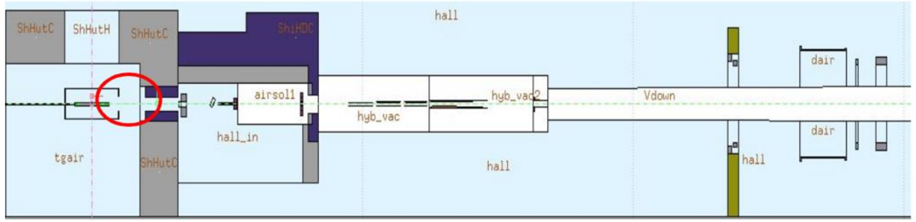


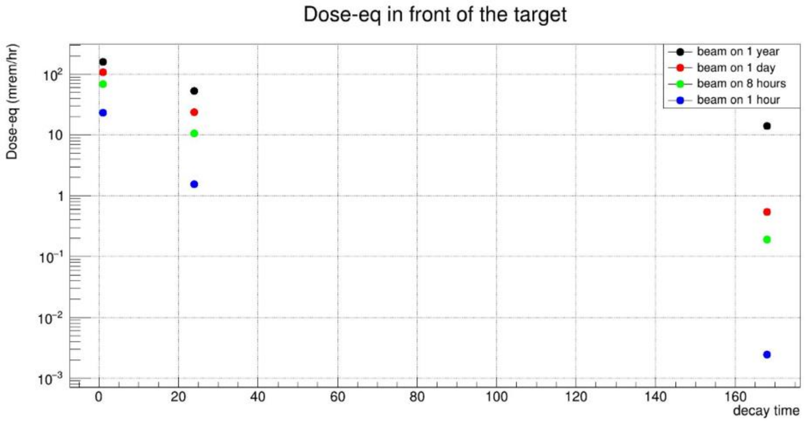
- The important parts of the experimental design have been implemented in FLUKA by RadCon (Lorenzo Zana)
  - Additional detail has been added by Jhih-Ying Su (U. Mass)
- Using this simulation setup we will evaluate the expected activated radiation dose once the experiment is turned off

- FLUKA sims confirm the G4 calculations showing the 1MeV NEIL dose in the electronics bunkers is comparable to total doses of previous successful experiments

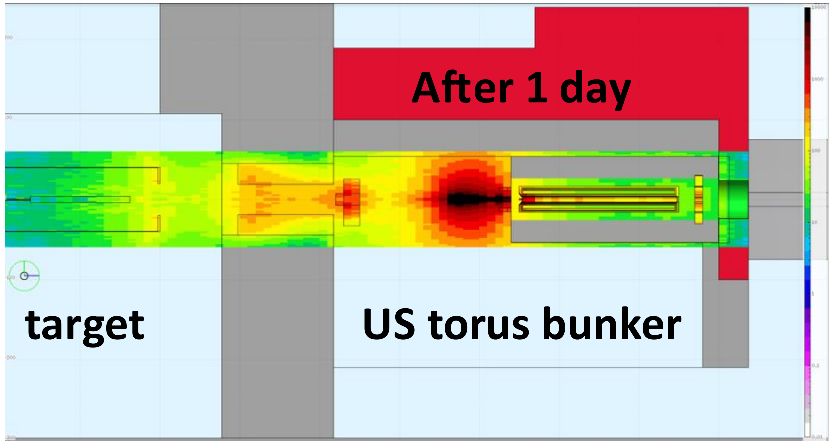
FLUKA activation studies target/US torus

In front of the target





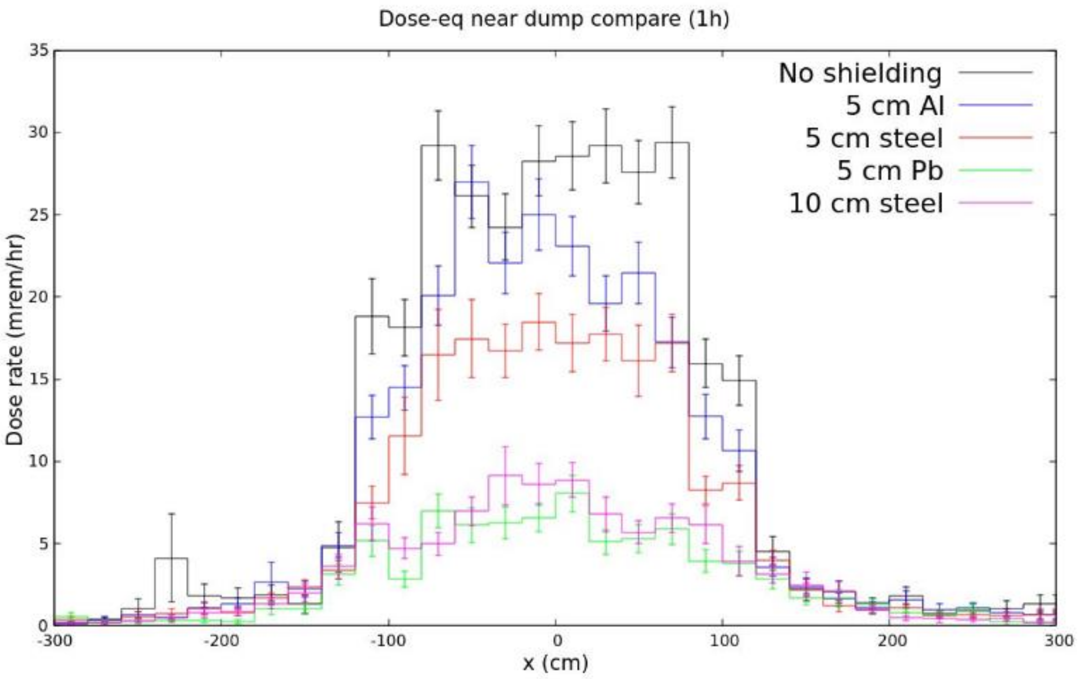
Operation time	Cooling time 1 hour dose rate (mrem/h)	Cooling time 1 day dose rate (mrem/h)	Cooling time 1 week dose rate (mrem/h)
1 hour	23 ± 0.1	1.5 ± 0.01	0.002 ± 3 x 10^{-5}
8 hours	69 ± 0.4	10.7 ± 0.08	0.19 ± 0.002
1 day	108 ± 0.6	23.6 ± 0.2	0.54 ± 0.006
1 year	160 ± 0.9	52.6 ± 0.3	14.17 ± 0.11

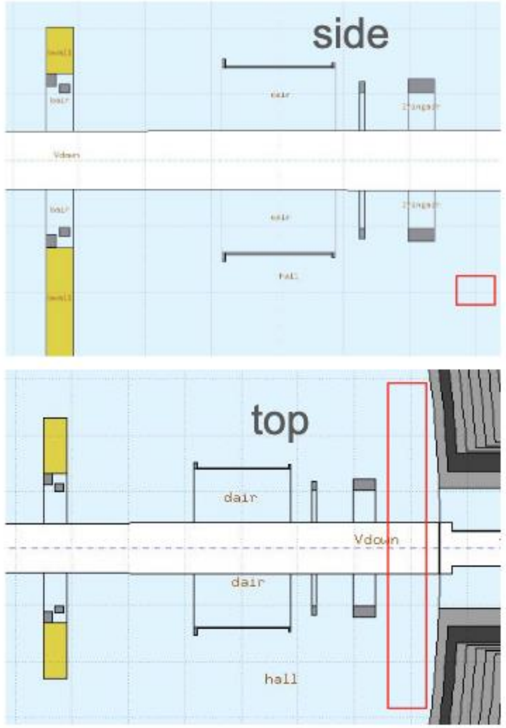


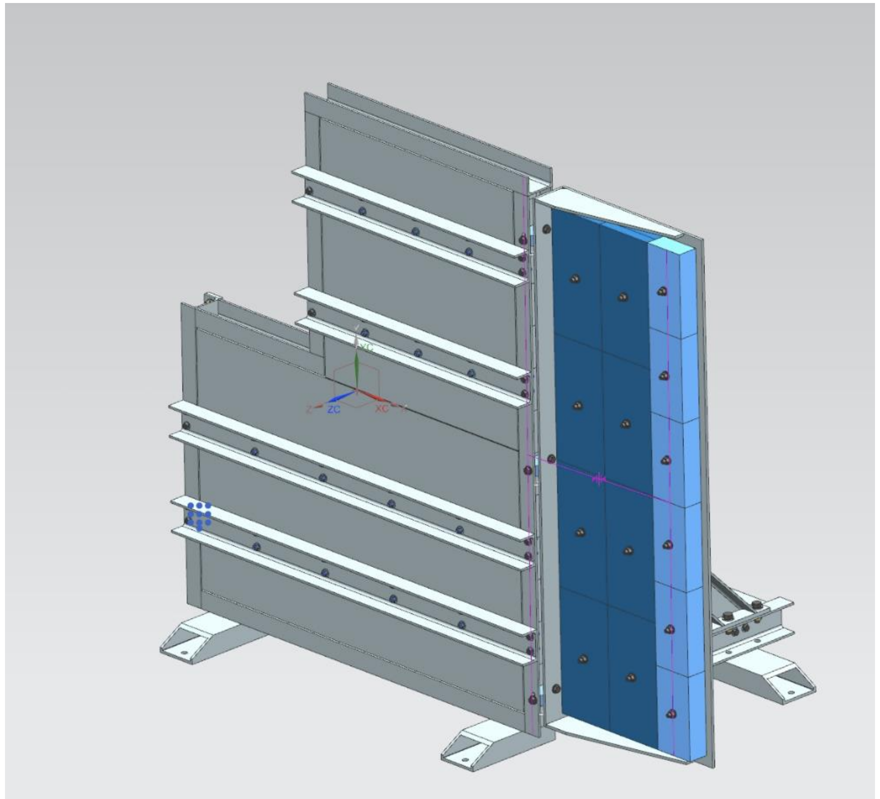
- Of particular interest at this point is the target region where we may need access in case of issues
- We can see that after one day of cooldown we still have regions with ~100 rem on contact
  - The cone coming from collimator 1 is visible and will have the option to move the blocker in the way in case access is needed

FLUKA activation studies dump/detector region

Behind the pion donut (1 year operation, 1 hour after)







- The hall is designing a lead shield wall that will remove the splashback from the dump into the hall and allow for faster access once beam is off

Other considerations

- Ozone levels are expected to be high
  - Procedures will be in place for access similar to PREX-2 (monitors in the hall will monitor levels and access will be allowed after levels are acceptable)
- Nitric acid production is not expected to be high enough to result in damage to equipment around the beamline
- MOLLER shielding is not expected to be part of the credited controls since MOLLER itself will not create high enough radiation outside of the hall (highest levels are on the dome of hall A)
- Shielding materials were chosen to lower cost of disposal

Hall A Dome shielding

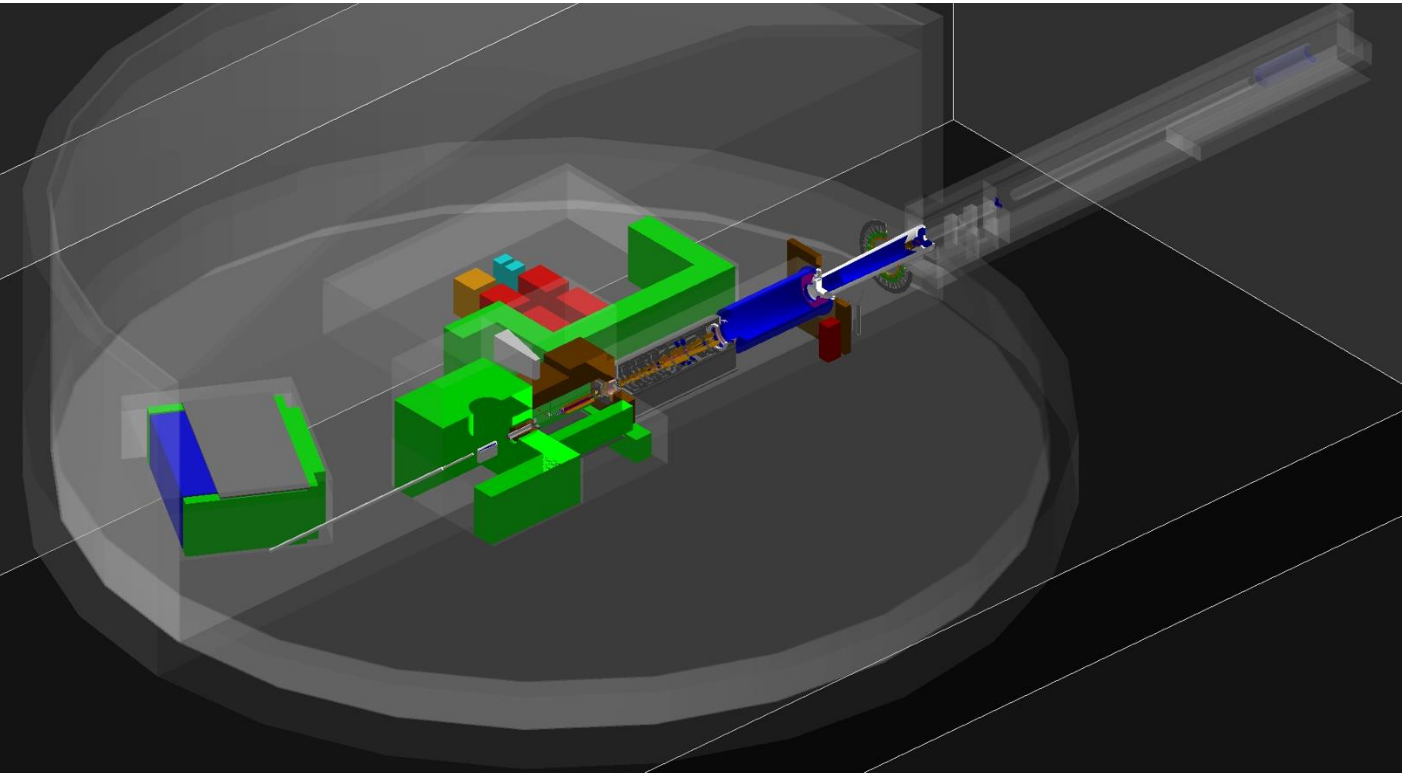
Point Name	Dry Density (Lb/CF)	Wet Density (Lb/CF)	% Moisture	Normal Soil Thickness (Ft.ft)	Conc = Thickness (Ft.ft)*
Max	**119.6**	**125.5**	**25.3**	**6.0**	**4.5**
Min	**89.6**	**104.6**	**4.9**	**1.9**	**1.3**
Avg	**99.1**	**113.5**	**14.5**	**3.3**	**2.2**

1.3' of concrete and 1.9' of soil (dry density of about 1.57g/cm3)

This gives a dose equivalent on top of the thinnest part of Hall-A shielding per 4h of exposure (accident) per 7kW of full unshielded power loss of 11GeV of 58mrem.

This is well below the limit of 15 rem limit for credited control shielding.

Conclusions

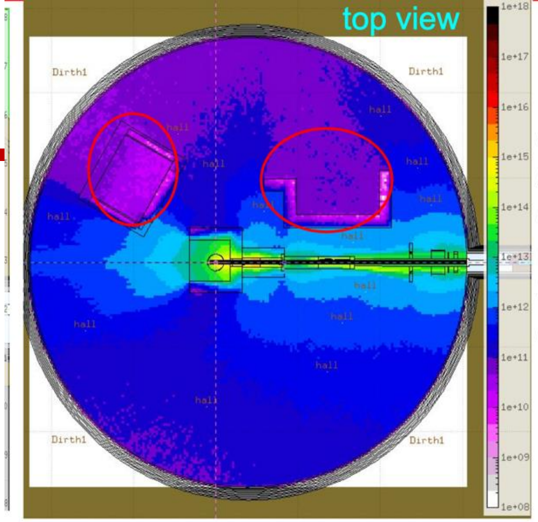


- The two independent boundary dose estimates show that MOLLER will produce a significant dose on the boundary but well within the limit set by the lab
- Using the tools we have on hand we evaluated the damage to materials and electronics throughout the hall due to prompt radiation in close collaboration with the engineering team
- The current design has gone through several iterations with the design team and we believe that it will ensure the experiment will withstand the large radiation field created during data taking
  - The current design will allow for safe operation of the experiment for the entire 344 PAC days
- We are working closely with RadCon to address any radiation issues that may arise and incorporation of simulation results into the access and de-installation plans

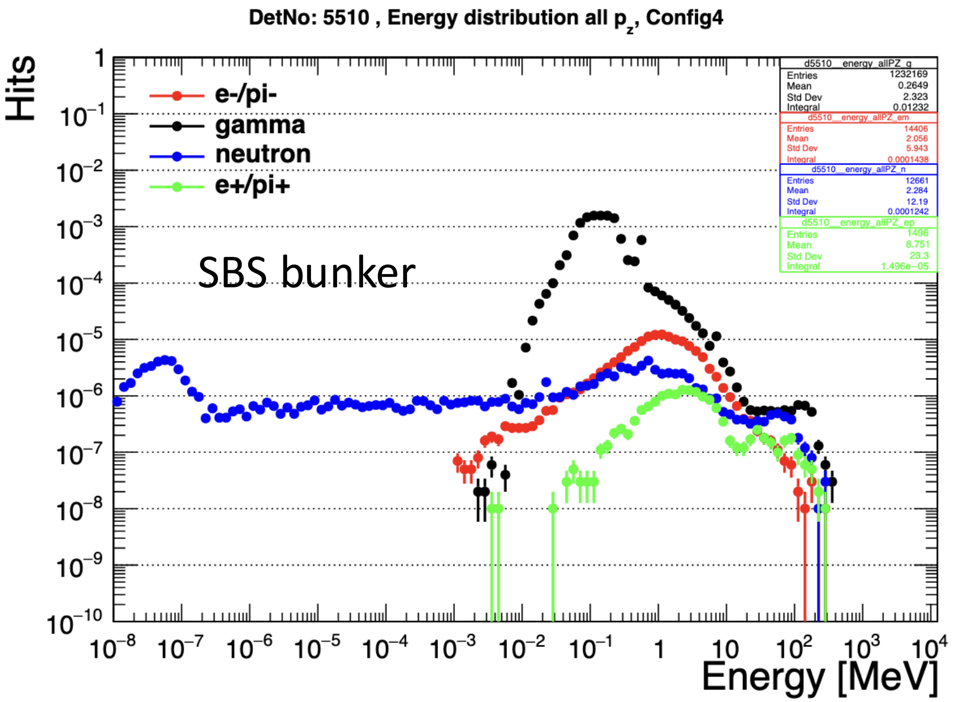
Appendix

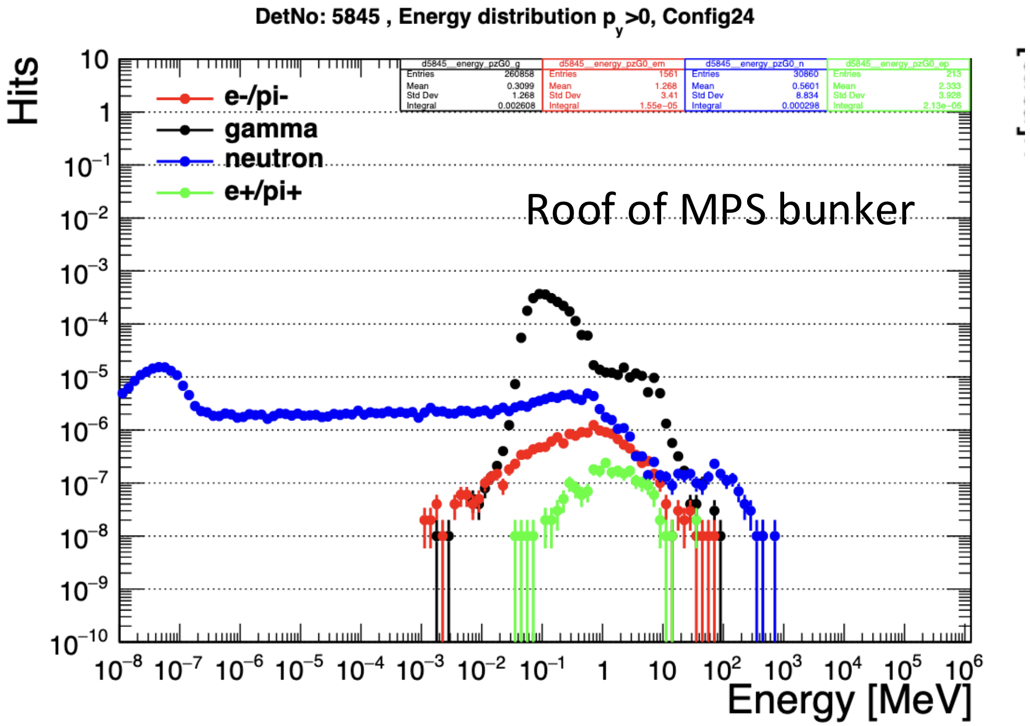
Bunker comparison

- The MPS bunker sees slightly more neutrons compared to the SBS bunker in during MOLLER



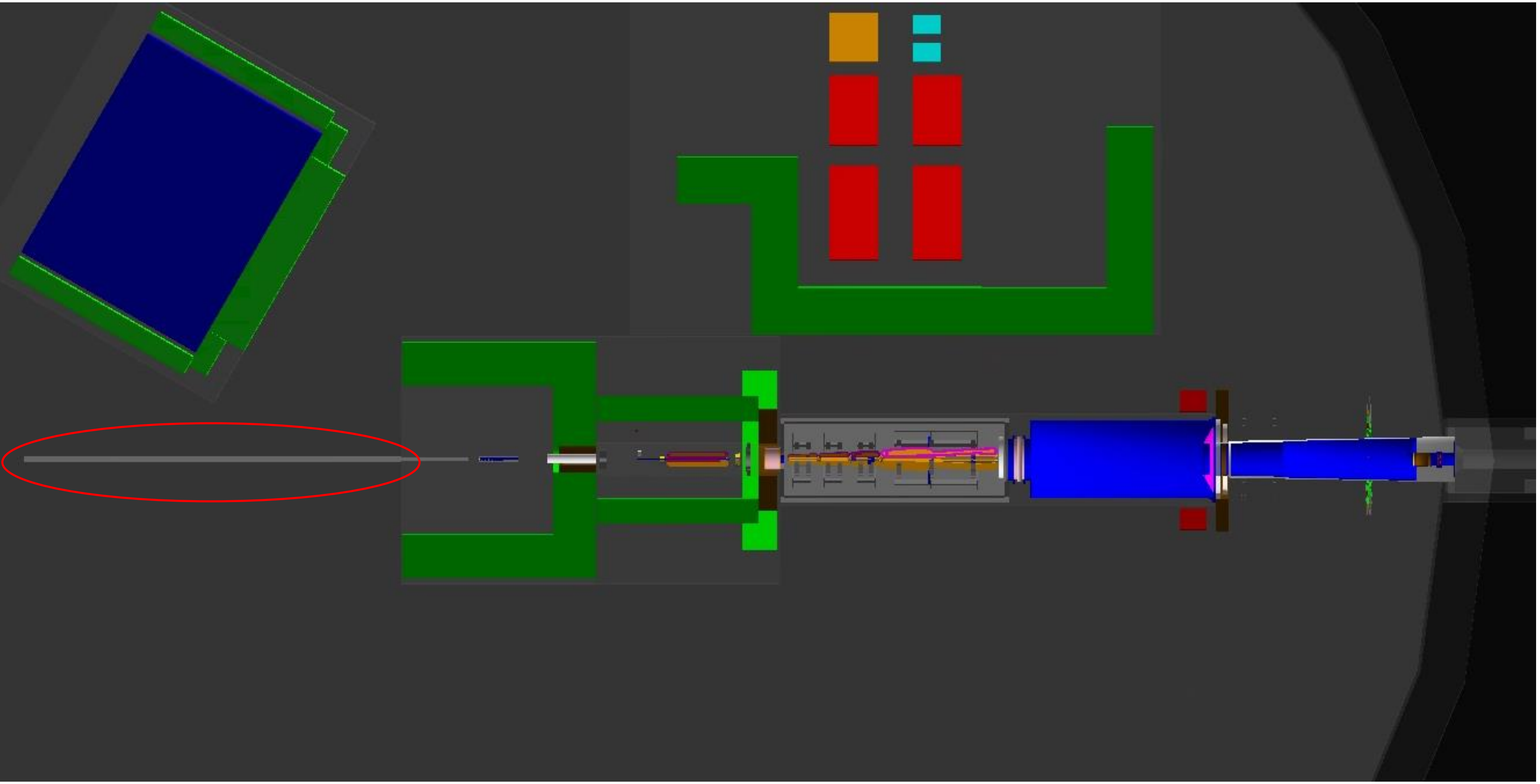
1 MeV Neutron equivalent silicon damage map of 344 days exposure





Simulations: Electronics damage areas of interest

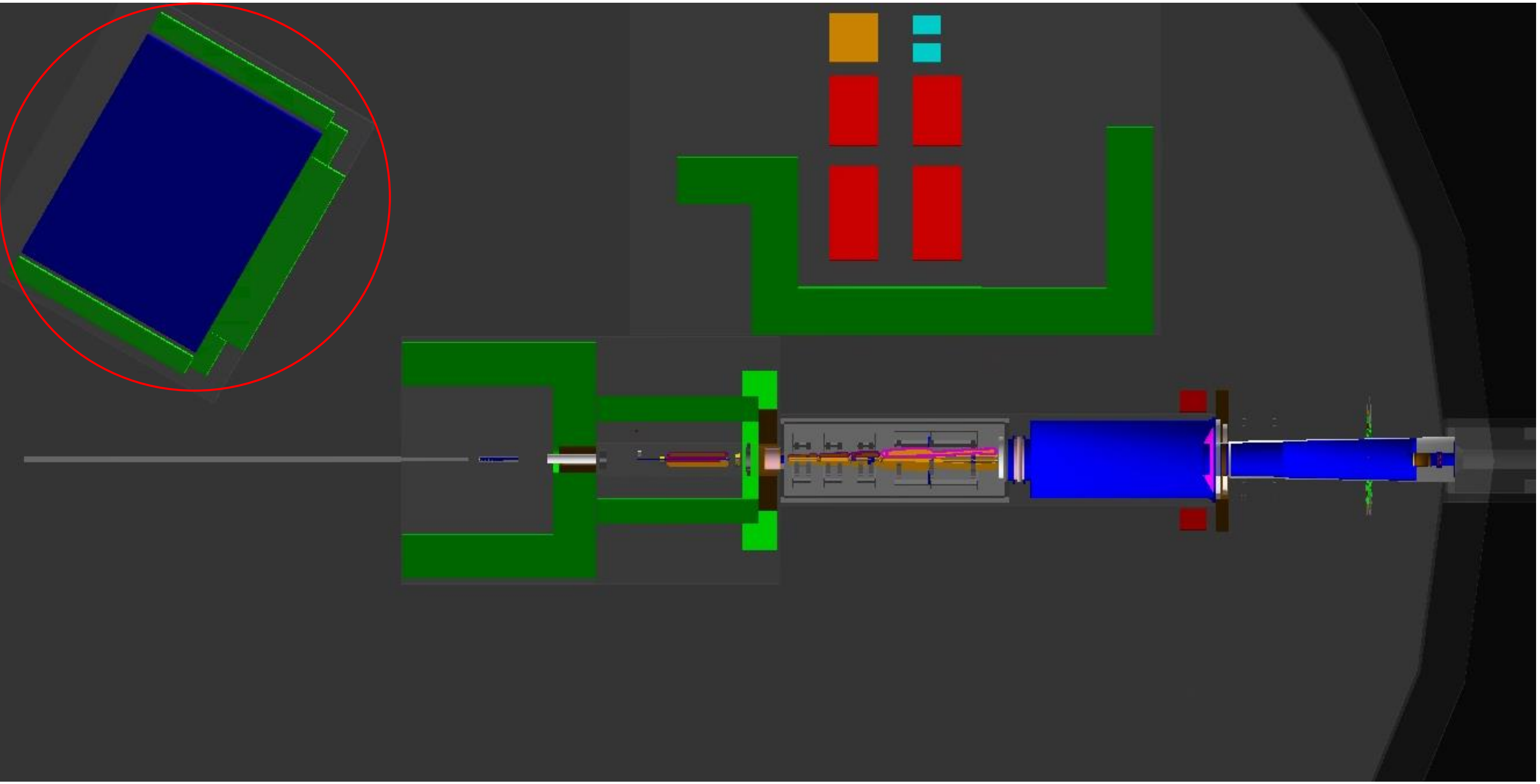
Upstream beamline



- Beam monitoring components, Moller polarimeter components, Compton tunnel
  - Most of the rad-soft components have been removed from the beamline
- We look at both permanent damage (NIEL) and overall fluxes of particles and the levels are several orders of magnitude below component thresholds

Simulations: Electronics damage areas of interest

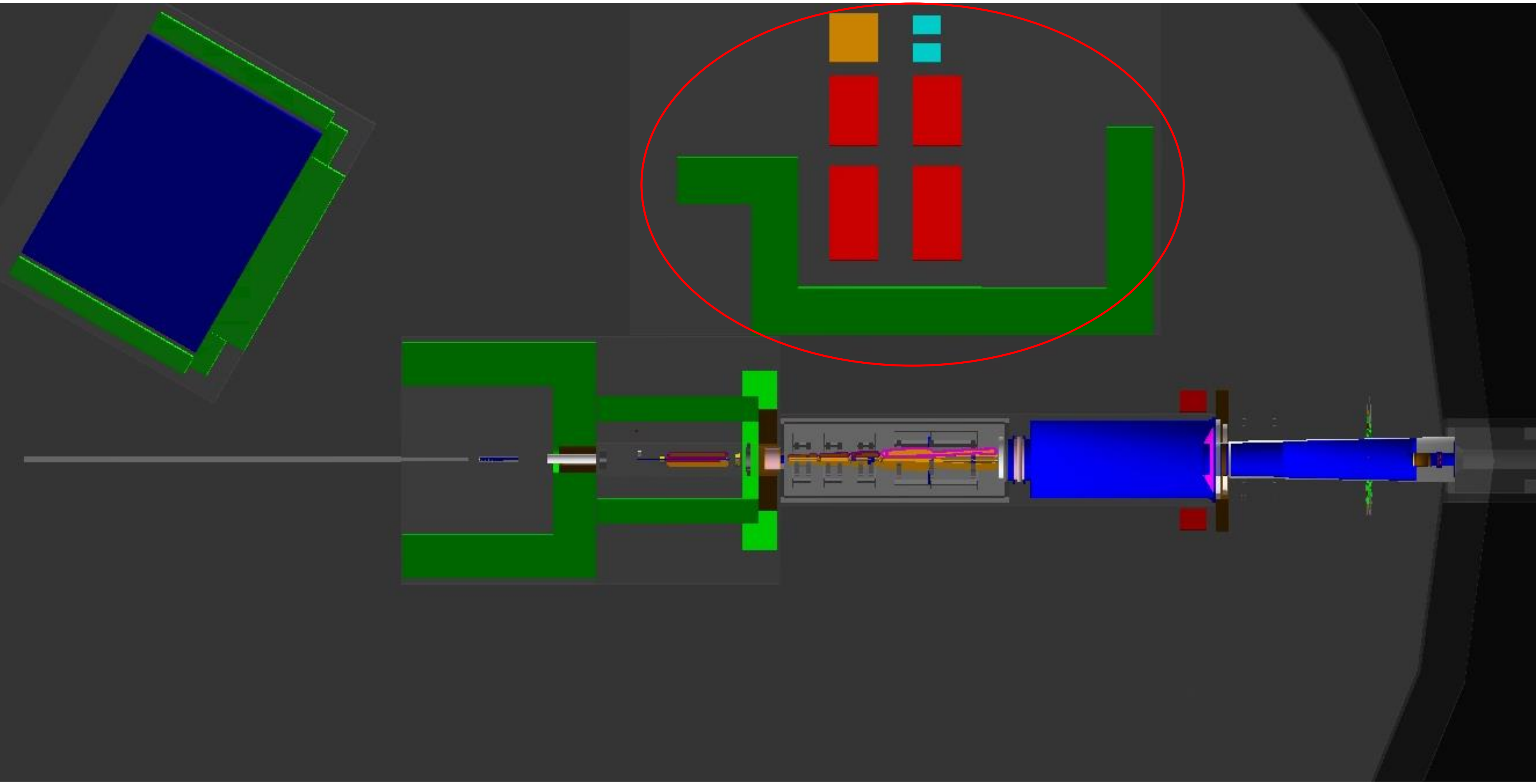
SBS bunker



- The MOLLER DAQ electronics are going to be located in the existing SBS bunker
- We evaluate both long term (NIEL and TID) and short term damage and concluded that the bunker gives adequate levels of protection

Simulations: Electronics damage areas of interest

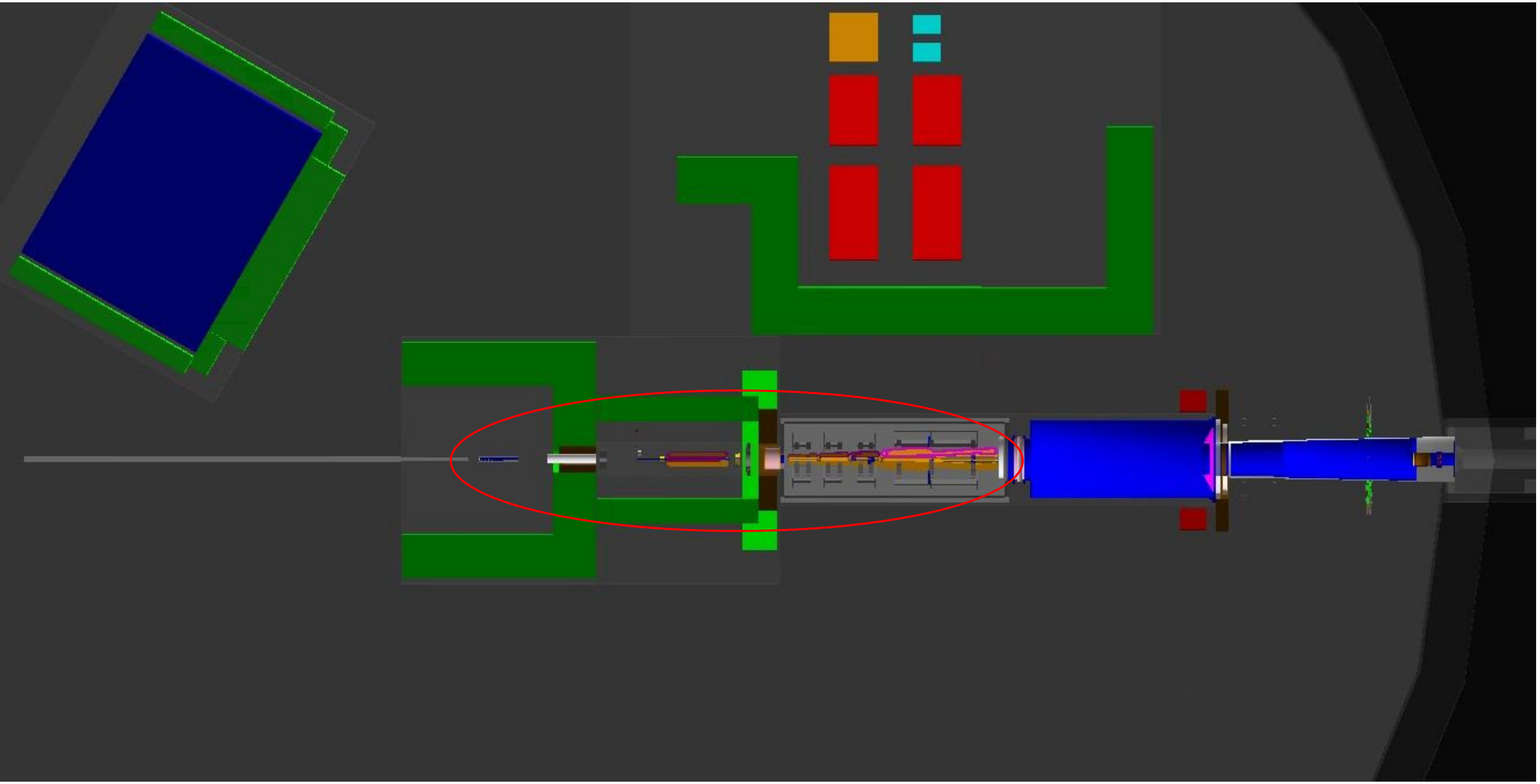
Magnet Power Supply bunker



- The MOLLER torus magnet power supplies are located in this bunker along with miscellaneous electronics
- We evaluate mainly long term damage (NIEL and TID) and the levels are comparable to what we estimated in the SBS bunker

Simulations: Electronics damage areas of interest

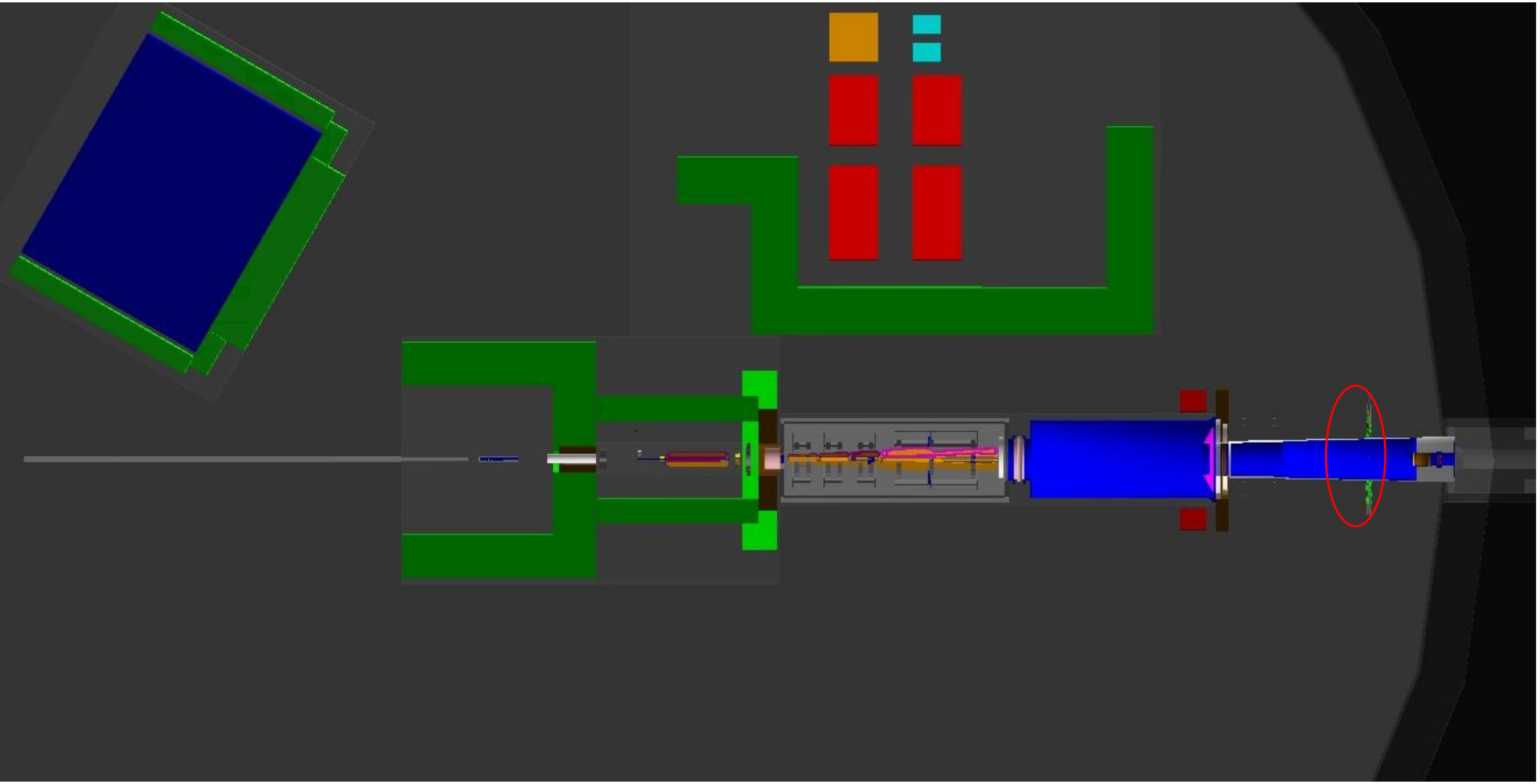
Radiation damage to o-rings, pipes



- The vacuum sealing components along the beamline from the target to the dump are evaluated to long term damage (TID)
- We also take a look at the materials used to supply the magnets with utilities to ensure they will survive through the course of the experiment
- This is done in close collaboration with the engineering team to allow us to change the design or shielding to allow a reasonable safety margin for these components

Simulations: Electronics damage areas of interest

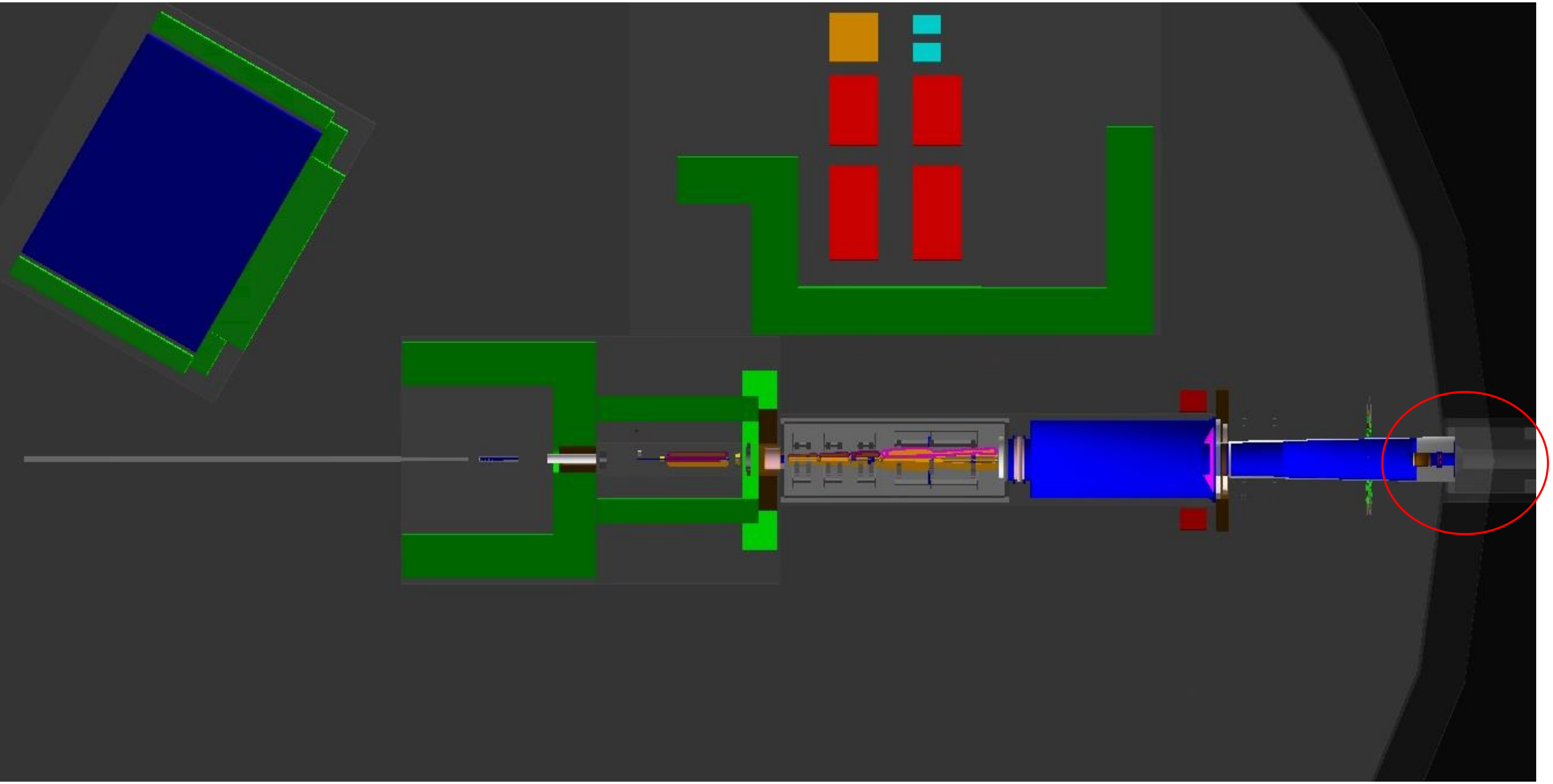
Main Detector area



- The main detector area is monitored to ensure that changes in the shielding do not increase backgrounds beyond what is acceptable for the physics
- In particular re-scattering from potentially polarized atoms in different components has been evaluated and we have blocked line of sight to the detectors through the inclusion of the US torus wall and the detector wall
- The long term radiation damage to the quartz in the main detectors and their PMTs has been evaluated (TID)

Simulations: Electronics damage areas of interest

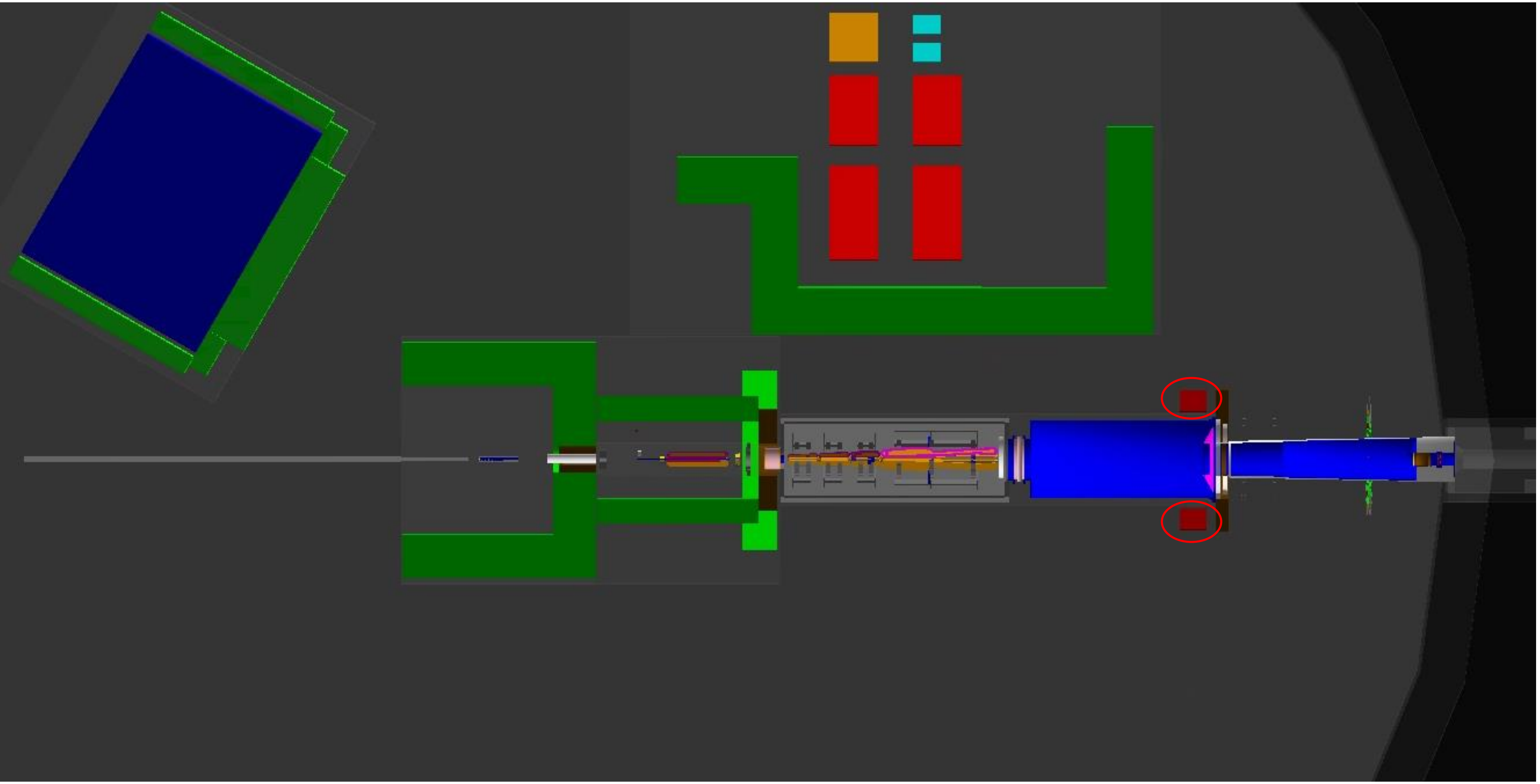
Potential sources from downstream of the MD



- We are aware that the dump region (the neck down close to the end of the hall, the aperture and diffuser) can be a significant sources of secondary radiation and have implemented it in detail in our simulations
  - These sources are subdominant to the sources coming from the Shower Max detectors

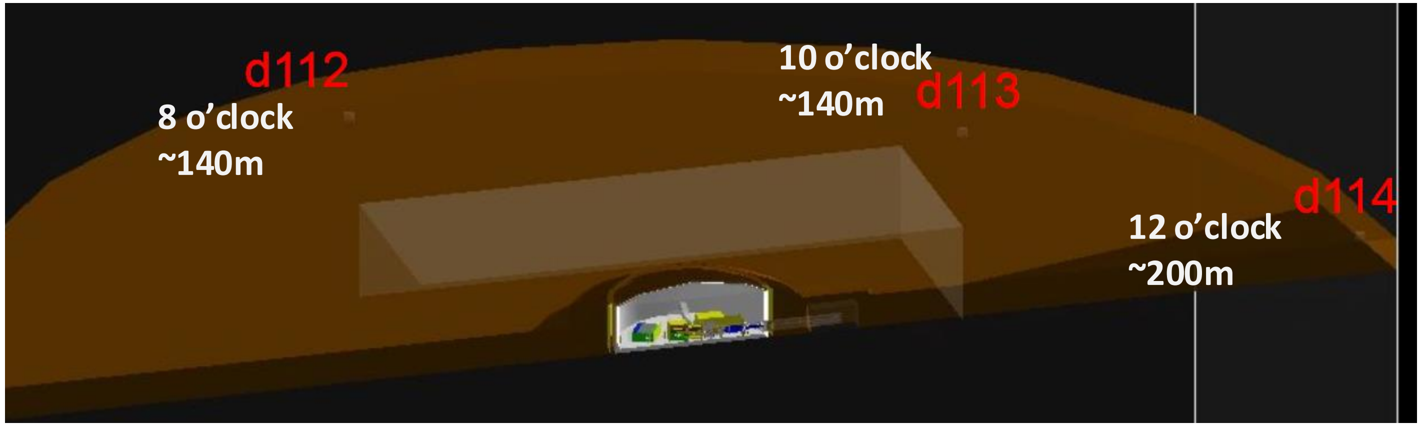
Simulations: Electronics damage areas of interest

GEM racks



- The electronics used for the readout of the GEMs and some power supplies for the main detectors are going to be housed upstream of the barite detector wall
- We have evaluated radiation spectrum reaching these locations and concluded that 1inch of aluminum will be sufficient to moderate the radiation to acceptable levels

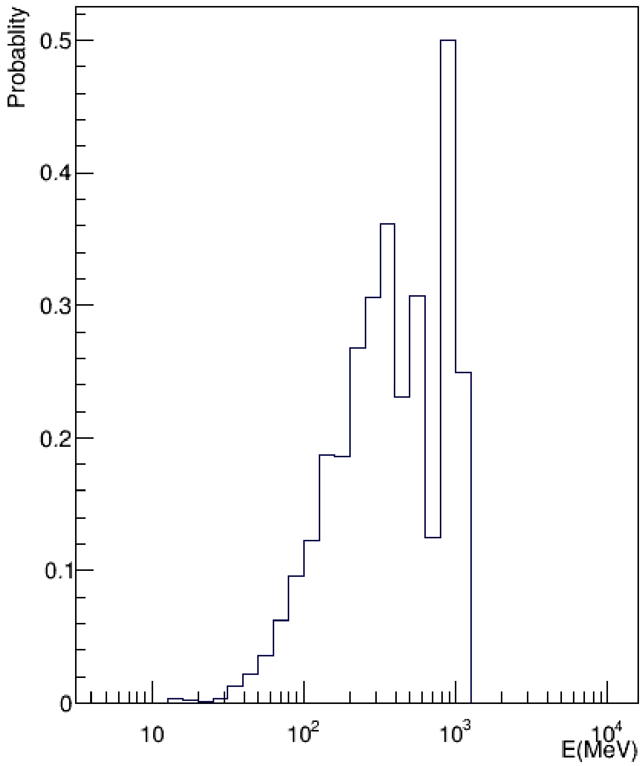
Simulations: G4 secondary simulation



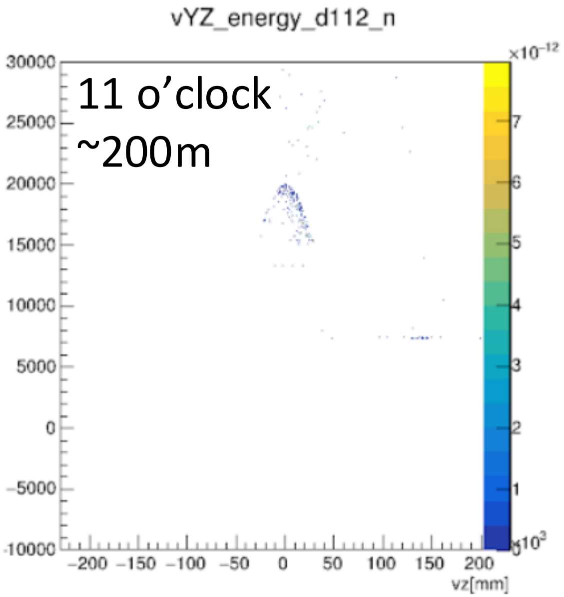
- Beyond the detailed geometry inside the hall we have implemented the dirt overburden on top of the hall, the ground around the hall and the atmosphere above
- We placed 3 detectors around the hall at locations similar to the locations where the actual boundary dose monitors exist
- This allows us to identify the amount of radiation at these locations and the properties of the neutrons produce this radiation

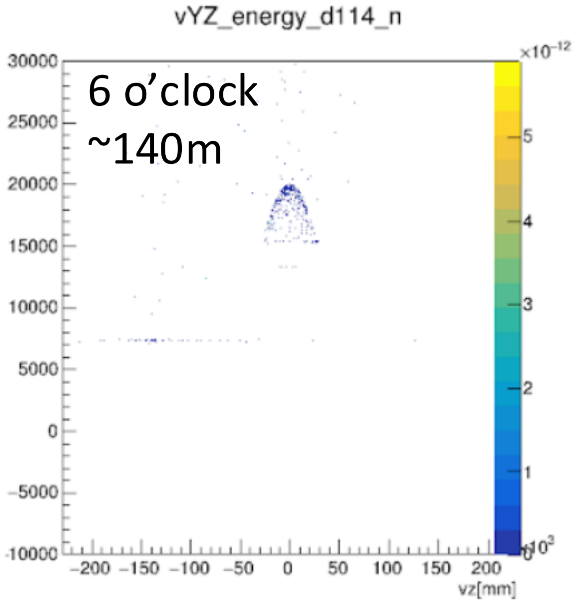
Jefferson Lab

Simulations: neutron radiation



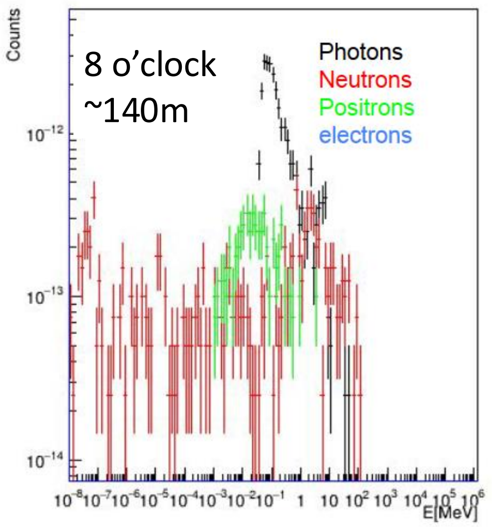
- The ratio between neutrons that produced hits on the boxes to the total number of neutrons gives us a probability that a particular energy neutron will produce hits at the boundary

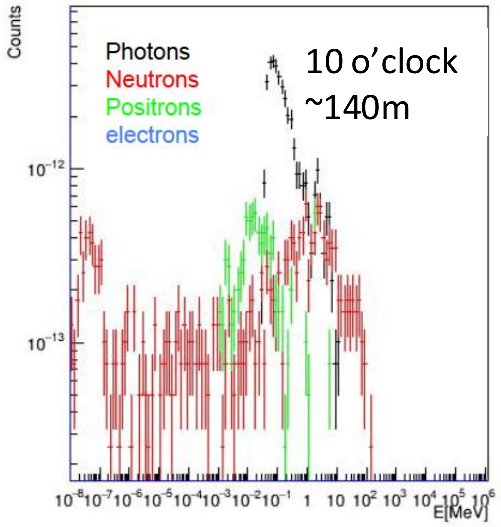


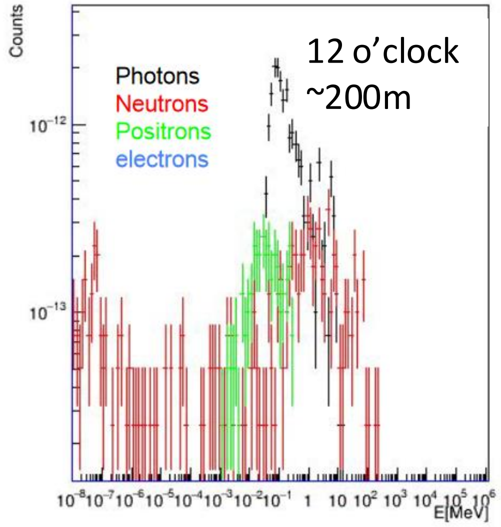


- We can see that the source of neutrons for the different boxes is not exactly the same with each box being affected by neutrons "pointing" in its particular direction
- However the overall magnitude of the radiation will be determined by the distance from the hall center

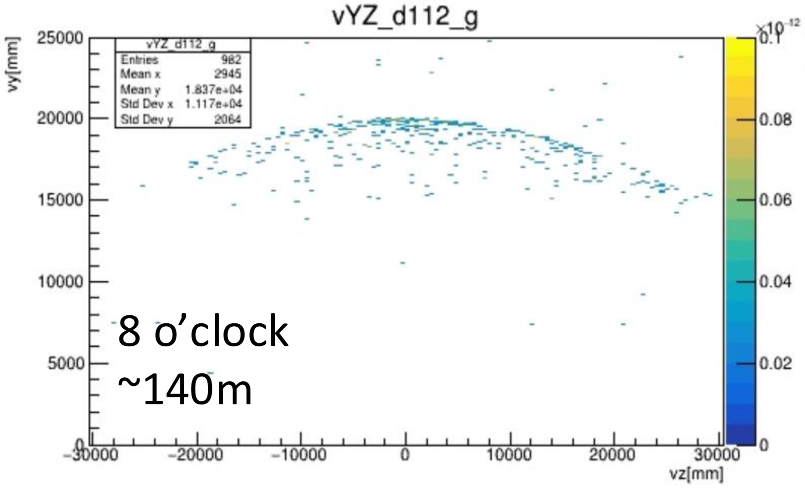
Simulations: G4 secondary simulation

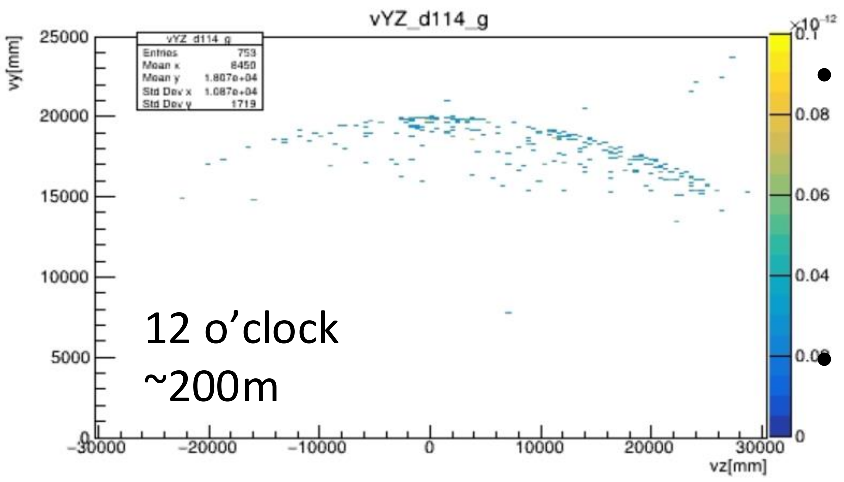






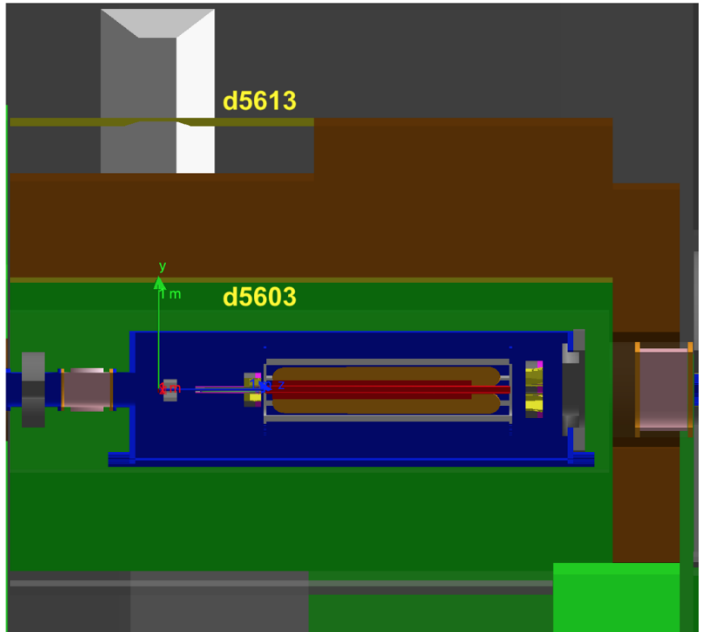
- The energy distributions at these locations shows a clear dependence on distance from the center of the hall rather than a directionality
- This confirms previous RadCon observations that the dominant radiation mechanism is showering in the atmosphere above the hall

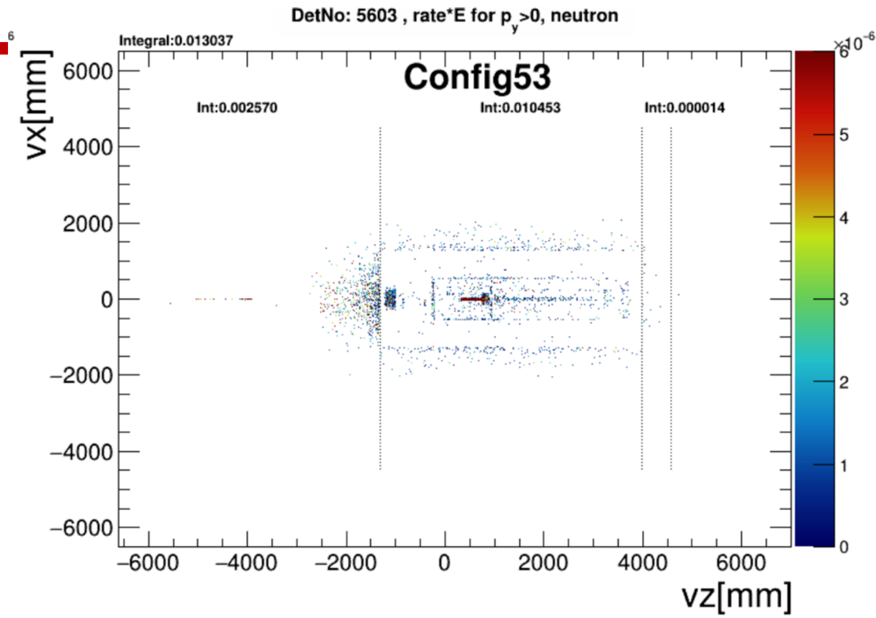


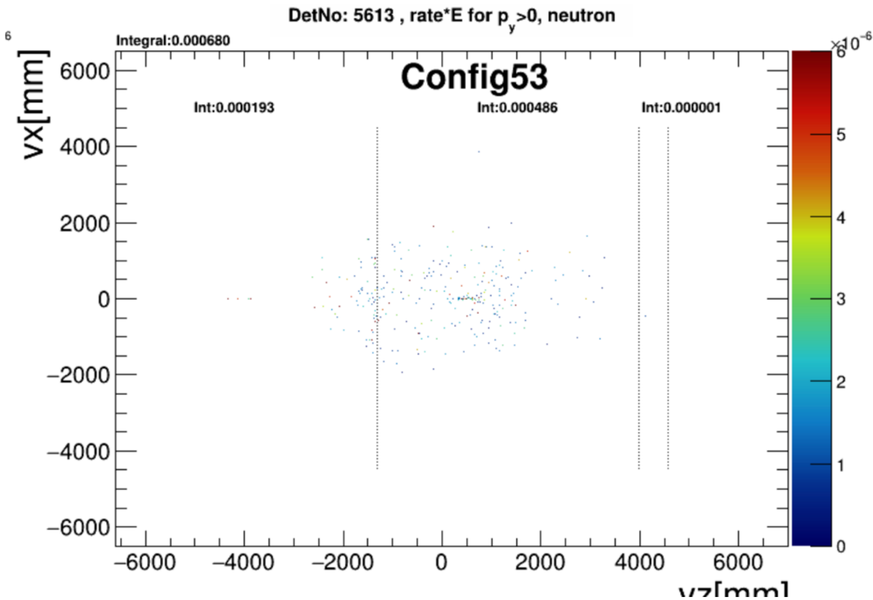


- We can see that the source of neutrons for the different boxes is not exactly the same with each box being affected by neutrons "pointing" in its particular direction
- However the overall magnitude of the radiation will be determined by the distance from the hall center

Simulations: neutron radiation

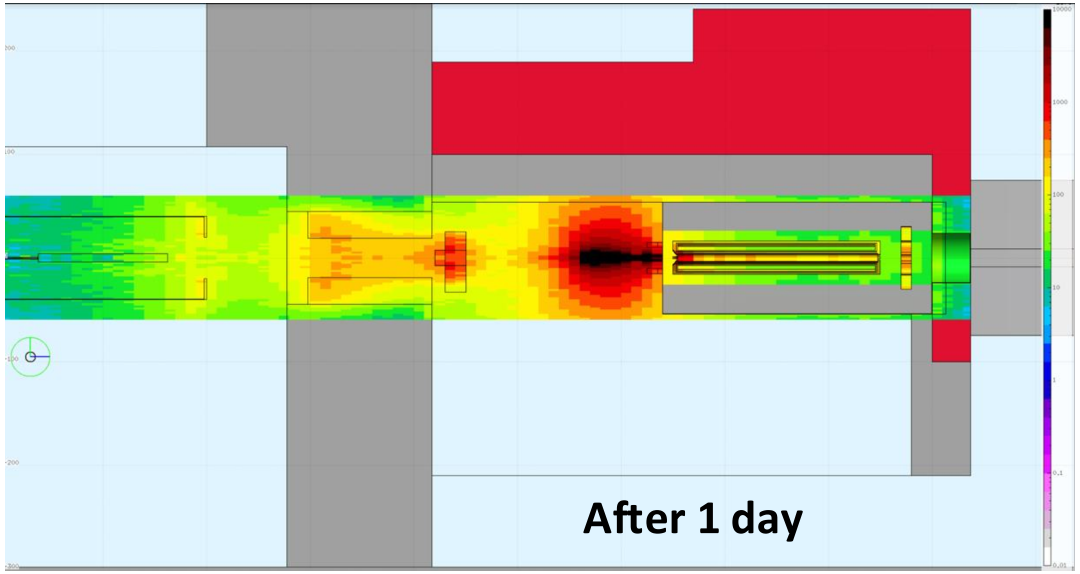


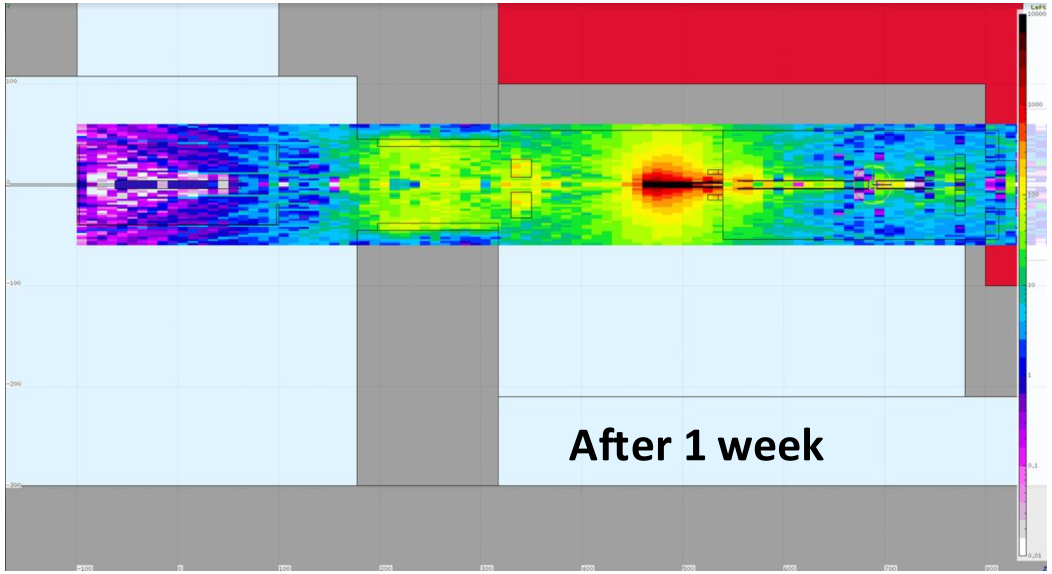


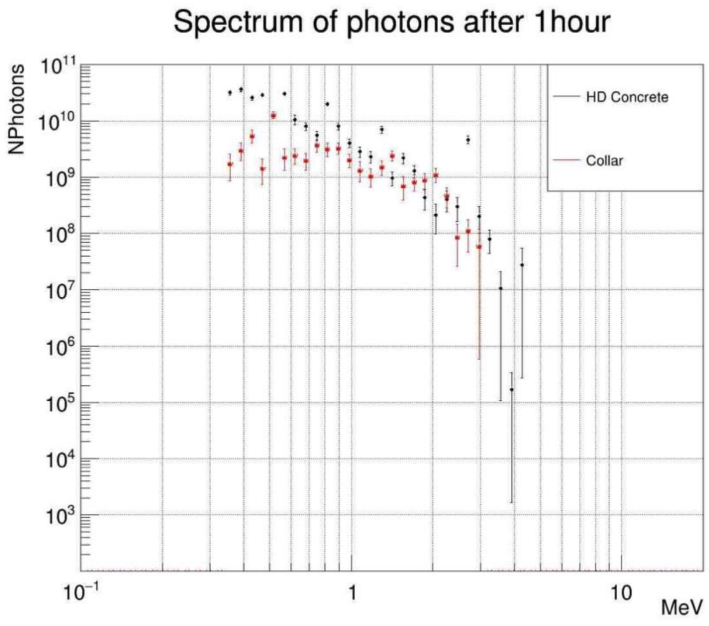


- The source of high energy neutrons are the locations with high energy depositions (the target and collimator 1 regions)

FLUKA activation studies







- Radiation after 1 week is significantly decreased
- Spectrum of photons streaming upstream from collimator 1 into the target bunker is limited below 10MeV
    - A few cm of Pb would be sufficient to significantly reduce the activated radiation spectrum inside the target bunker

Simulations: G4 of other setups

	PREX-II	CREX - 5°	PREX-I	HAPPEX-II	PV-DIS
Target	lead (0.6g/cm^2)	Ca (1 g/cm^2)	lead (0.6g/cm^2)	20cm LH_2	20cm LD_2
Beam E	1 GeV	2.0 GeV	1 GeV	3 GeV	6 GeV
Septum	shielded fringe	shielded fringe, TOSCA model	original septum fringe	original septum fringe	no septum, no fringe
collimator	PREX-II	PREX-II	PREX-I	PREX-I	none
target position	z=-1m	z=-1m	z=-1m	z=-1m	z=0
Shielding	shielded	shielded	none	none	none (no septum)
Current	70 µA	150 µA	70 µA	55 µA	100 µA
Beam Charge	170 C	470 C	82 C	87 C	150 C

- The radiations levels have been calculated in areas with sensitive electronics for previous experiments in hall A
- Even PREX-1 didn't have significant issues with SEU events (vacuum issues prevented the collection of the full dataset)

Flux rates for PREX-II and CREX are below HAPPEX-II or PVDIS

1MeV n_{eq} / cm^2

HRS power supply	PREX-I	PREX-II	CREX	P2/P1	CREX/P1	P2/H2	P2/PVDIS
neutron	1.0E+11	7.6E+09	1.5E+10	7%	20%	70%	73%
electron	1.2E+11	1.4E+10	2.1E+10	11%	12%	94%	84%
total	**2.3E+11**	**2.1E+10**	**3.6E+10**	9%	16%	83%	80%

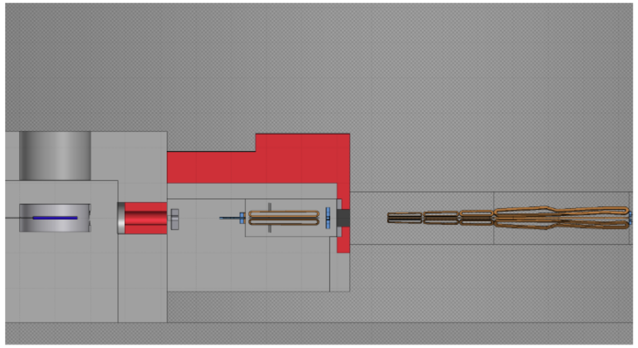
NIEL thresholds: Semiconductor damage ~10^{13}, Optocoupler damage ~10^{11}

SEU or SEL events are instantaneous (not cumulative) effects

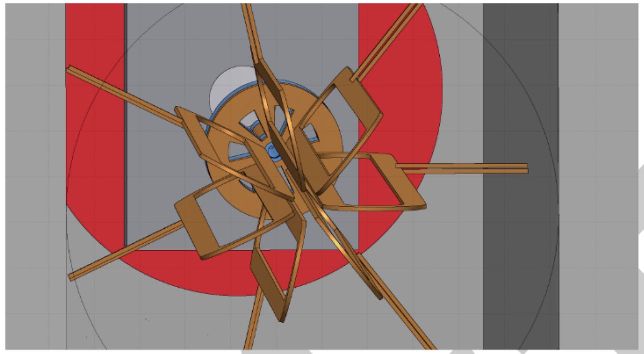
Hall Detector (n,E>10MeV) MHz/m^2	PREX-1	PREX-2	CREX	H2	PVDIS
HRS Platform	8 ± 3	<1	<0.6	<0.9	<5.2

- PREX-I is only configuration with non-zero result for high-energy neutron flux in HRS platform
  - Shielded from pivot region by dipole, so this points to E&M radiation scattered around the hall

Simulation: FLUKA activation of coil cooling water

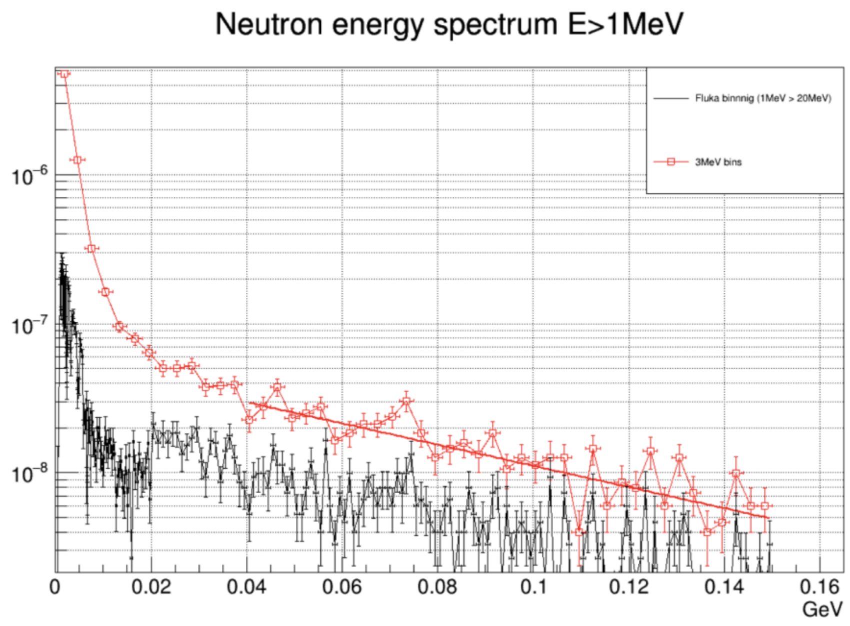


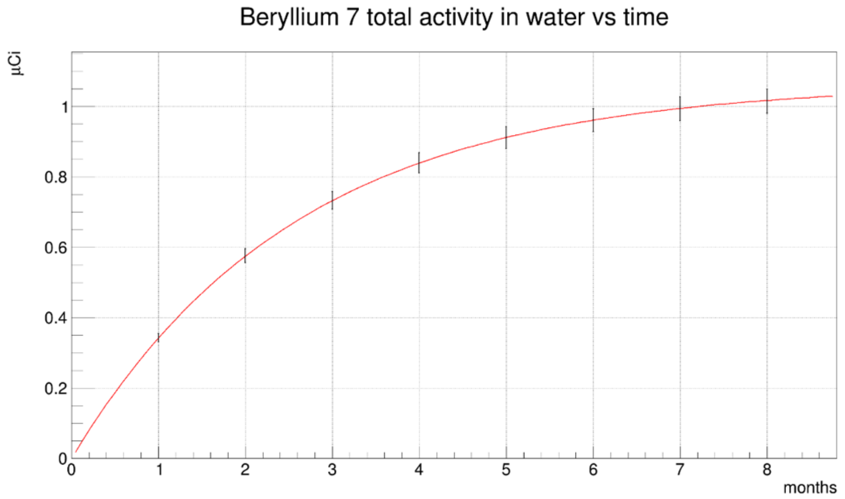
(a) Side view of the target area and the two magnet system: Upstream Torus and Downstream Hybrid Torus



(b) Upstream magnet view from the back. One can see a particular of the back of the main Moller collimator and the block lead shielding that is placed to stop direct line of sight of the solenoid from the target.

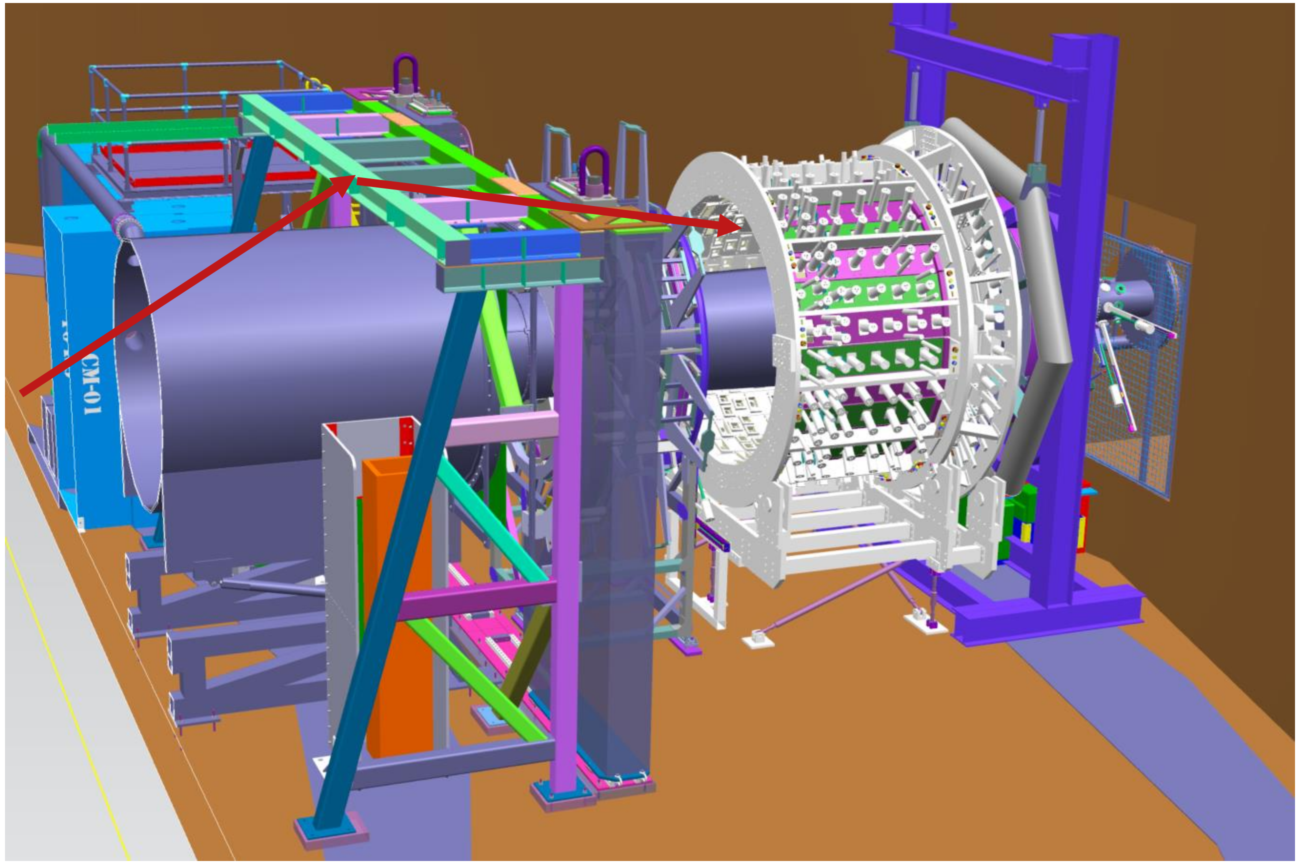
Figure 2: Current status of the Fluka Moller simulation.



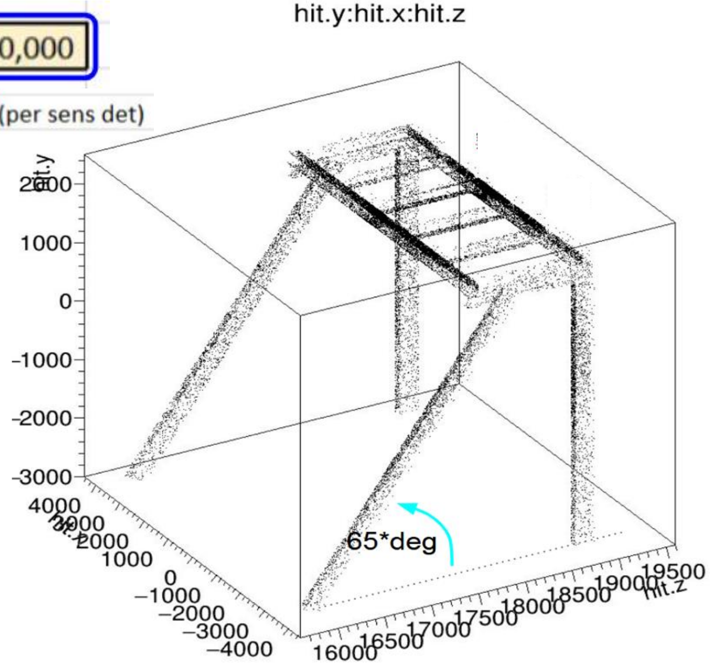


- The total activity produced in the water cooling water system during the Moller experiment will be dominated by Tritium activity and will accumulate during the 3 years of running and 344 PAC days to 0.51µCi. The Be7 activity is 1.02µCi. These are well below the limits established for the system.

Simulations: Materials



Total Prims	10,000,000,000	
Total Secondarie	500,000	(per sens det)



(9928 Main Detector) Total Fractional - 0&1		
Secondaries	Electrons	Gammas
9098	1.17E-09	2.16E-09

- Rescattering from the barite wall support reaching the main detector quartz area was estimated to be ~2E-9 per electron on target
- Given the goal to limit the potentially polarized rescattering this rate was higher that the 1E-11 that was acceptable for structural steel

Material	X_r	Spin Polarization (P_f)	Frac e- on Target
Mild Steel	2000	1E-02	1E-11
Stainless Steel (Worst)	1	1E-05	1E-08
Stainless Steel (Ideal)	0.01	1E-07	1E-06
Aluminum	0.0001	1E-09	1E-04
Inconel 625	0.001	*1E-08*	1E-05
Brass/Bronze (Worst)	0.001	*1E-08*	1E-05