GEANT4 Simulation of radiation during APEX

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This report addresses charge item 4:

> *Are the radiation levels expected to be generated in the hall acceptable? i.e. has the impact of the radiation generated in the hall equipment and infrastructure been properly calculated and mitigated?*

This report provides information on radiation environments in the hall A during APEX experiment.

APEX Readiness Review

April 07, 2016

UNIVERSITY of VIRGINIA

Content of the performed study

- **We developed a detailed GEANT4 model to study radiation environments in hall A.**
- This model was used to simulate APEX experiment and calculate radiation dose at different areas in hall A.
- Similar computations were done for PREX-I and Real Compton Scattering (RCS) to benchmark our results.
- Analysis was also performed to identify the locations of radiation sources (shown in backup slides).

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Outline of this report

1. Experiment Safety Assessment Document (ESAD) for experimental hall A base equipment, approach - 3 slides
2. Radiation damage to electronics – 8 slides
3. Geant4 model of JLab hall A – 5 slides
4. Overview of APEX– 4 slides
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ESAD for experimental hall A base equipment - 1/3

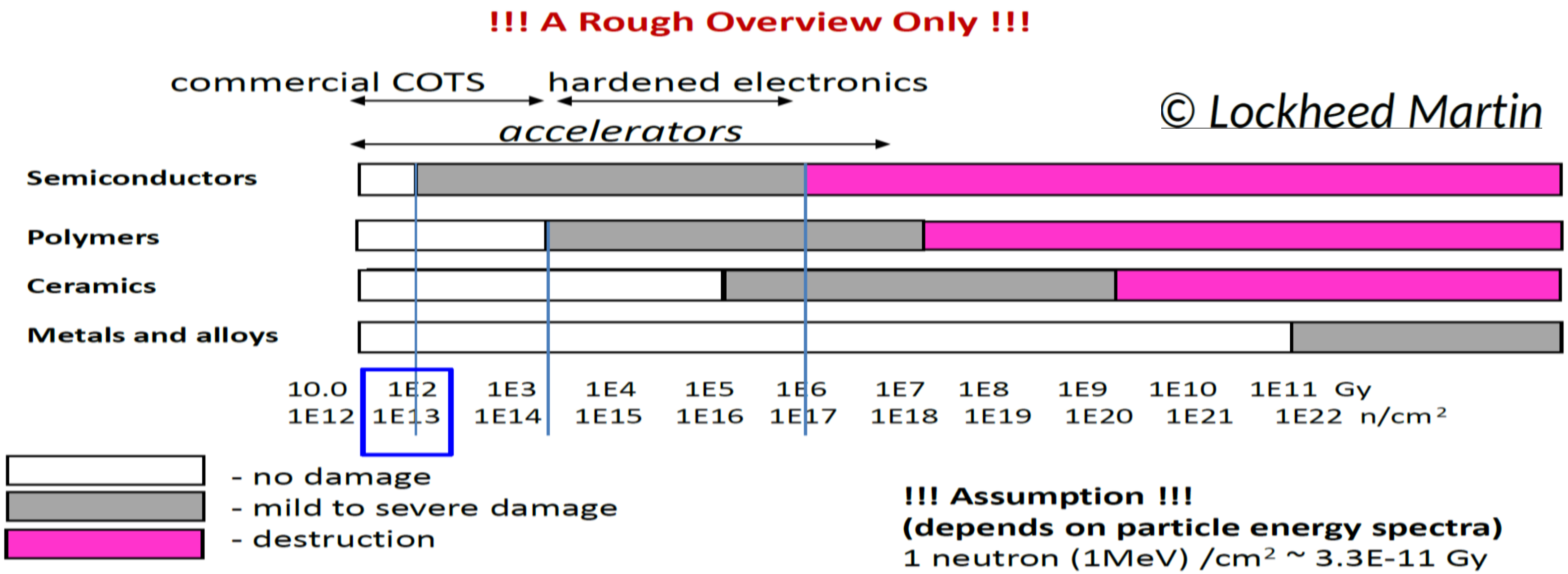
Chapter 2: General Hazards

2.1 Radiation

CEBAF's high intensity and high energy electron beam is a potentially lethal direct radiation source. It can also create radioactive materials that are hazardous even after the beam has been turned off. There are many redundant measures aimed at preventing accidental exposure of personnel to the beam or exposure to beam-associated radiation sources that are in place at JLab. The training and mitigation procedures are handled through the JLab Radiation Control Department (RadCon). The radiation safety department at JLab can be contacted as follows: For routine support and surveys, or for emergencies after-hours, call the RadCon Cell phone at 876-1743. For escalation of effort, or for emergencies, the RadCon manager (Keith Welch) can be reached as follows: Office: 269-7212, Cell: 757-876-5342.

Radiation damage to materials and electronics is mainly determined by the neutron dose (photon dose typically causes parity errors and it is easier to shield against). Commercial-off-the-shelf (COTS) electronics is typically robust up to neutron doses of about $10^{13}\, n/cm^2$. If the experimental equipment dose as calculated in the RSAD is beyond this damage threshold, the experiment needs to add an appendix on "Evaluation of potential radiation damage" in the experiment specific ESAD. There, the radiation damage dose, potential impact to equipment located in areas above this damage threshold as well as mitigating measures taken should be described.

ESAD for experimental hall A base equipment - 2/3

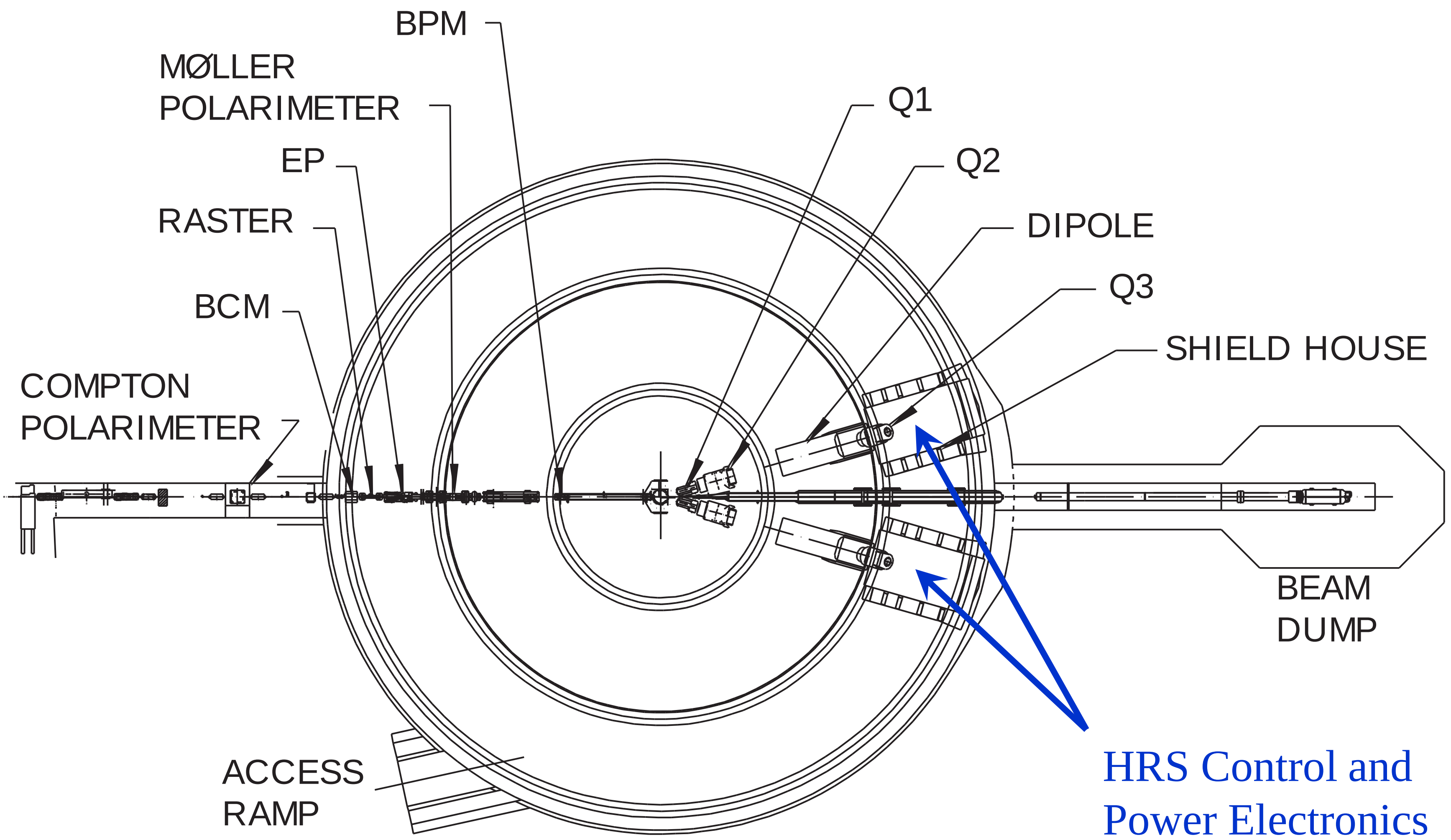


- According to the scale shown above semiconductor electronics are typically robust until "1MeV equivalent neutron fluence" reaches 1E+13 $n\ cm^{-2}$.
- However, recent studies (ref. given below) show that **"soft" electronics** such as **optocouplers** could be damaged even at 1E+11 $n\ cm^{-2}$ fluences.

Reed, Robert, et al. "Test Report of Proton and Neutron Exposures of Devices that utilize Optical Components and are contained in the CIRS Instrument." *Greenbelt,(Maryland) NASA/Goddard Space Flight Center*20771 (1997).

- Down time increases for a large system due to variations in the damage thresholds. Individual probability is likely proportional to the radiation dose!

ESAD for experimental hall A base equipment - 3/3



According to Jack Segal, the highest radiation risk during an experiment is at Hall A HRS control and power electronics.

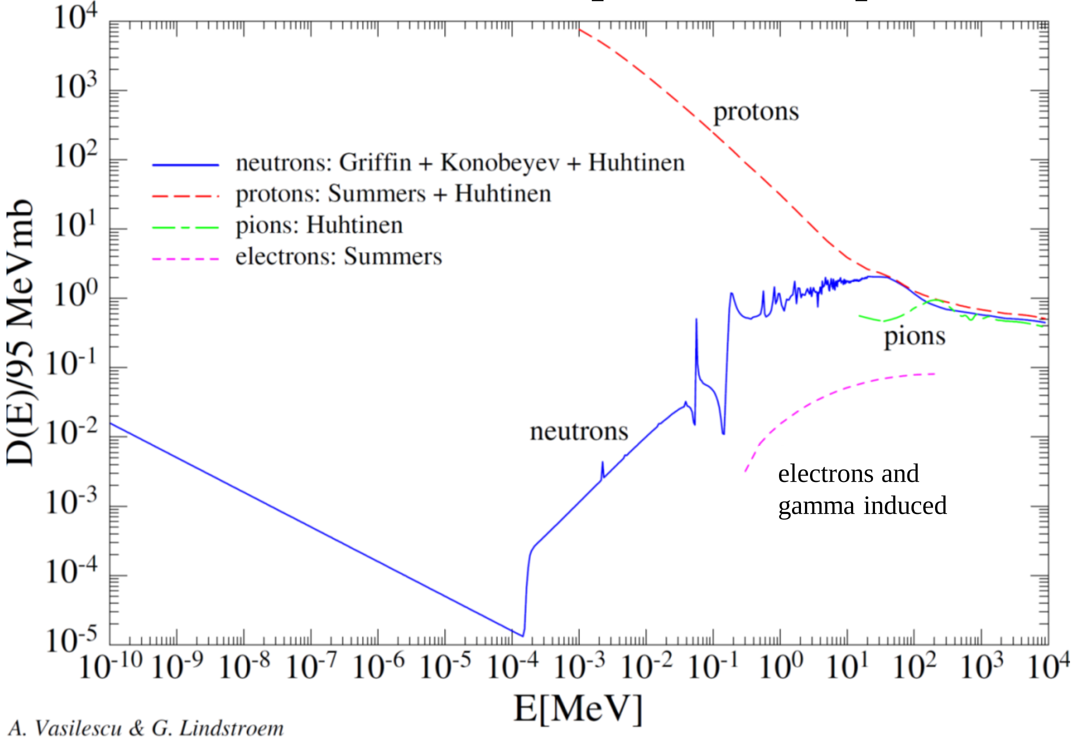
Radiation damage to electronics - 1/8

- **It is a standard to express the silicon radiation damage by "1 MeV equivalent neutron fluence"**

- The following equation gives you "1MeV equivalent neutron fluence" which produces the same damage as an arbitrary radiation field with a spectral distribution $\phi(E)$.

$$\Phi_{\mathrm{eq}}^{1\mathrm{MeV}} = \int_0^{\infty} \frac{\mathrm{D(E)}}{95\ \mathrm{MeV\ mb}} \phi(\mathrm{E})\mathrm{dE}$$

Damage function of silicon for neutrons, electrons, protons and pions



where 95 MeV mb is a constant due to accepted normalization point.

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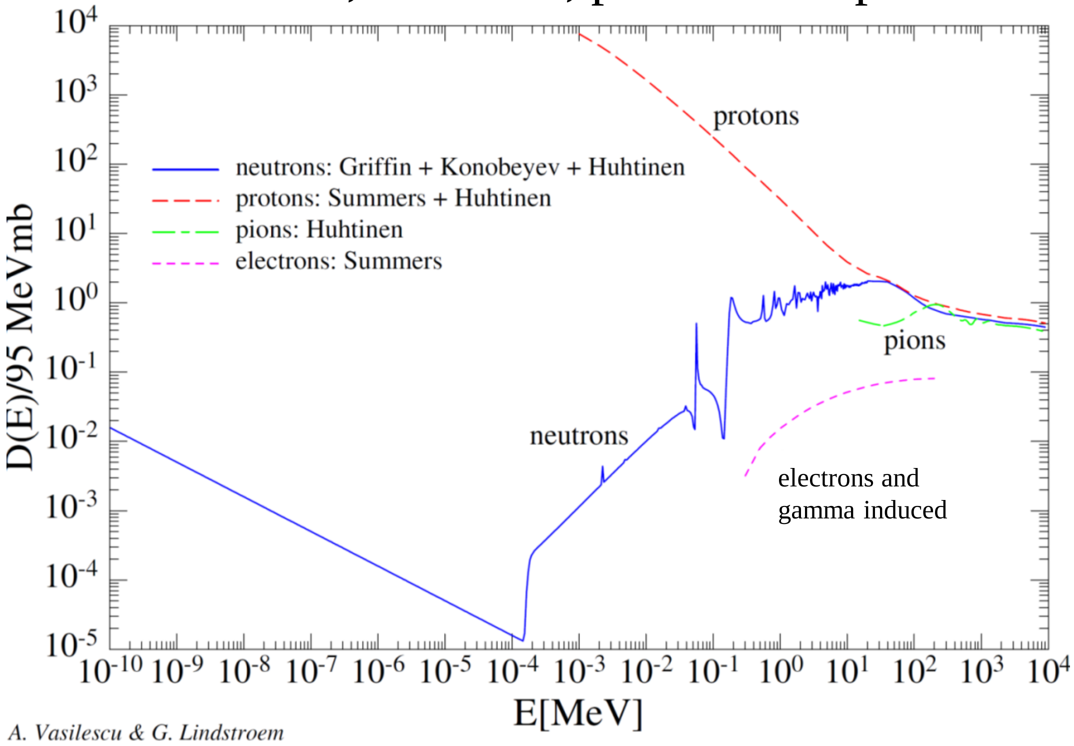

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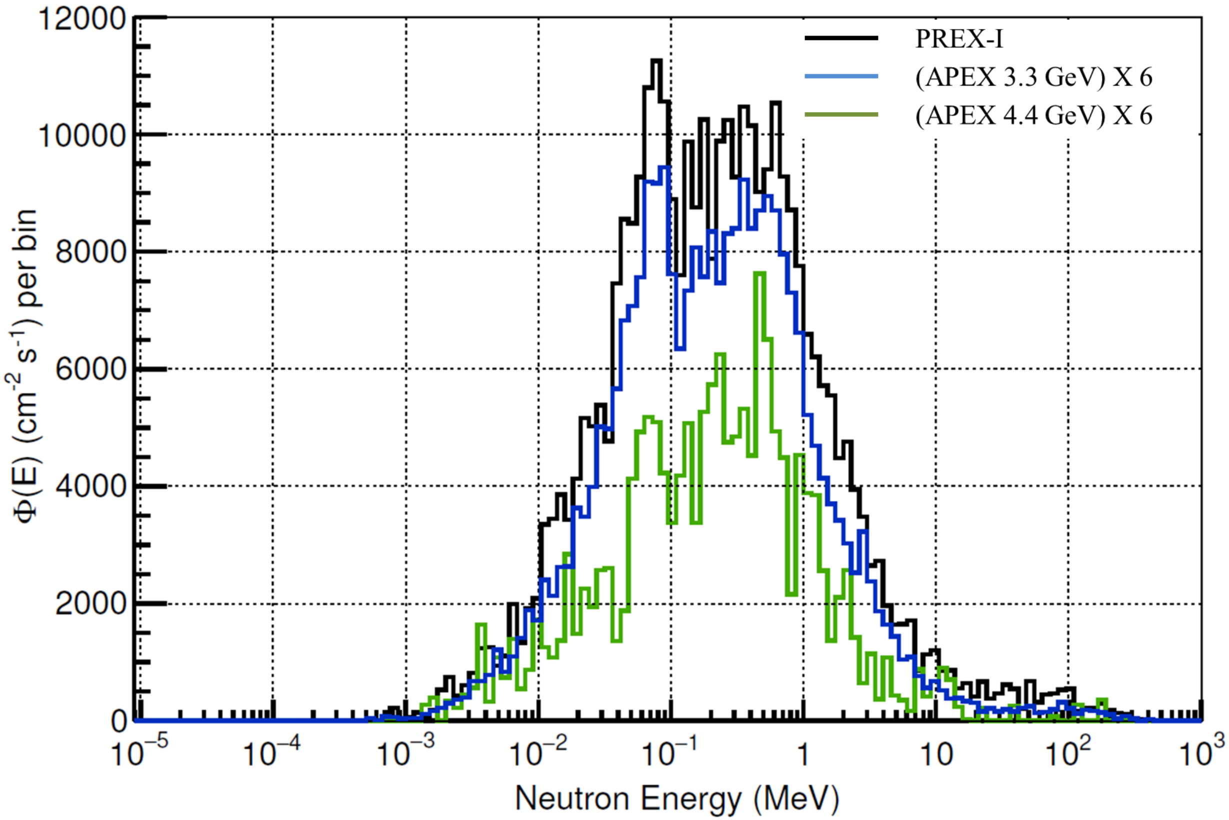
Radiation damage to electronics - 2/8

- Plots show neutron spectrums at HRS electronics area for APEX and PREX-I.
- All these neutron spectrums have a similar shape.
- This energy range is well covered by RadCon standard neutron detectors.

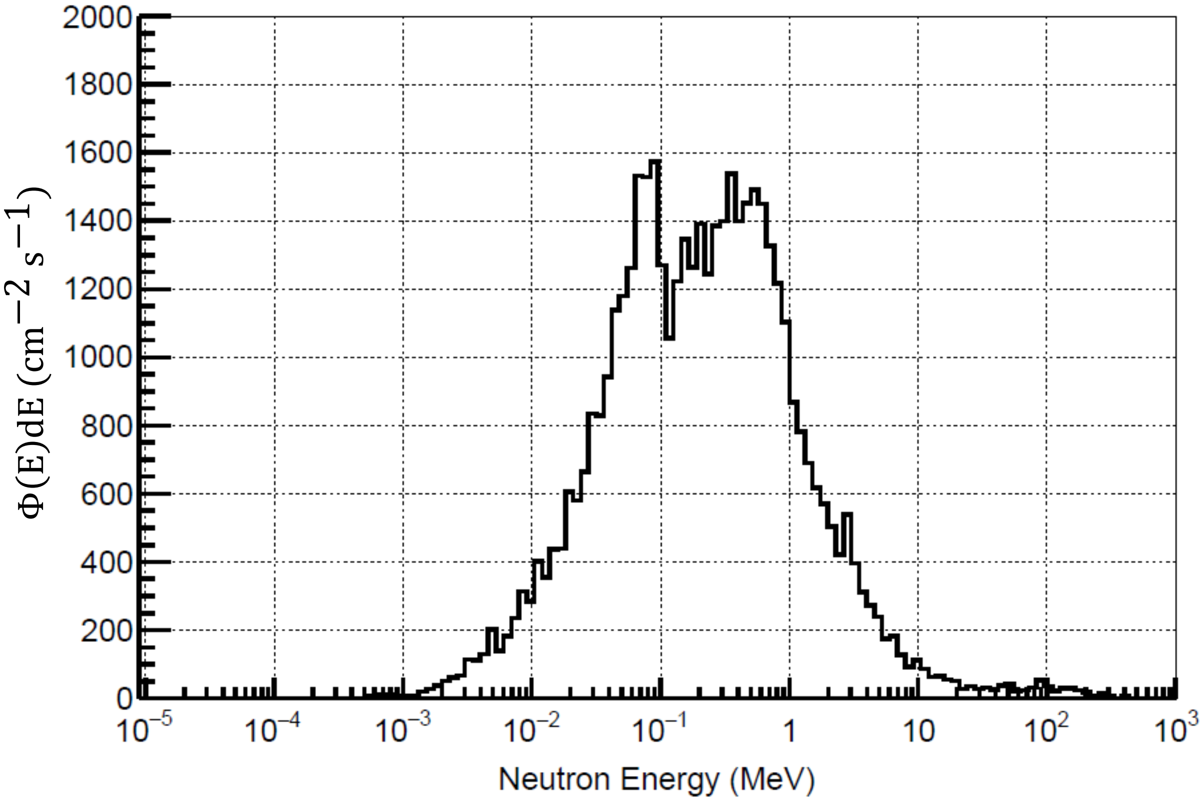


Radiation damage to electronics - 3/8

$$\Phi_{eq}^{1MeV} = \int_0^{\infty} \frac{D(E)}{95\ \text{MeV mb}} \boxed{\phi(E)dE}$$

- **Black line indicates neutron fluence rate.**

Neutron Spectrum
at HRS-left detector
APEX 3.3 GeV



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$$\Phi_{eq}^{1MeV} = \int_0^\infty \frac{D(E)}{95\ \text{MeV mb}} \phi(E) dE$$

- Black line indicates neutron fluence rate.
- **Red line is the damage folded neutron fluence.**

Neutron Spectrum
at HRS-left detector
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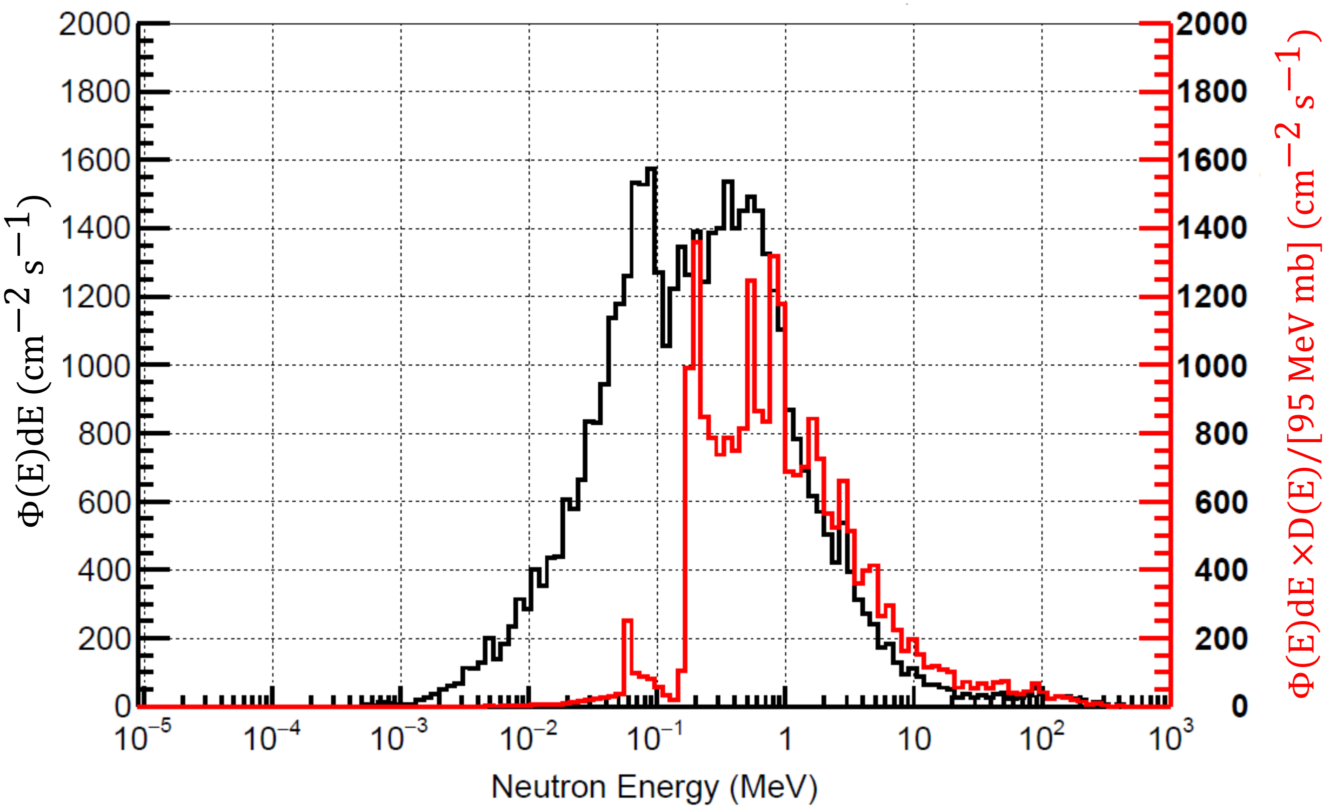
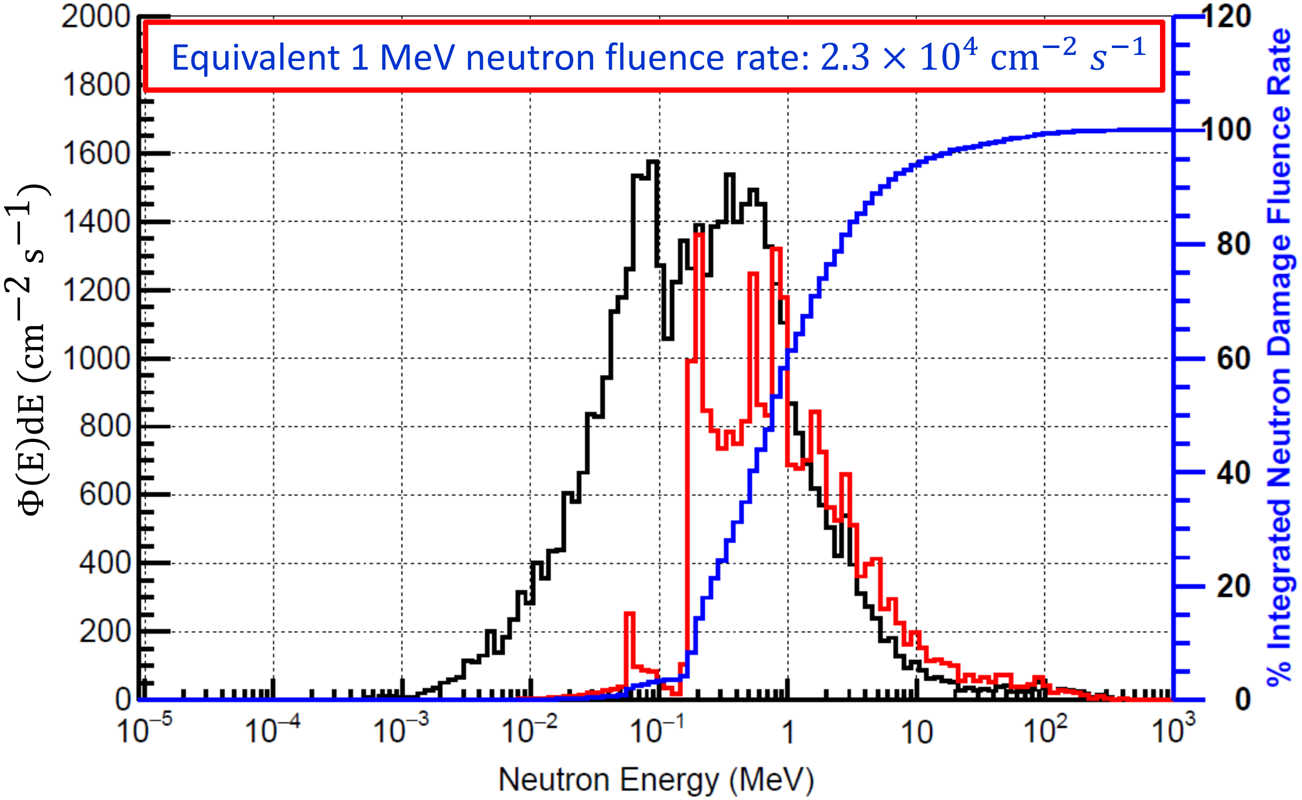


Radiation damage to electronics - 3/8

$$\Phi_{eq}^{1MeV} = \int_0^\infty \frac{D(E)}{95 \text{ MeV mb}} \phi(E) dE$$

- Black line indicates neutron fluence rate.
- Red line is the damage folded neutron fluence.
- **Blue line is the integrated damage as a percentage.**

Neutron Spectrum
at HRS-left detector
APEX 3.3 GeV



Conclusion: 0.1 MeV to 10 MeV neutrons are doing the most damage.

Radiation damage to electronics - 4/8

Table below summarizes the "1 MeV equivalent neutron fluence" due to neutrons and electrons at HRS control electronics for PREX-I, RCS and APEX. (Go to backup slides for the full list)

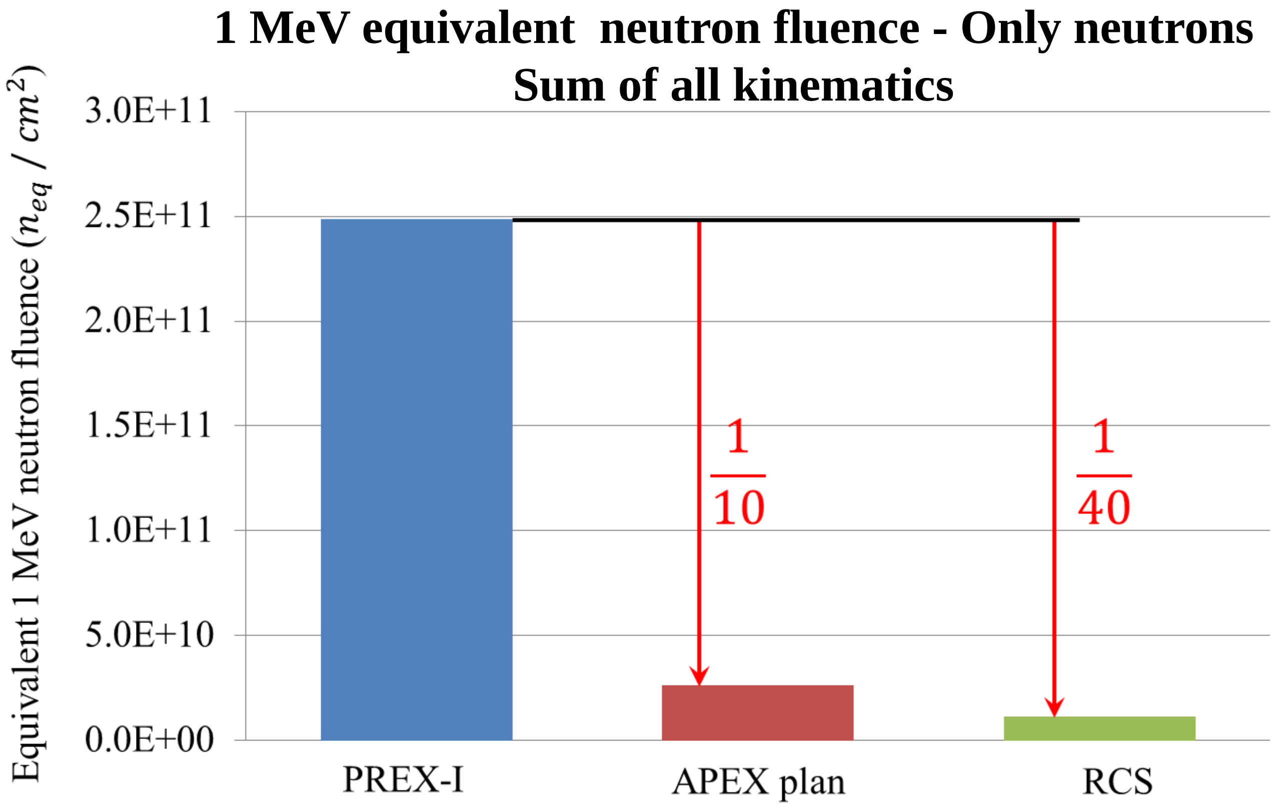
	Days	Particle type	1 MeV neutron equivalent fluence rate $(\boldsymbol{n_{eq}\ cm^{-2}\ s^{-1}})$	Total 1 MeV neutron fluence in HRS-Left $(\boldsymbol{n_{eq}\ cm^{-2}})$
PREX - I	16 effective days	neutrons $e^-/\ e^+$	1.8E+05 6.9E+04	**3.4E+11**
RCS, 3.481 GeV	16 effective days	neutrons $e^-/\ e^+$	5.0E+03 2.1E+03	**9.8E+09**
APEX, 4.4 GeV	12 PAC days	neutrons $e^-/\ e^+$	1.1E+04 3.7E+03	**1.5E+10**

Radiation damage to electronics - 5/8

APEX Plan

Energy	Current	Thickness
1.1 GeV	50 μA	0.7% r.l. Carbon
2.2 GeV	100 μA	2.8 % r.l. Tungsten
3.3 GeV	120 μA	5.3 % r.l. Tungsten
4.4 GeV	90 μA	5.3 % r.l. Tungsten

Projected HRS electronics damage during APEX is compared with PREX-I and RCS electronics damage.

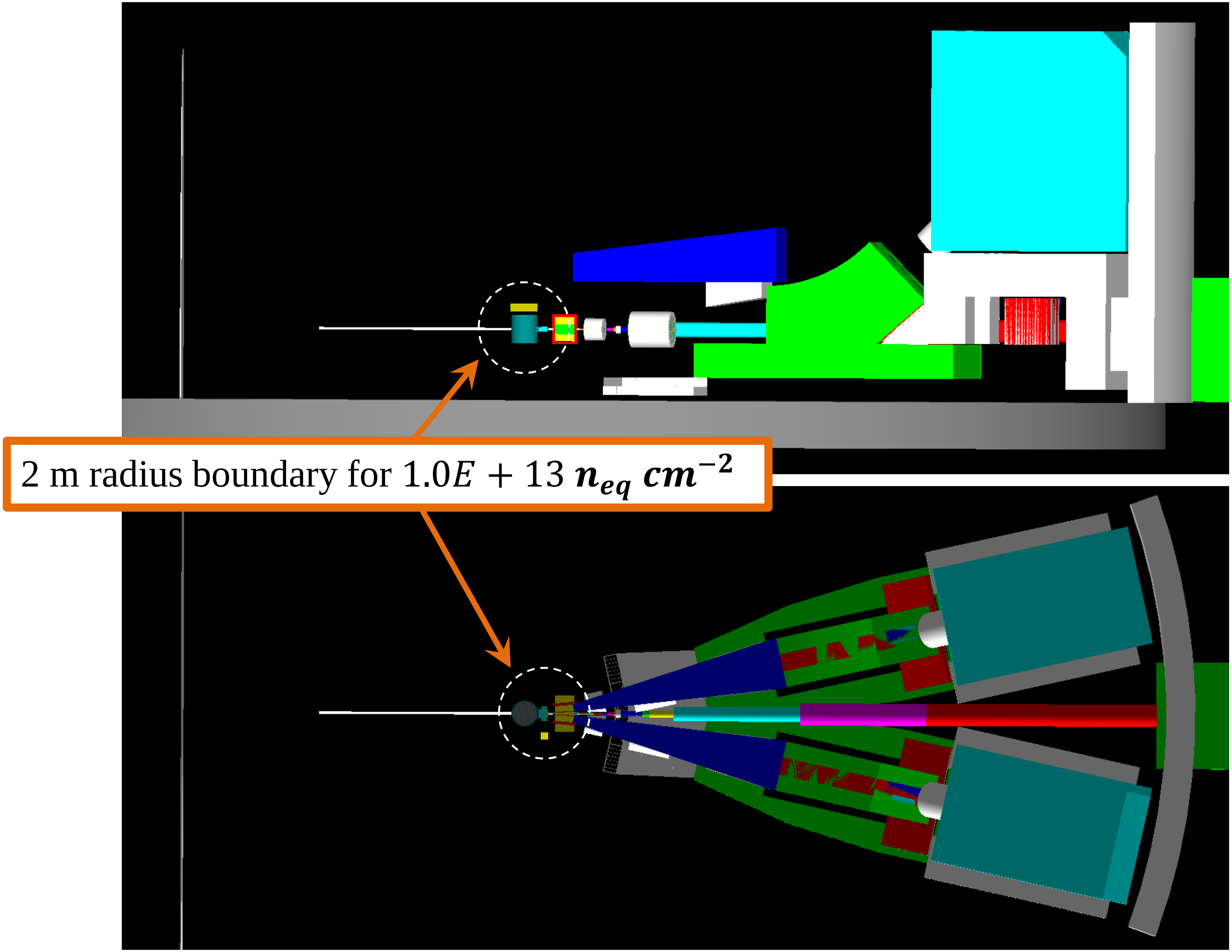


Radiation damage to electronics - 6/8

1 MeV neutron fluence at several locations in hall A for APEX

Location	1 MeV equivalent neutron fluence ($n_{eq}\ cm^{-2}$) — **Only from neutrons**	1 MeV equivalent neutron fluence ($n_{eq}\ cm^{-2}$) — **Only from e^-/e^+**
HRS electronics area	$2.6E+10$	$9.4E+09$
Upstream (standard hall A equipment)	$1.5E+10$	$1.9E+08$
Target motion motor (1 m from beam)	$1.6E+13$	$1.7E+13$
SciFi motion motor (1 m from beam)	$1.5E+13$	$2.2E+12$

Radiation damage to electronics - 7/8



Radiation damage to electronics – 8/8

- Considerations based on PREX-I experience
  - BANU (Beam Available but Not in Use) - 50 % - 70 %
  - Down time was due to a number of different reasons
    - Target melting
    - Vacuum breaks
    - Radiation induced electronics problems

- Considerations for APEX
    - Robust W target
    - Vacuum – Metal O-rings on the beamline
    - Electronics – Dose reduction by a factor of 10 (neutrons)

Projected down time for APEX due to radiation < 7 %

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Results of sections 1 and 2

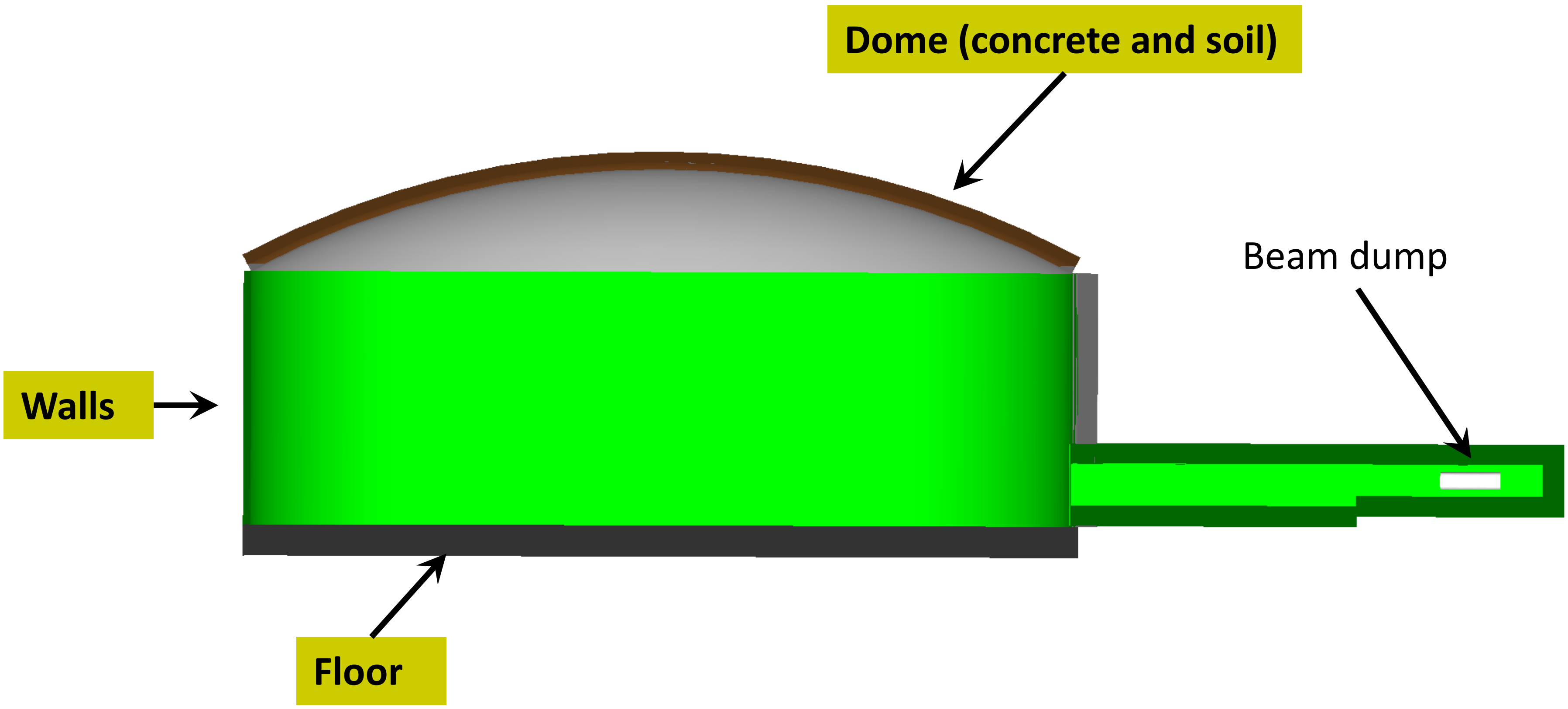
- APEX simulation shows that projected damage to HRS control electronics from neutrons is about factor of 10 lower than it was observed during PREX-I.

- APEX down time due to radiation induced electronic damage is projected to be below 7 %.

Geant4 model of JLab hall A – 1/5

List of components included in the model

- **Hall A floor, walls and dome**
- Hall A beam dump / water tank



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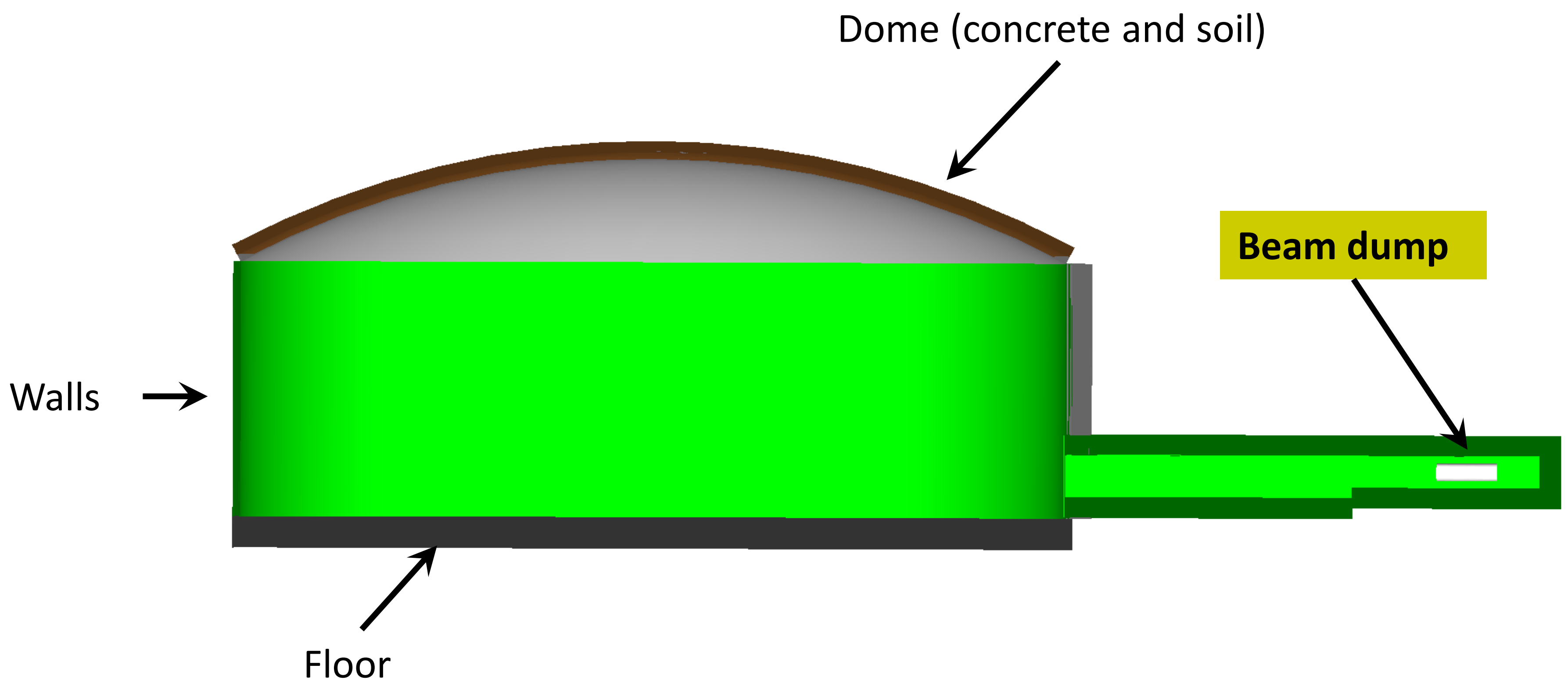

Geant4 model of JLab hall A – 2/5

List of components included in the model

- Hall A floor, walls and dome
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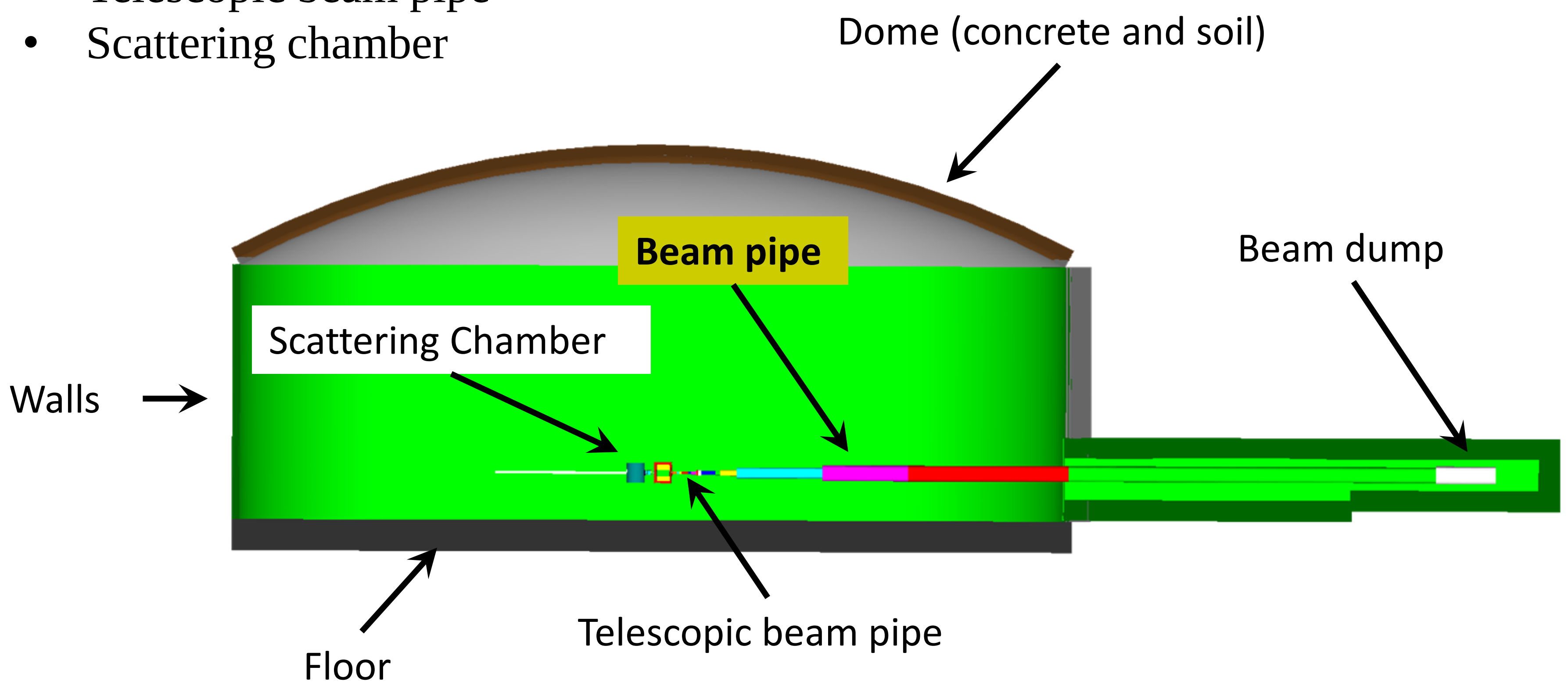
- **Hall A up/down stream beam pipe**
- Telescopic beam pipe
- Scattering chamber



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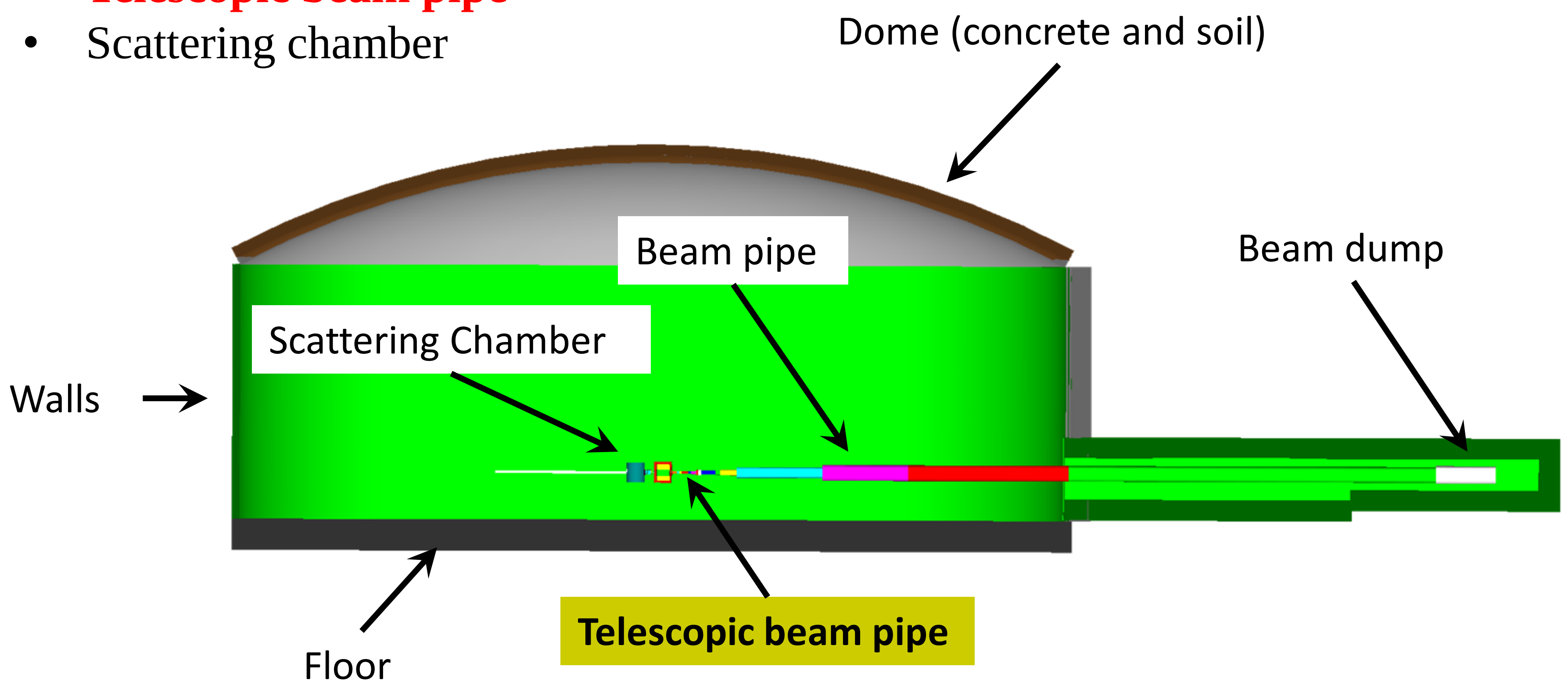

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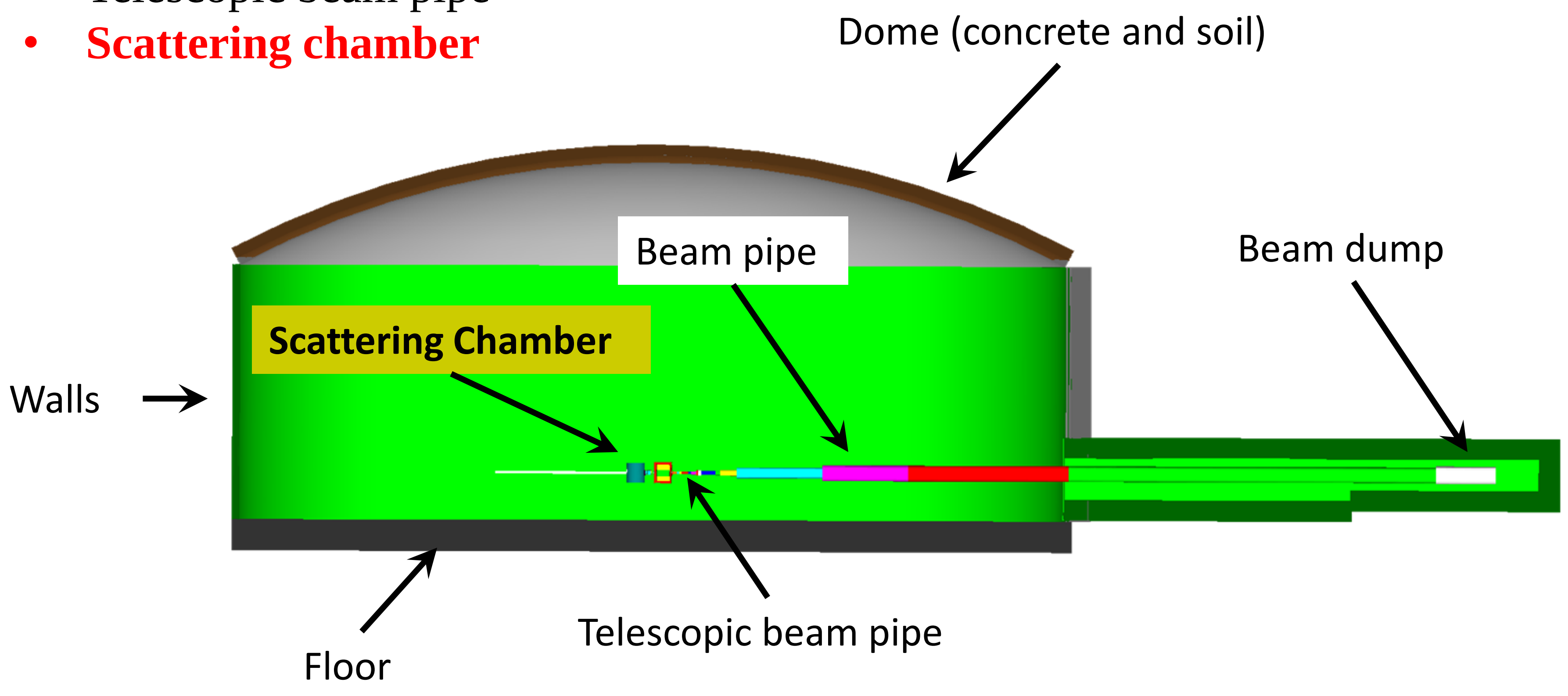

Geant4 model of JLab hall A – 3/5

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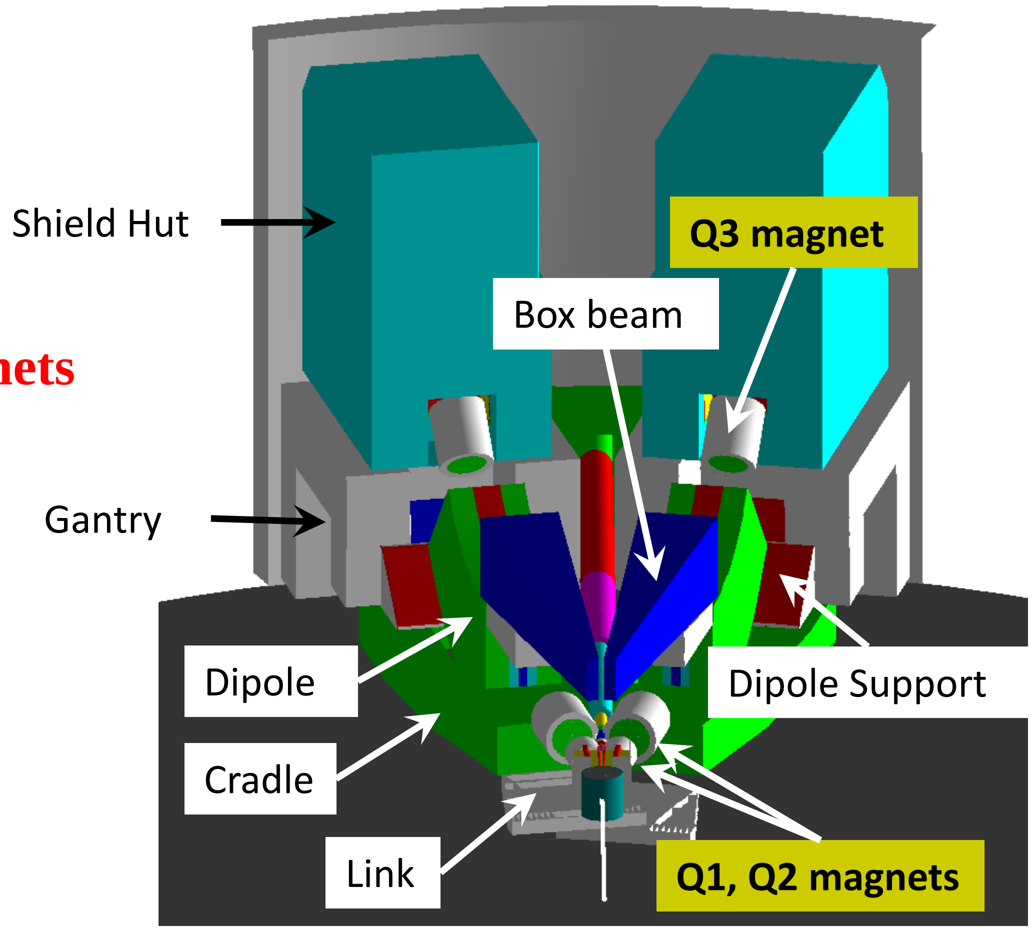
- **Q1, Q2 and Q3 quadrupole magnets**
- HRS Dipole magnet
- HRS Dipole support
- HRS Link
- HRS Cradle
- HRS Gantry
- Shield hut
- Front section of the box beam with line of sight shielding



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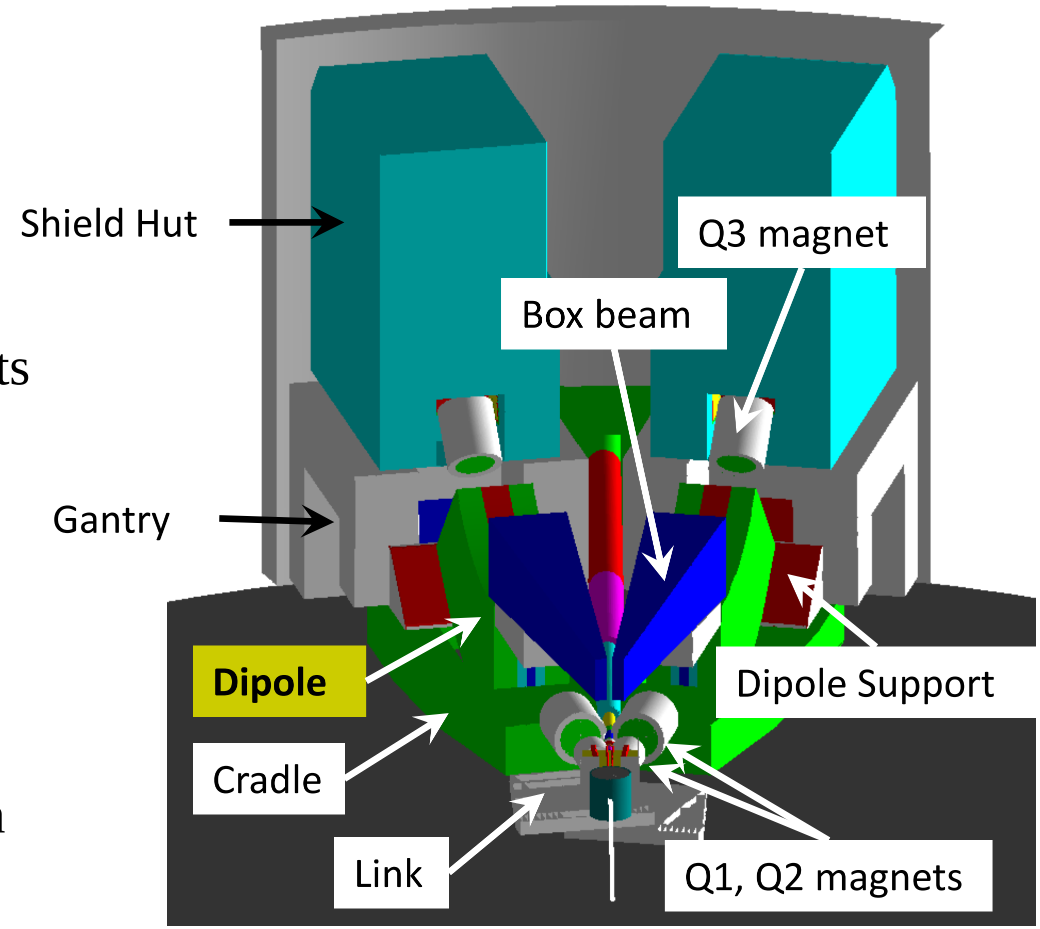

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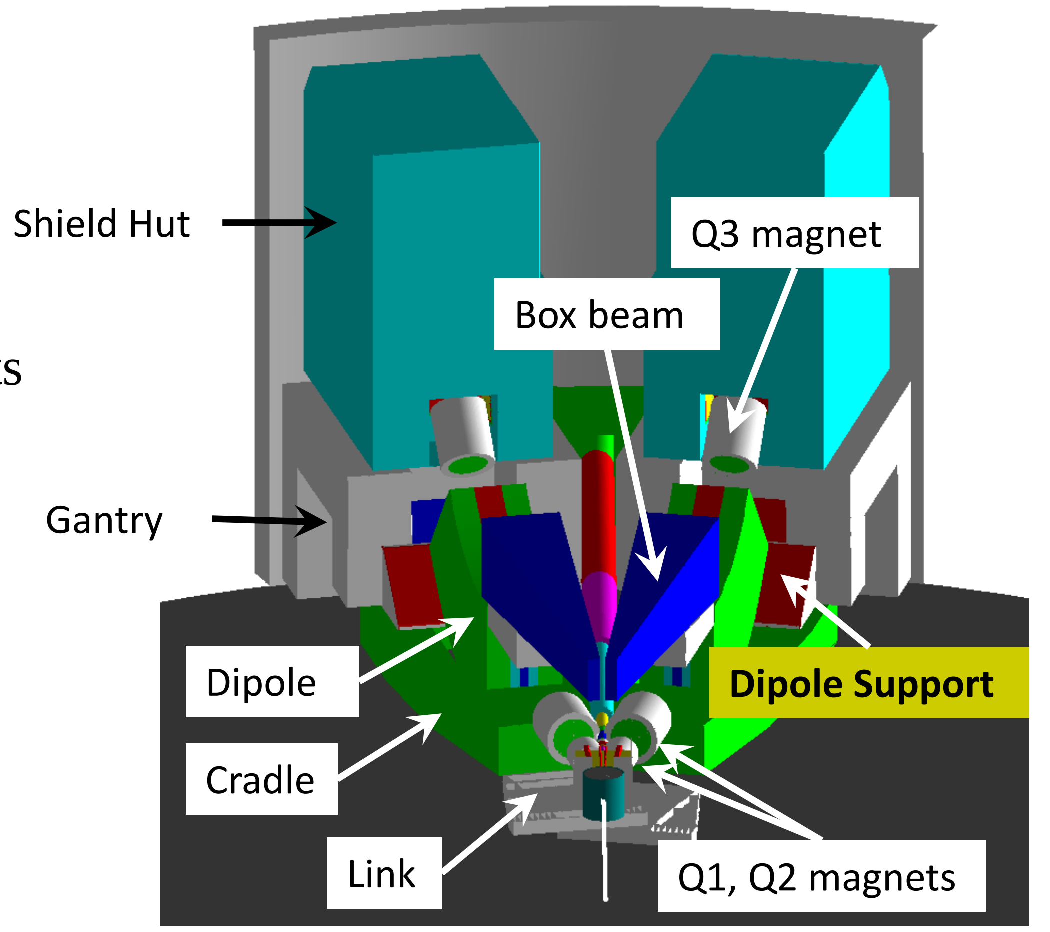

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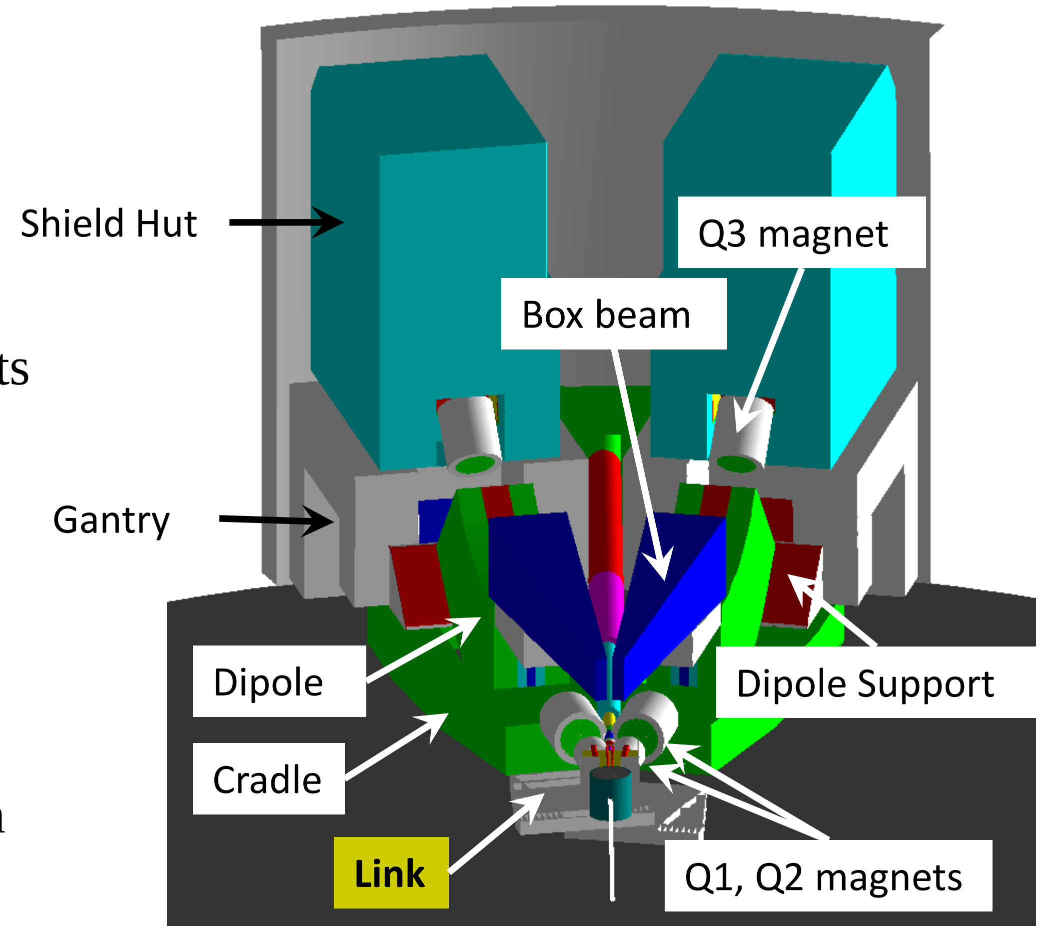

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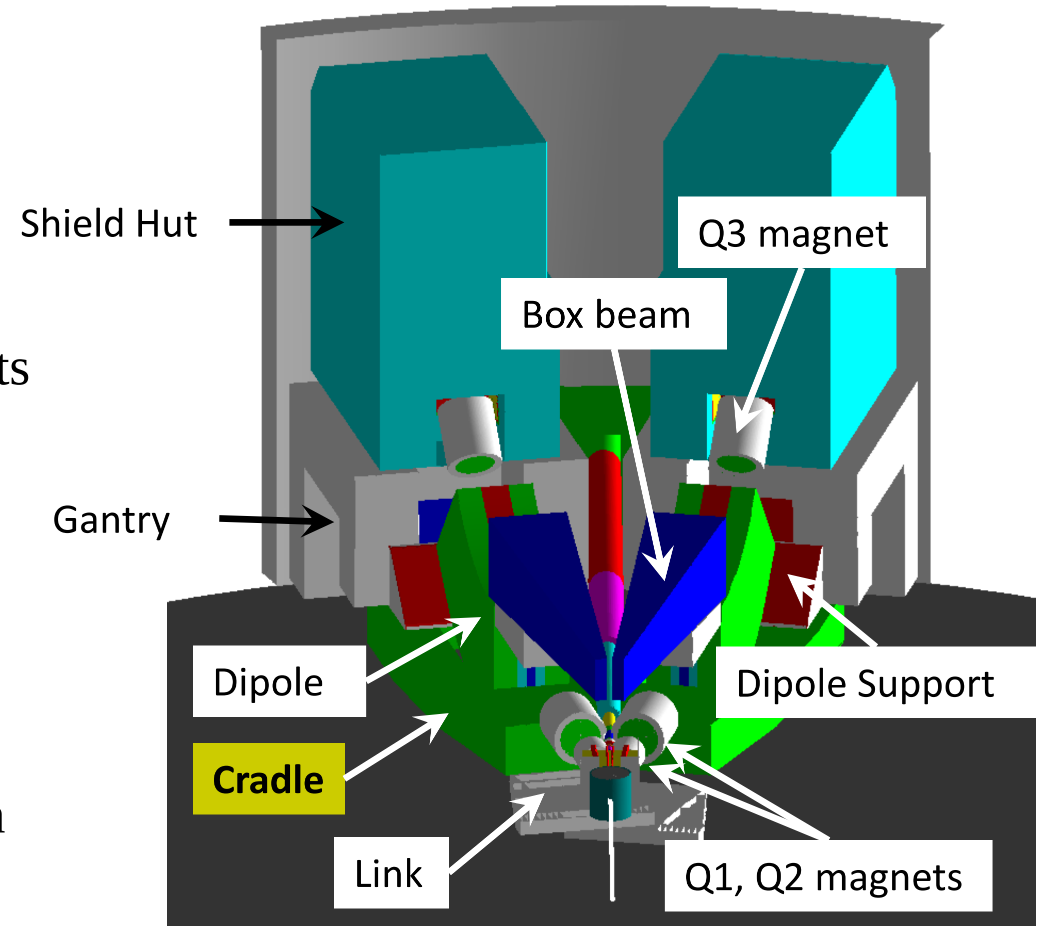

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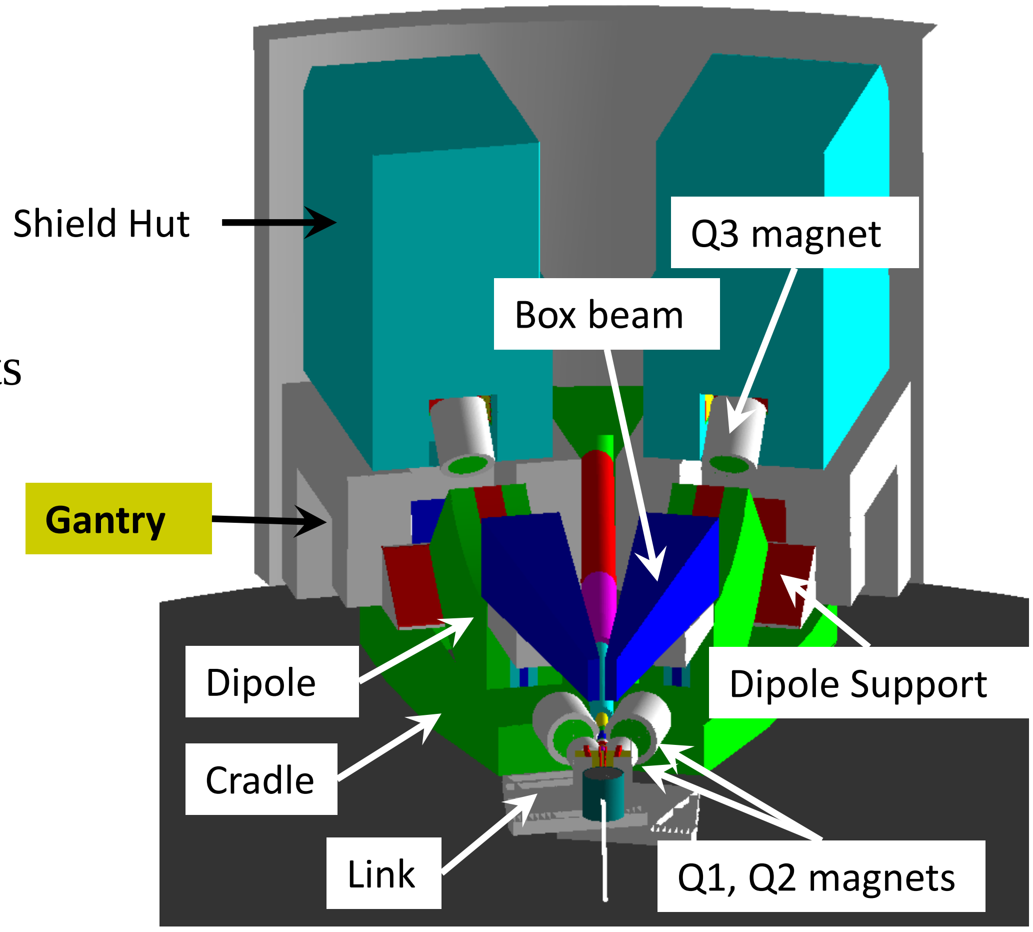

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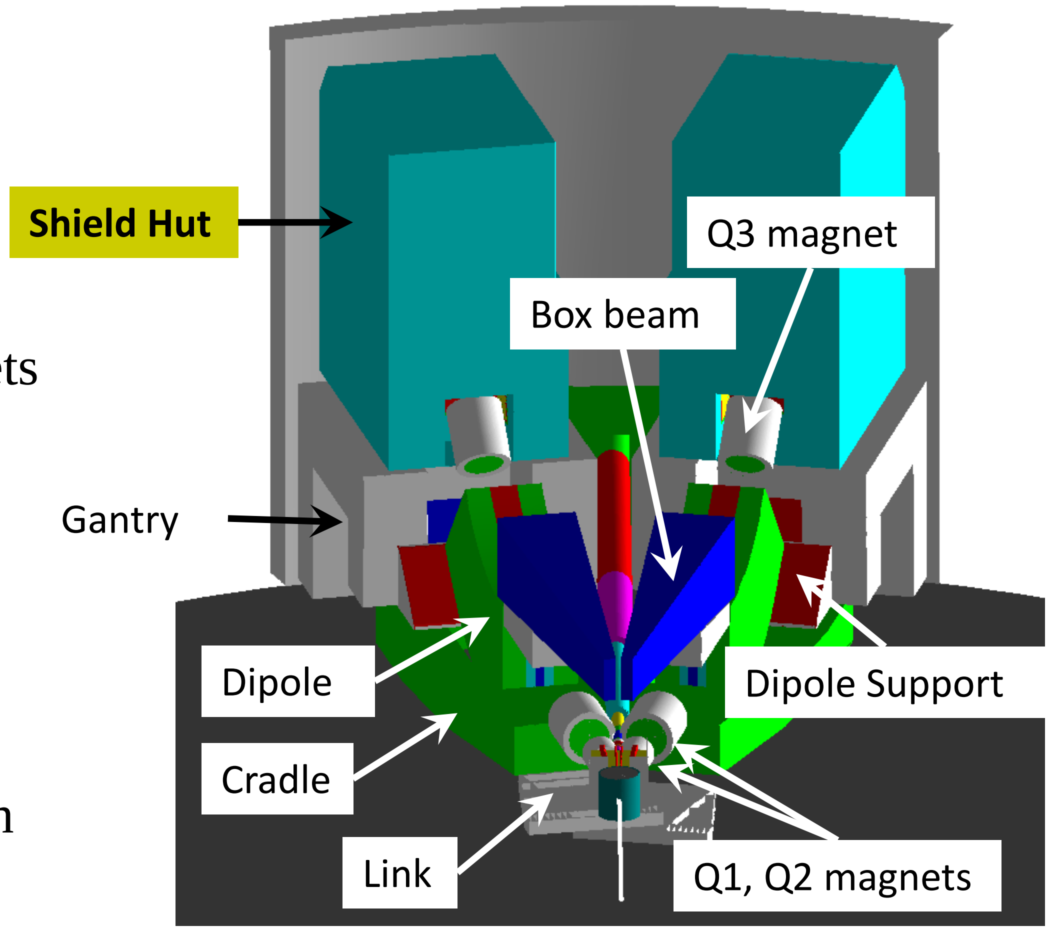

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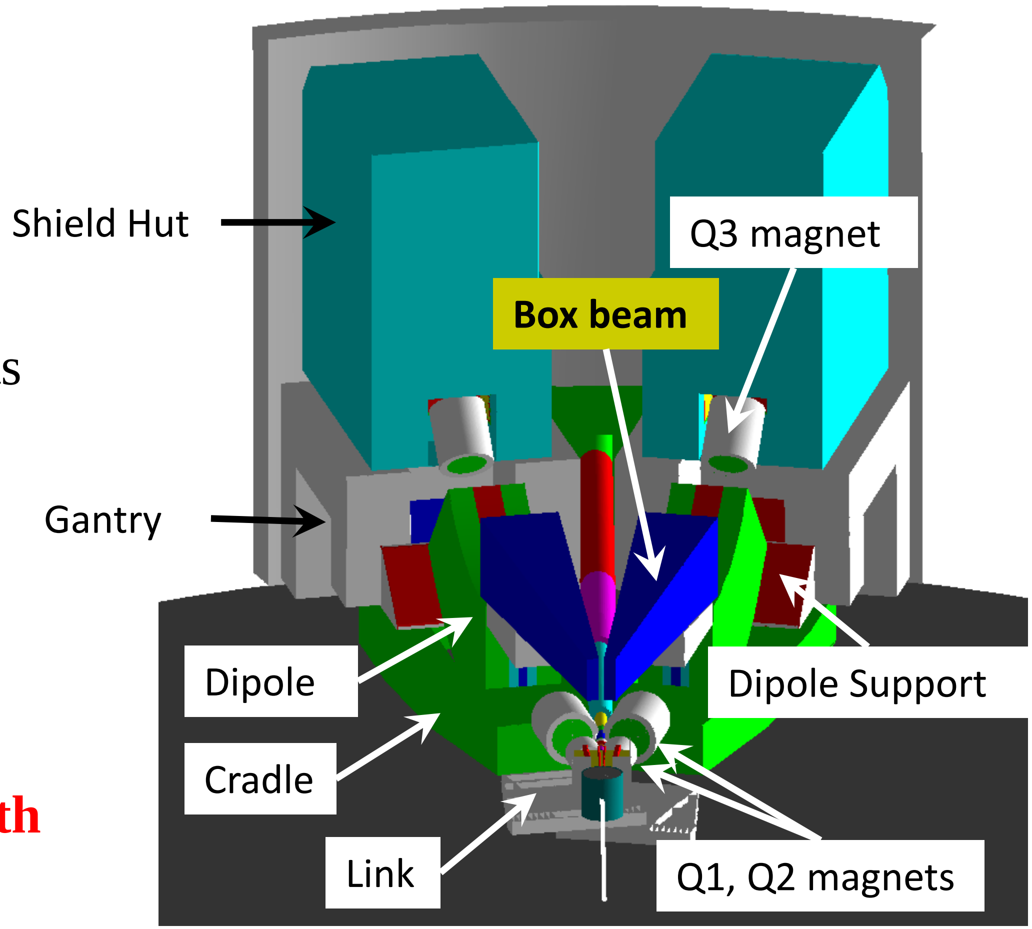
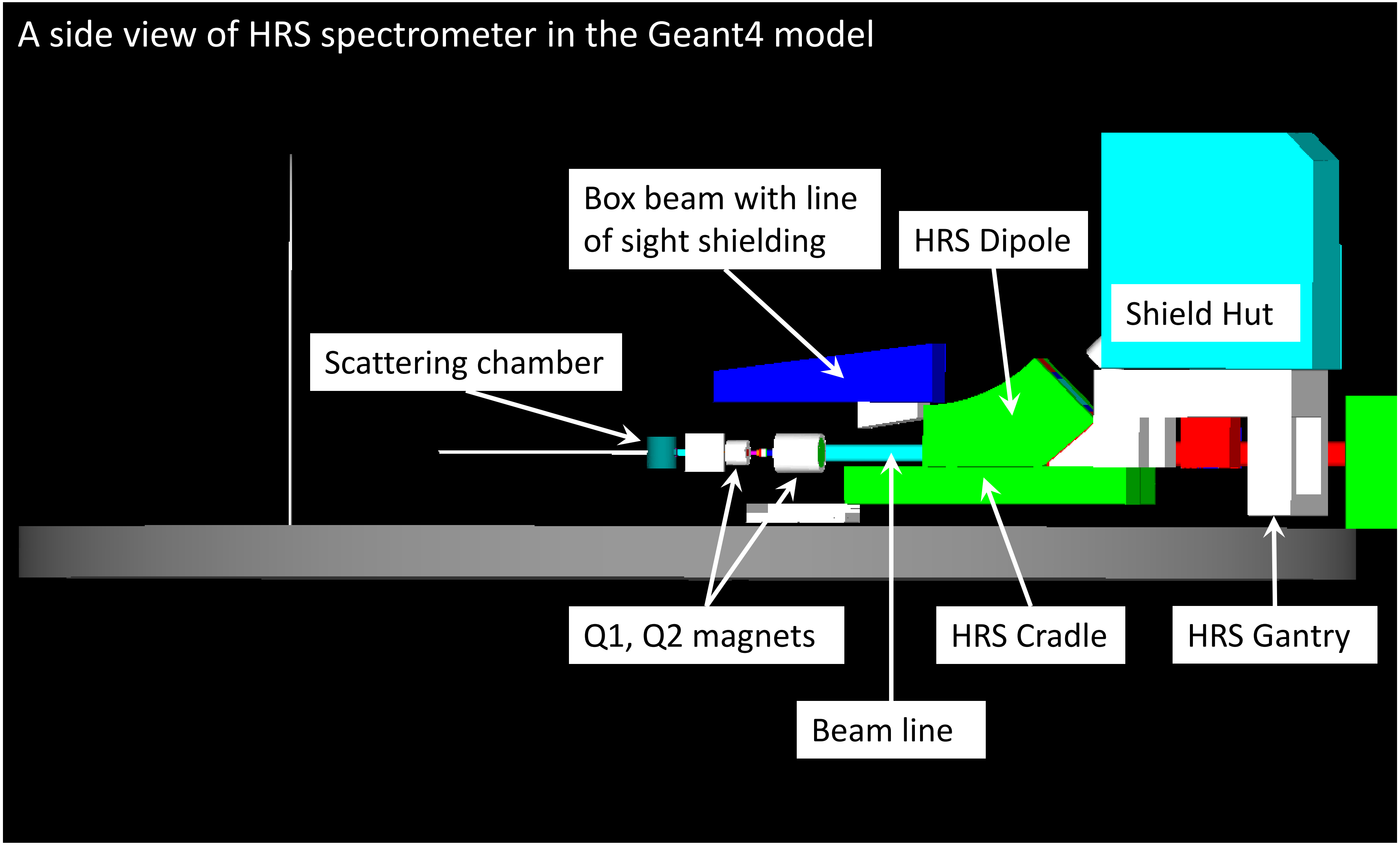


Geant4 model of JLab hall A – 4/5

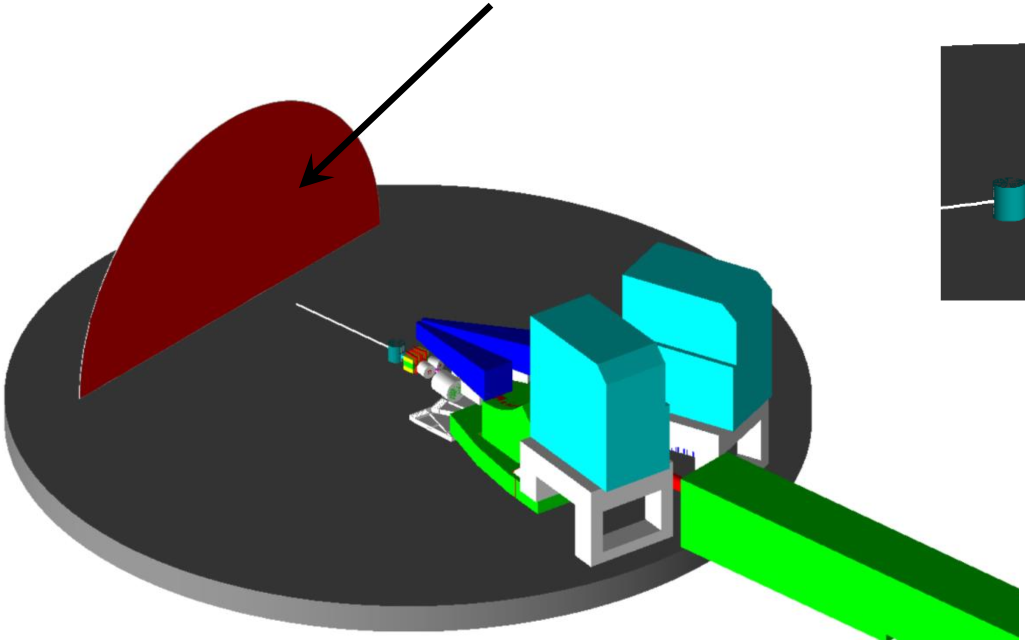


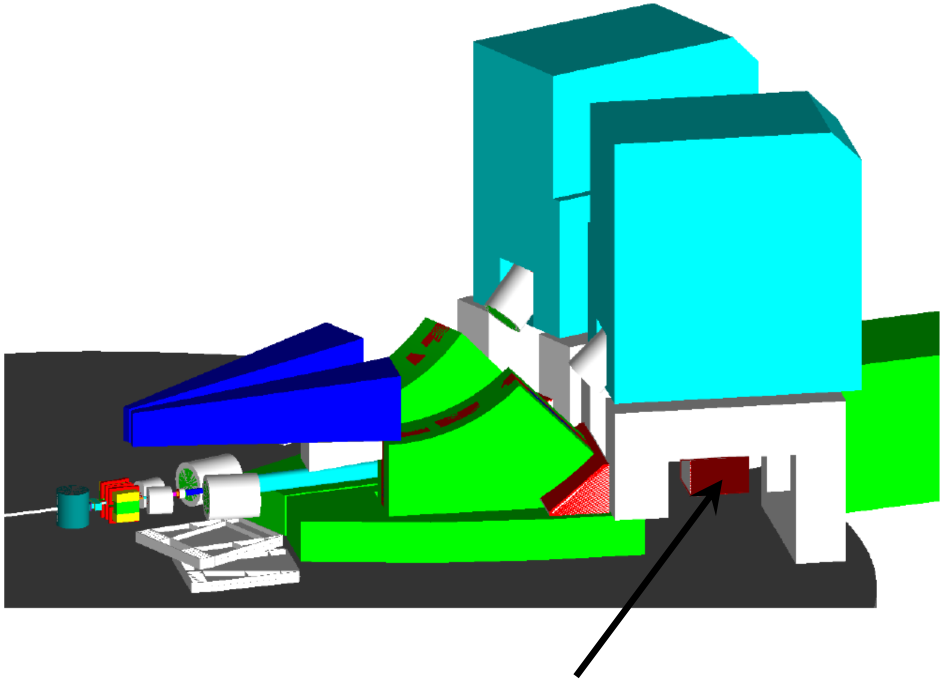
Geant4 model of JLab hall A – 5/5

There are two main "sensitive volumes" where radiation levels were evaluated.

A semi-circle with 15 m radius located 16 m upstream.

Thickness: 5 cm
Material : Plastic Scintillator





2m x 2m x 2m box placed close to HRS control electronics.

Material : Plastic Scintillator

Geant4 model of JLab hall A – 5/5

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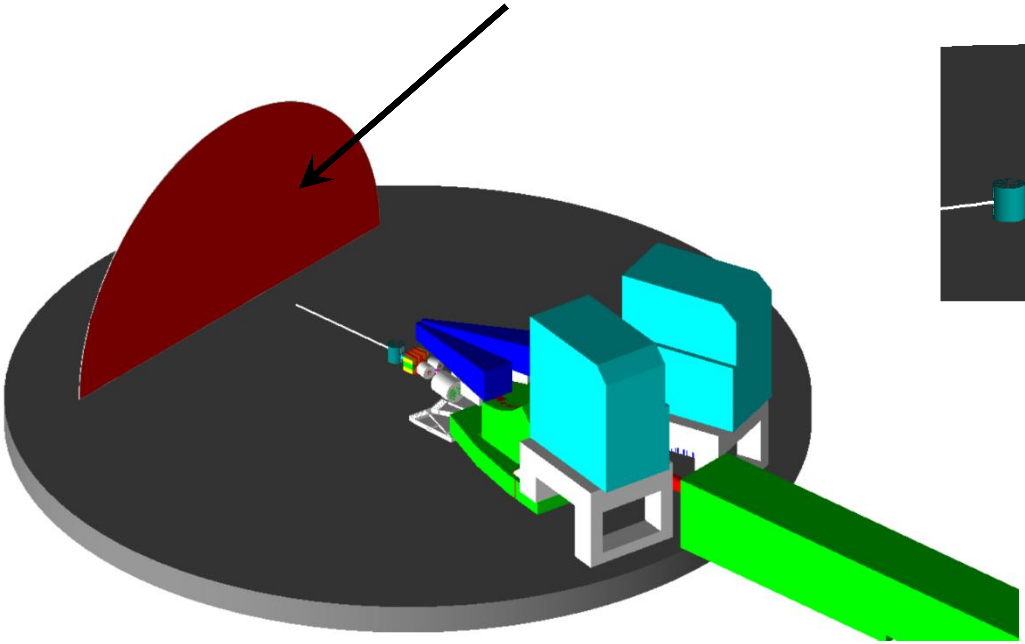

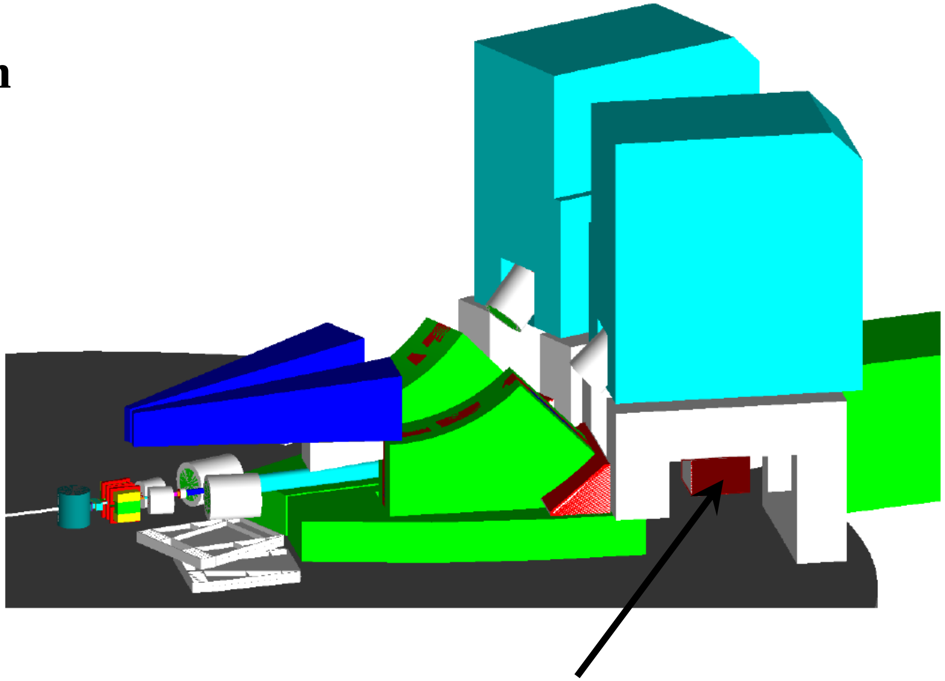

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Geant4 model of JLab hall A – 5/5

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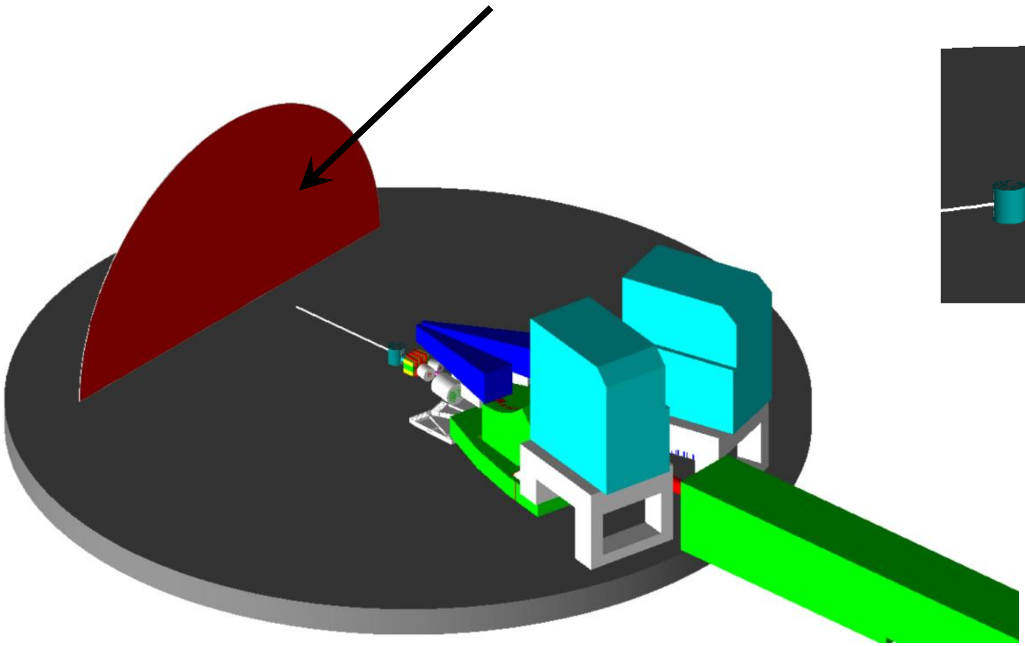

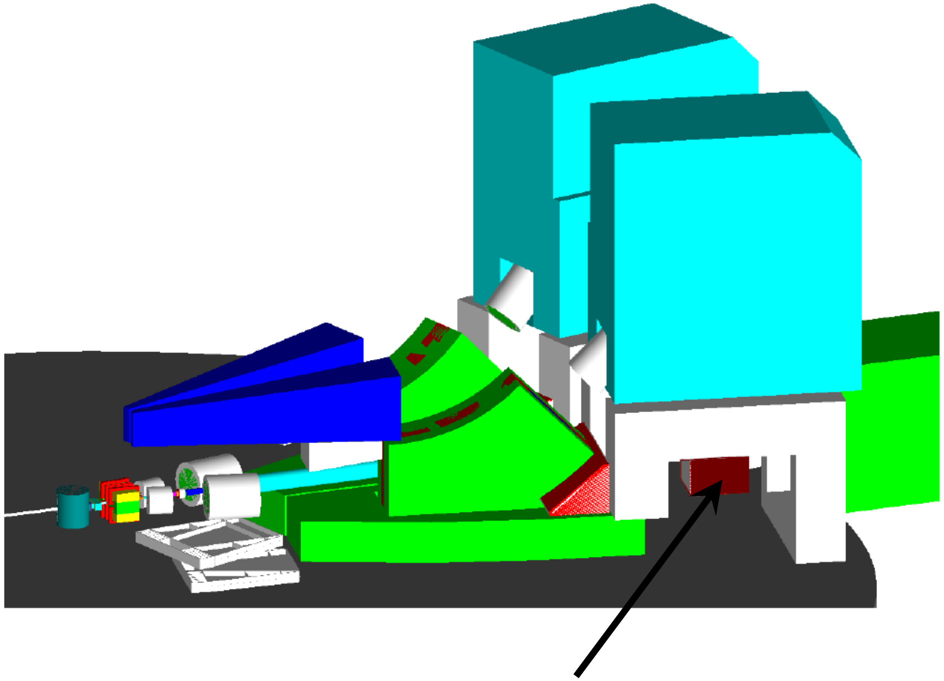

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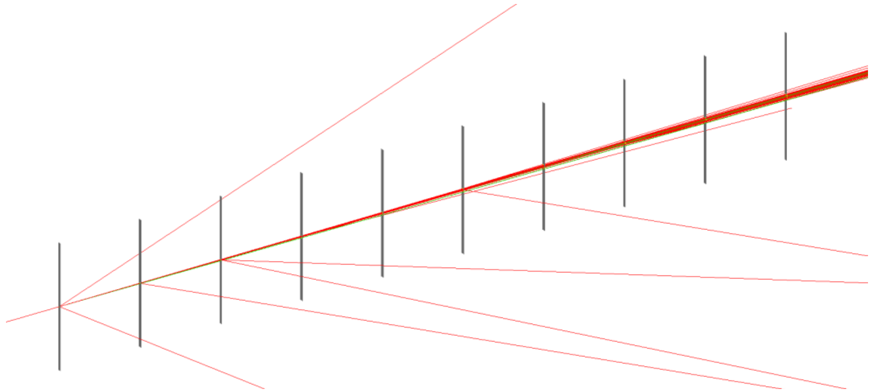
Overview of APEX - 1/4



APEX target structure

Beam energy and total target thickness

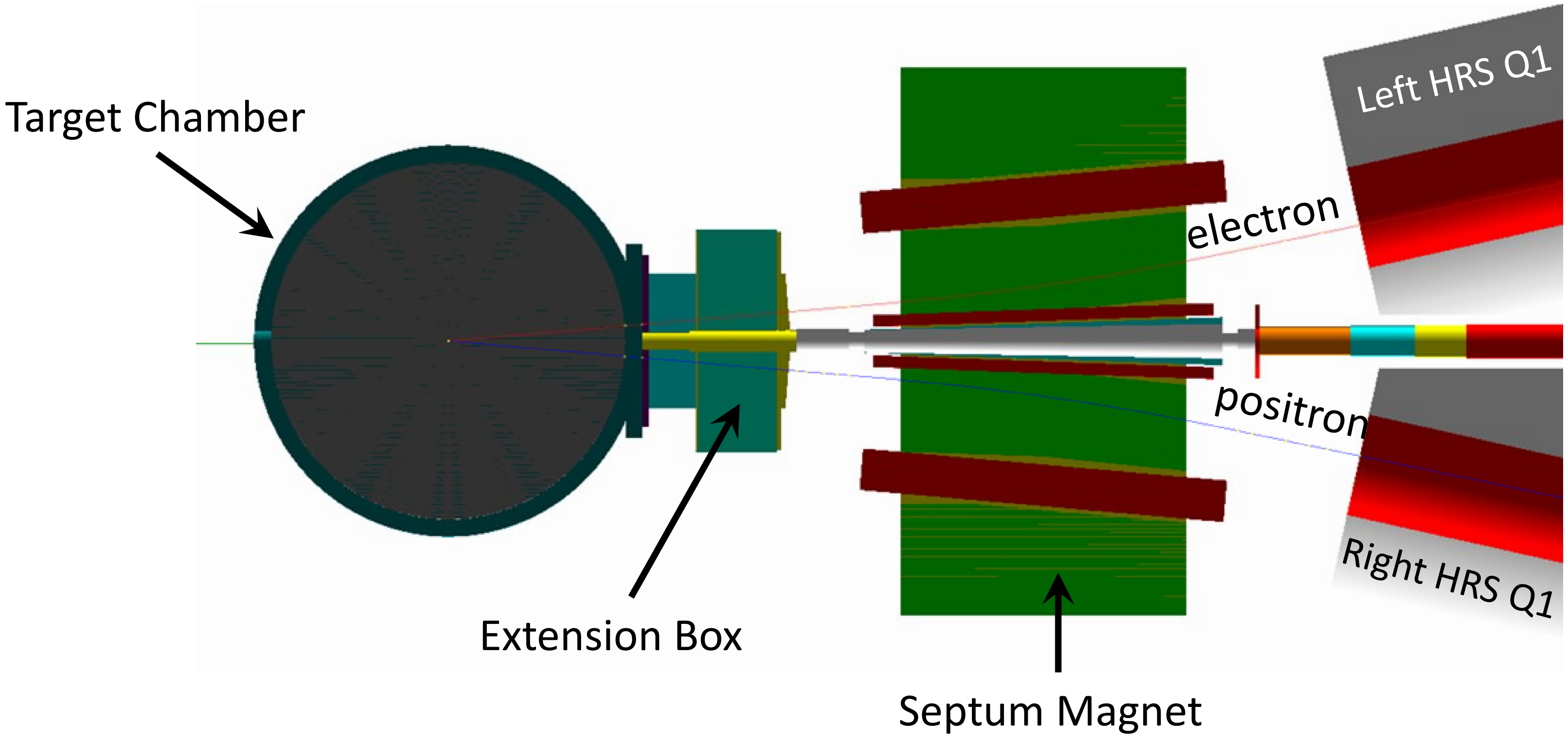
APEX, 1.1 GeV 50 μA	Carbon 0.7 % r.l. 300 mg / cm^2
APEX, 2.2 GeV 100 μA	Tungsten 2.8 % r.l. 190 mg / cm^2
APEX, 3.3 GeV 120 μA	Tungsten 5.3 % r.l. 360 mg / cm^2
APEX, 4.4 GeV 90 μA	Tungsten 5.3 % r.l. 360 mg / cm^2

APEX target consists of 10 flat ribbons which are **separated by 5.5 cm.**

Each ribbon is **8 cm in height** and **2.5 mm in width**. Different target thicknesses used for different run plans are shown in the table.

Overview of APEX - 2/4

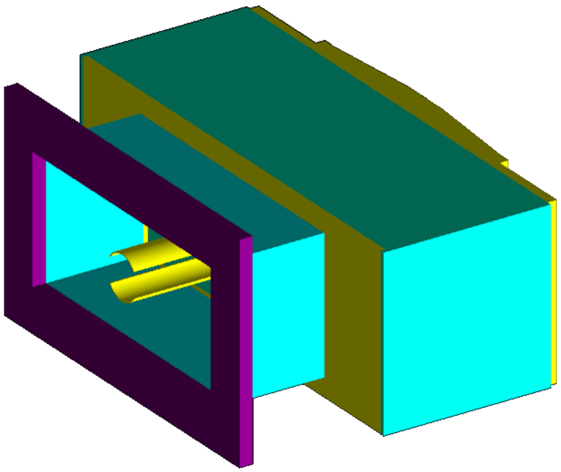
Beamline components included in APEX simulation

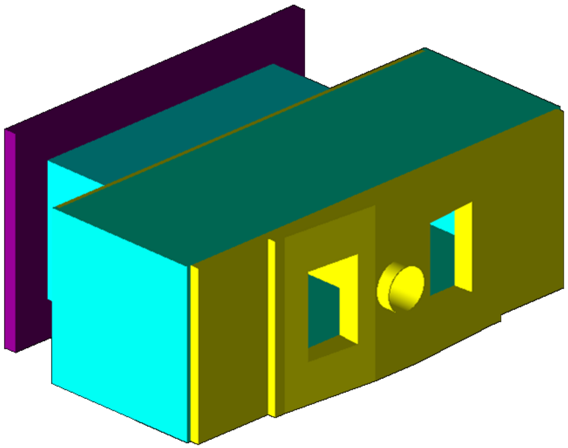


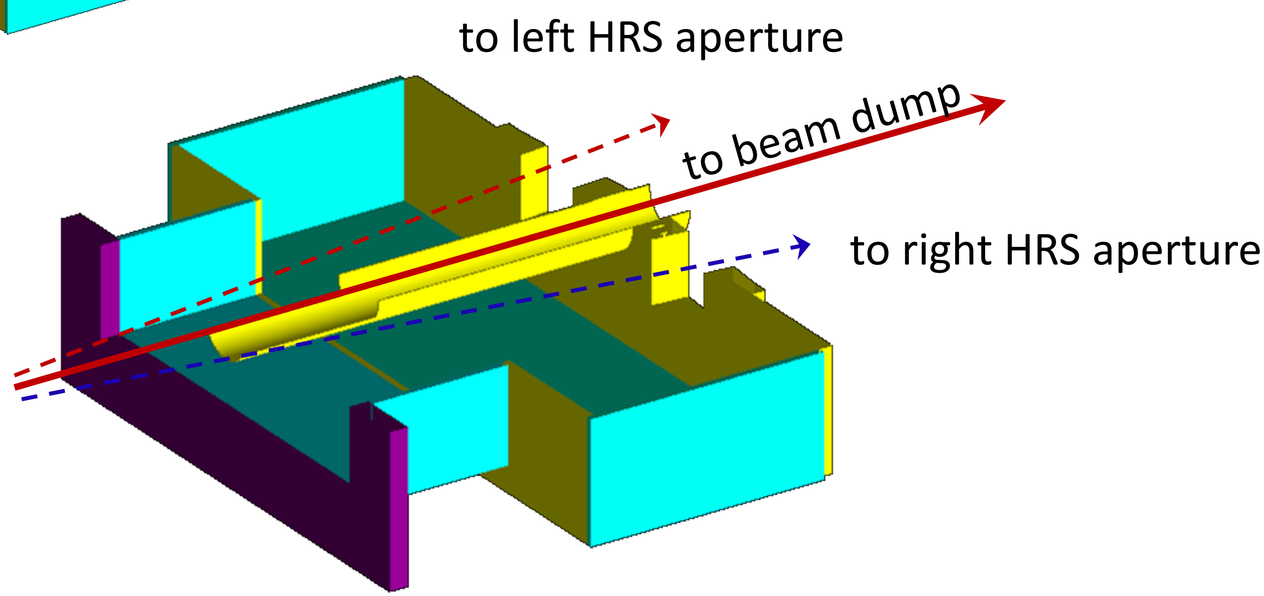
- APEX Extension Box
- APEX Septum Magnet with TOSCA field map
- HRS: positioned at 12.5°

Overview of APEX - 3/4

APEX extension box





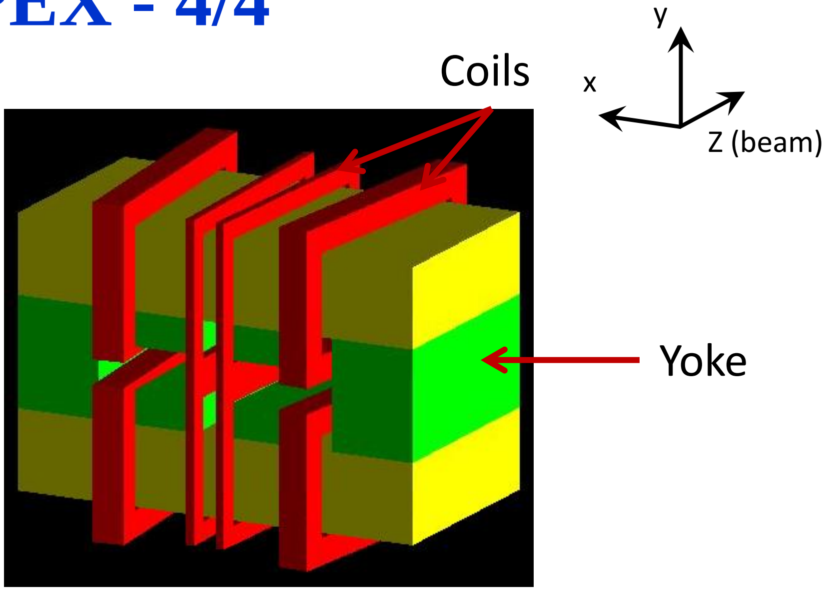


Overview of APEX - 4/4

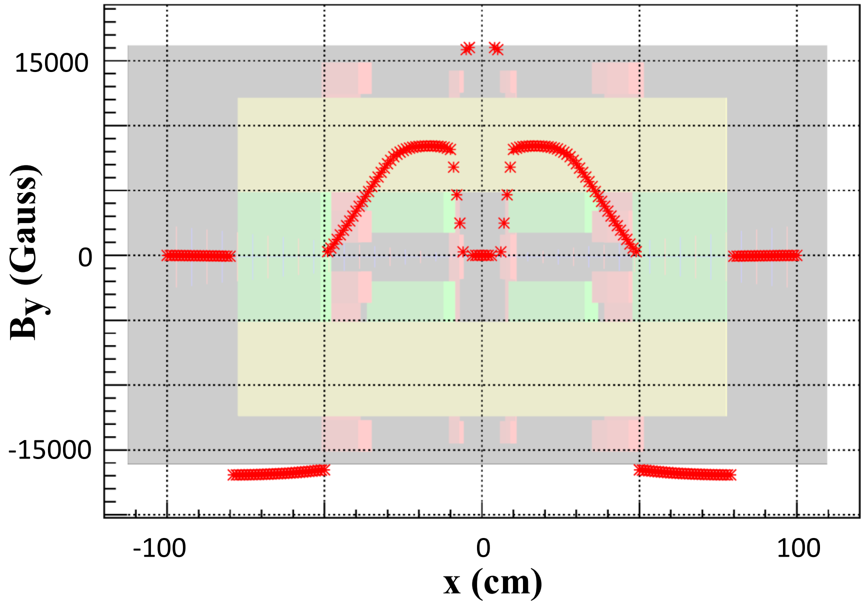
- APEX septum magnet spans across

  160 cm in x direction
  150 cm in y direction
  115 cm in z direction

- The TOSCA field map used in GEANT4 simulation, covers this entire region of the magnet.



A view of the APEX septum magnet from the target position.



Plot shows magnetic field component B_y along the x axis at y=0 and z=0.

Radiation dose calculations – 1/8

- **We evaluated biological damage due to radiation because of its convenience of reference and existing measurements were in units of biological damage.**

- We followed two methods to calculate radiation dose.

  Method1: Deposited energy in plastic scintillator was converted to biological damage dose (the method described here).

  Method2: Particle fluence was converted to biological damage dose using standard fluence-to-dose conversion coefficients in International Commission on Radiological Protection (ICRP) Publication 21.

  (see backup slides)

- Both methods were discussed with Pavel Degtiarenko at JLab Radiation Control Department.

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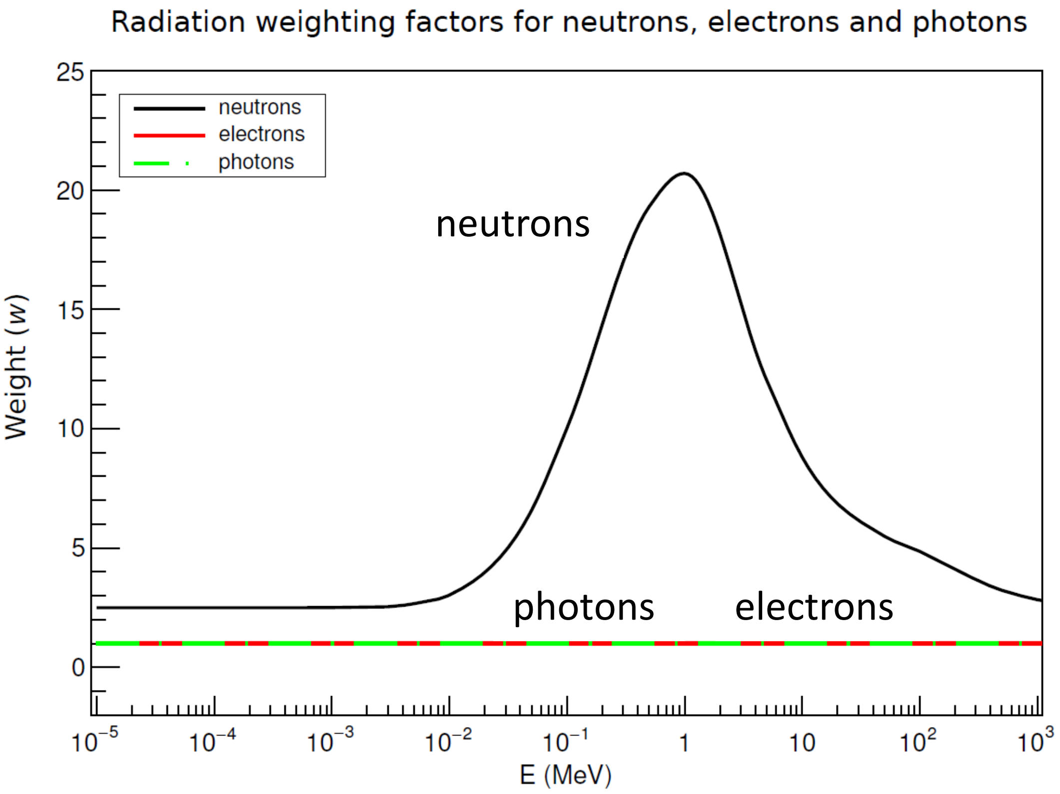
Radiation dose calculations – 2/8

- **Absorbed dose (in units of rad) was calculated using the deposited energy in plastic scintillator.**

- Absorbed dose in plastic scintillator was converted to biological damage dose (rem) using the relative biological effective factors shown in the plot.

Biological damage is a function of specific radiation type and its energy.



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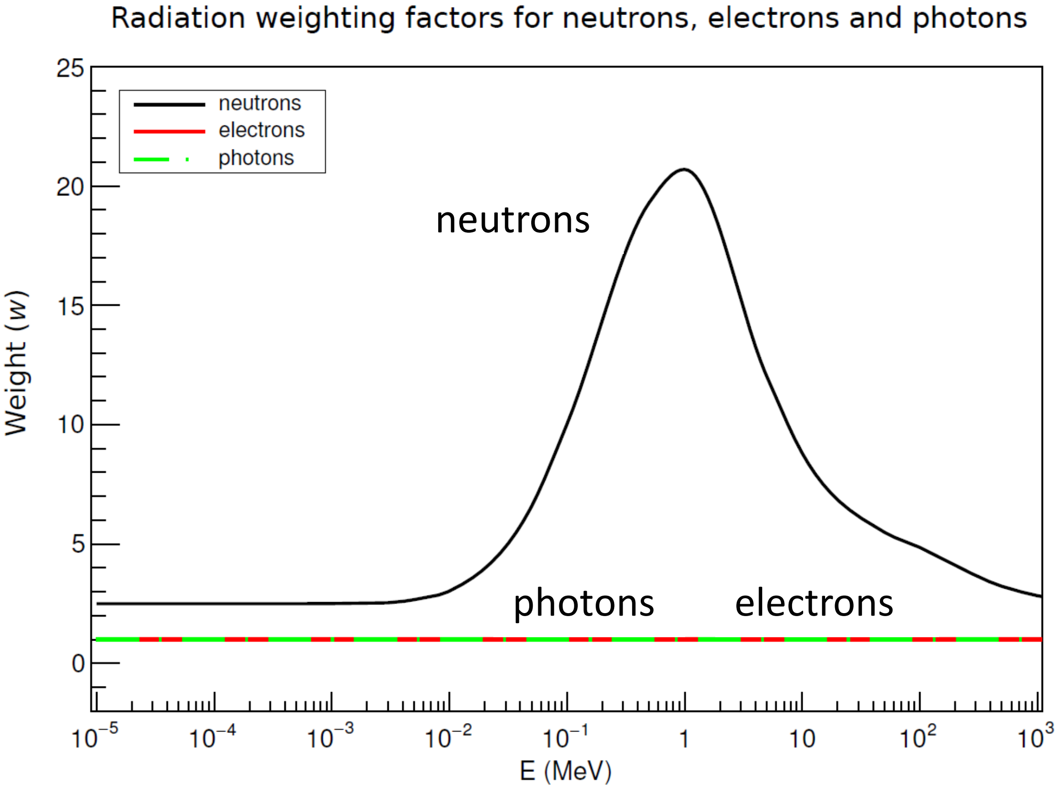
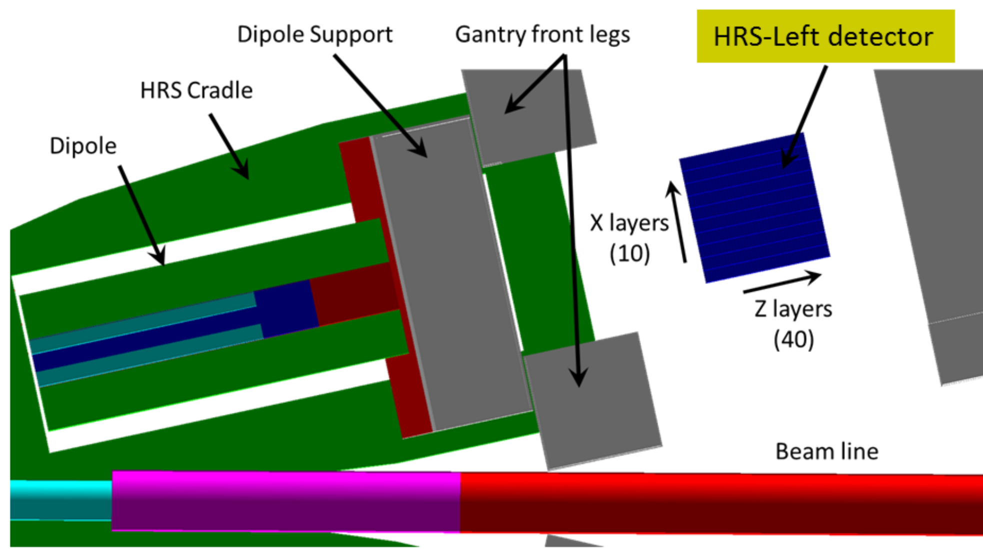


Radiation dose calculations – 3/8

- **During PREX-I the highest radiation damage was observed in HRS control electronics.**
- To study the dose distribution within the HRS-Left detector (2 m ×2 m ×2 m box), it was split in to 400 smaller boxes.
- There are 10 layers in X direction and 40 layers in Z direction.



Top view of left HRS in GEANT4 model (cross section)

Radiation dose calculations – 3/8

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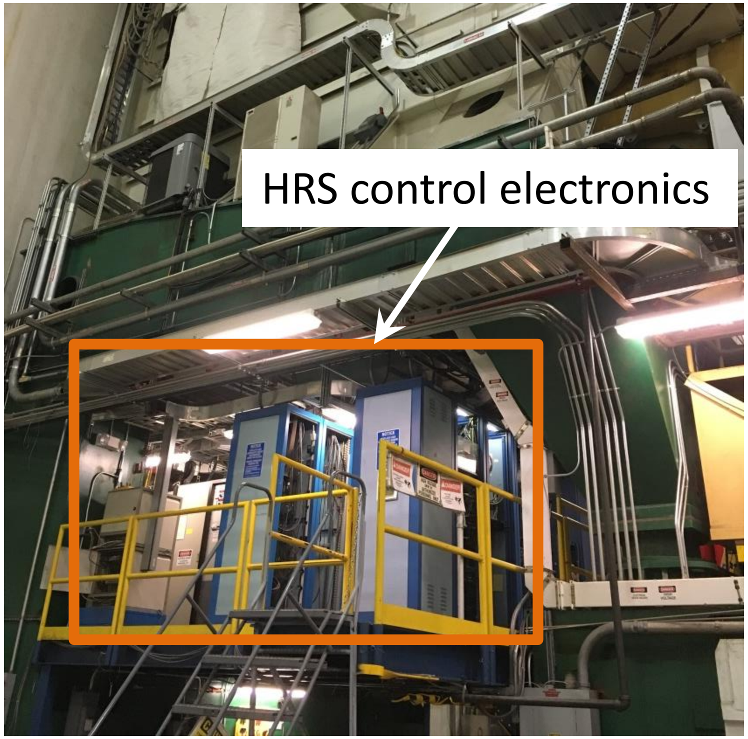

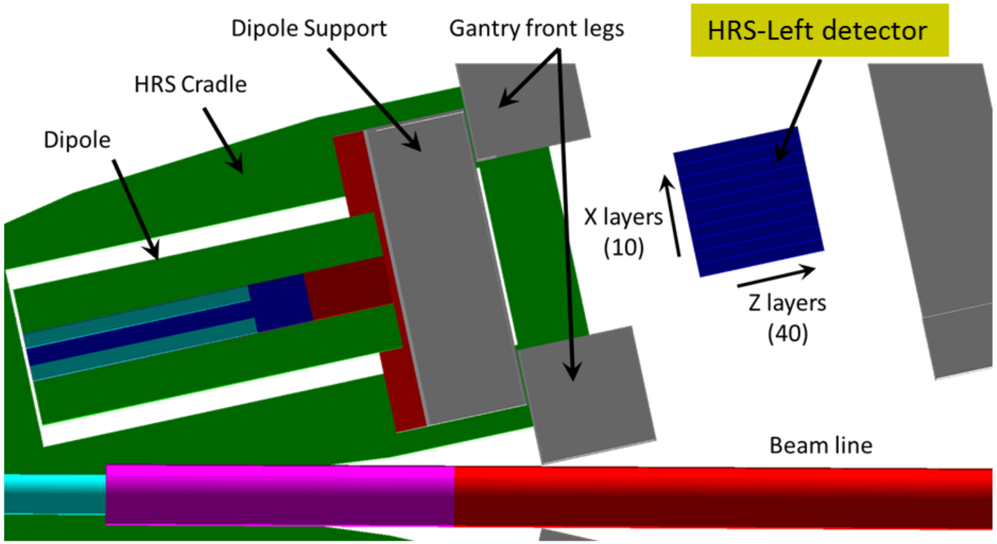

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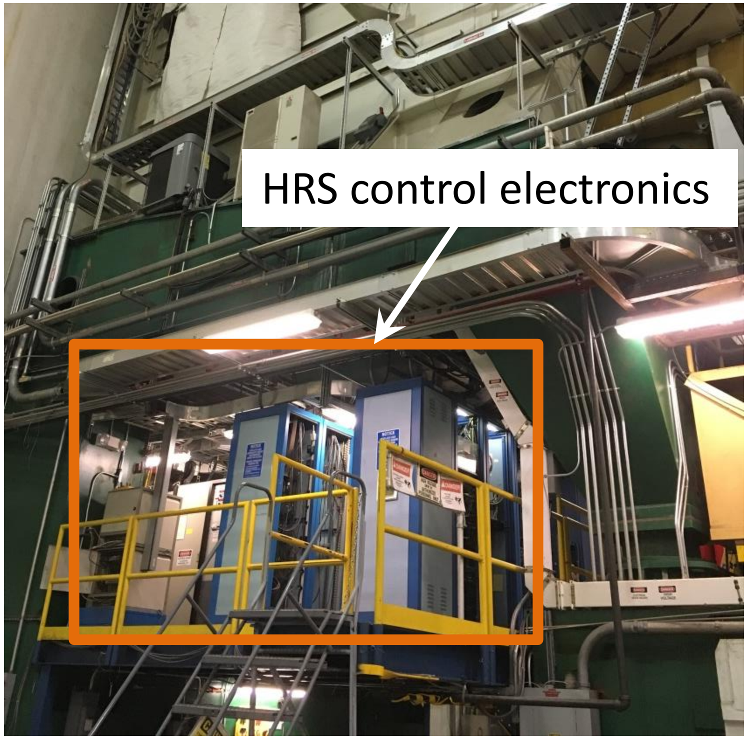
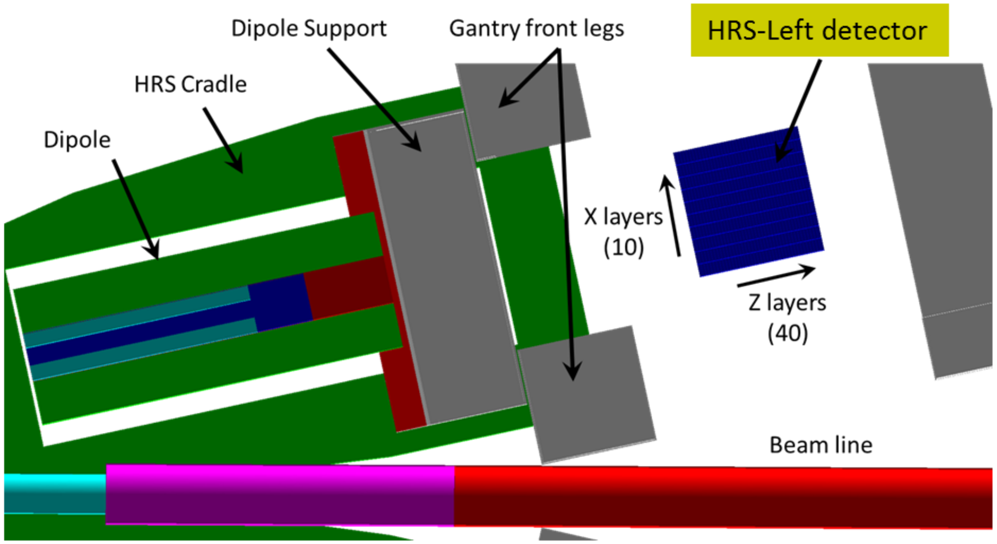
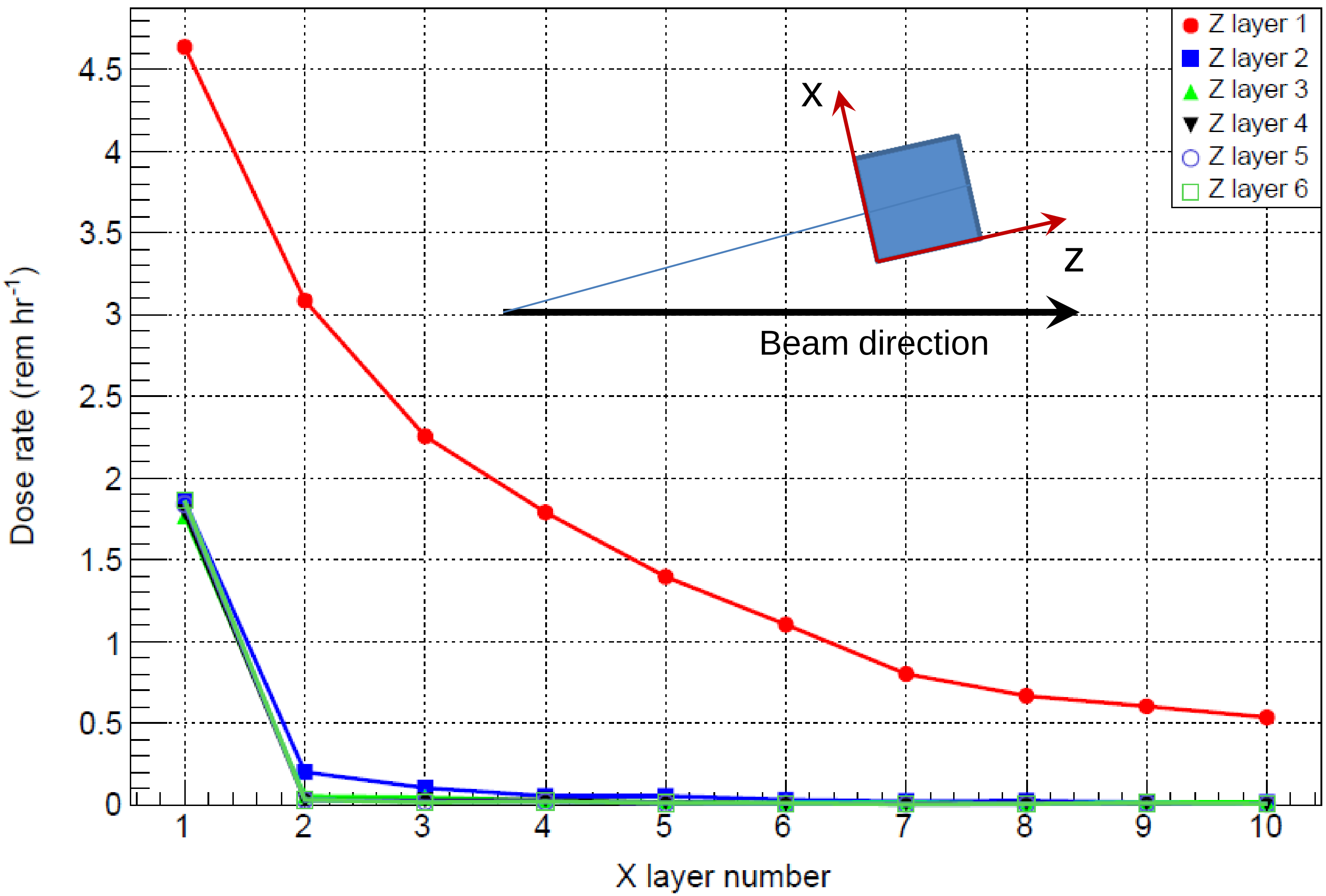




Top view of left HRS in GEANT4 model (cross section)

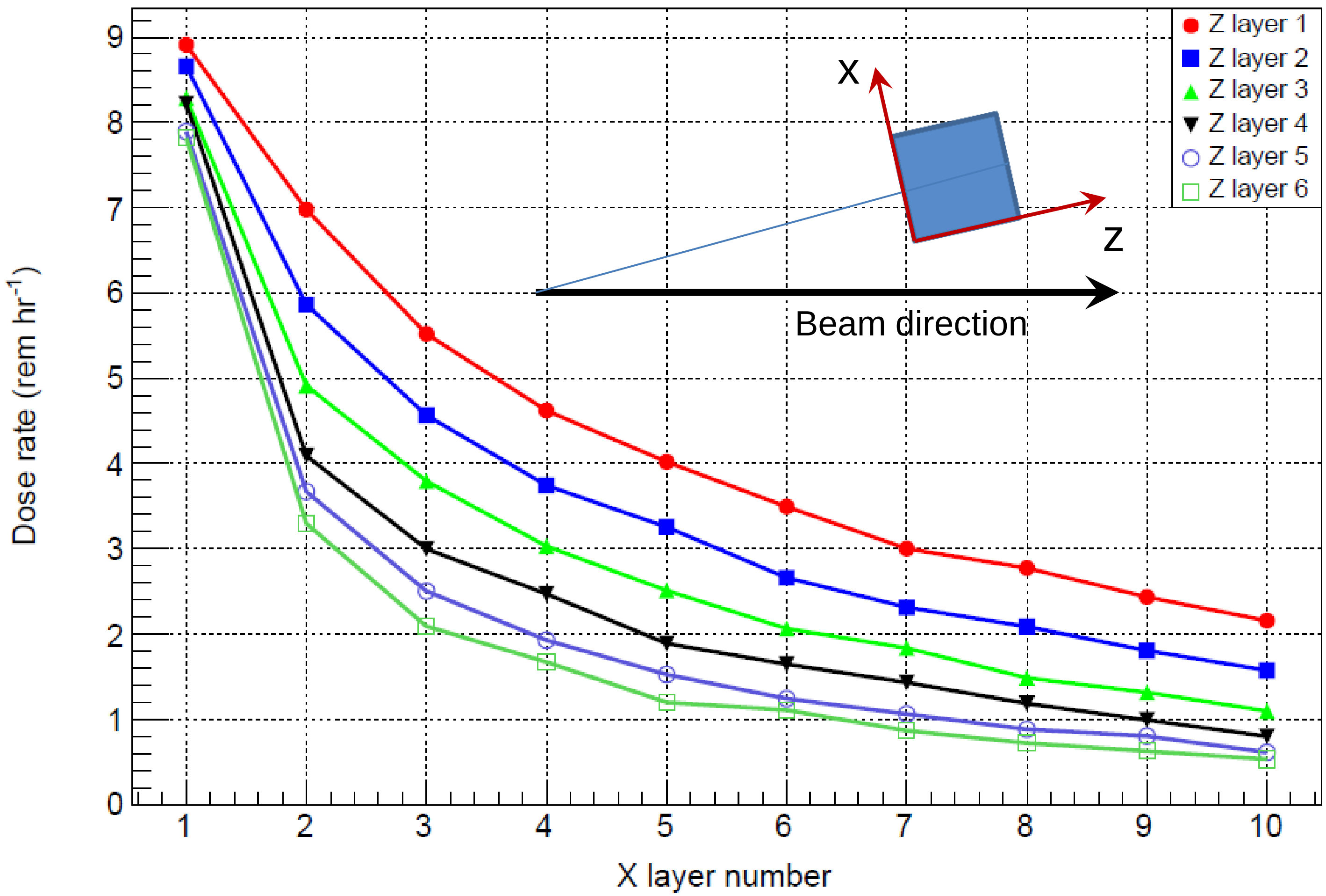
Radiation dose calculations – 4/8

Electron dose rate distribution within HRS-left detector volume for APEX 3.3 GeV setting.



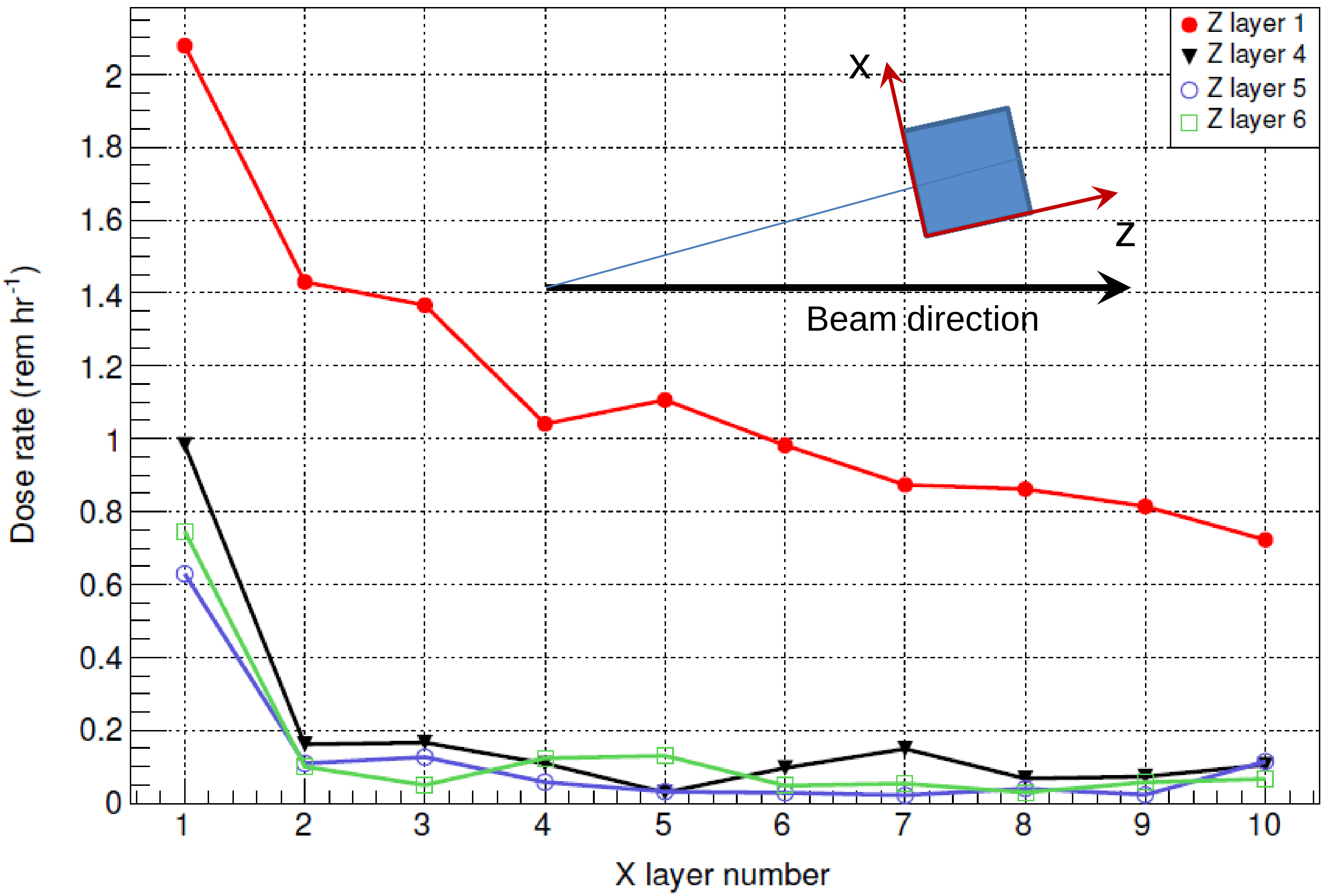
Radiation dose calculations – 5/8

Photon dose rate distribution within HRS-left detector volume for APEX 3.3 GeV setting.



Radiation dose calculations – 6/8

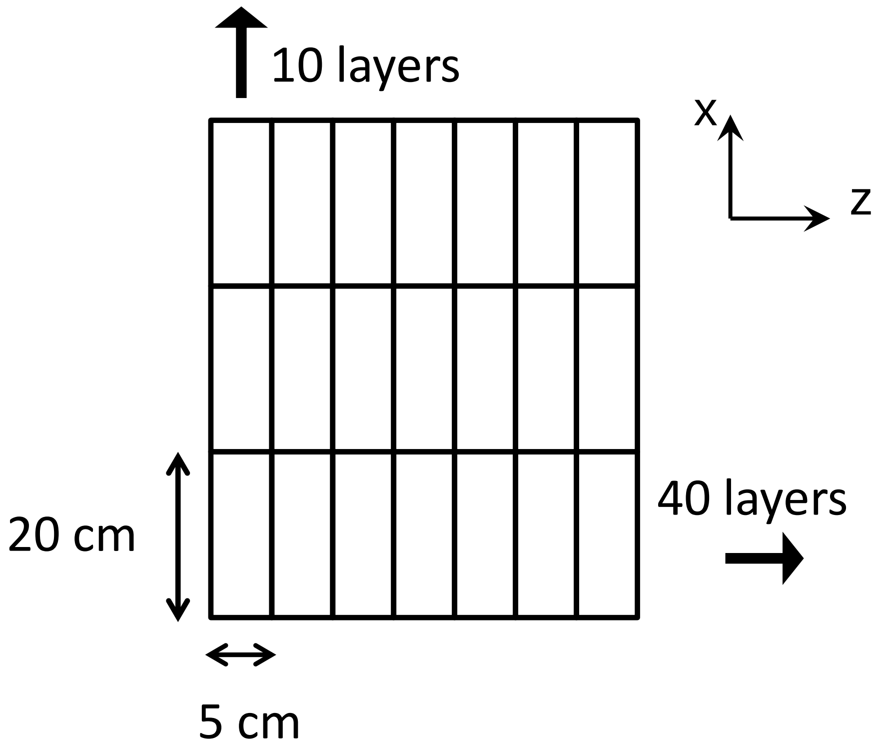
Neutron dose rate distribution within HRS-left detector volume for APEX 3.3 GeV setting.



Radiation dose calculations – 7/8

- **According to previous plots that most of the energy was deposited within the 1st layers in x and z direction.**

- To calculate average dose in HRS-left detector volume, deposited energy only in these two layers were considered.



Radiation dose calculations – 7/8

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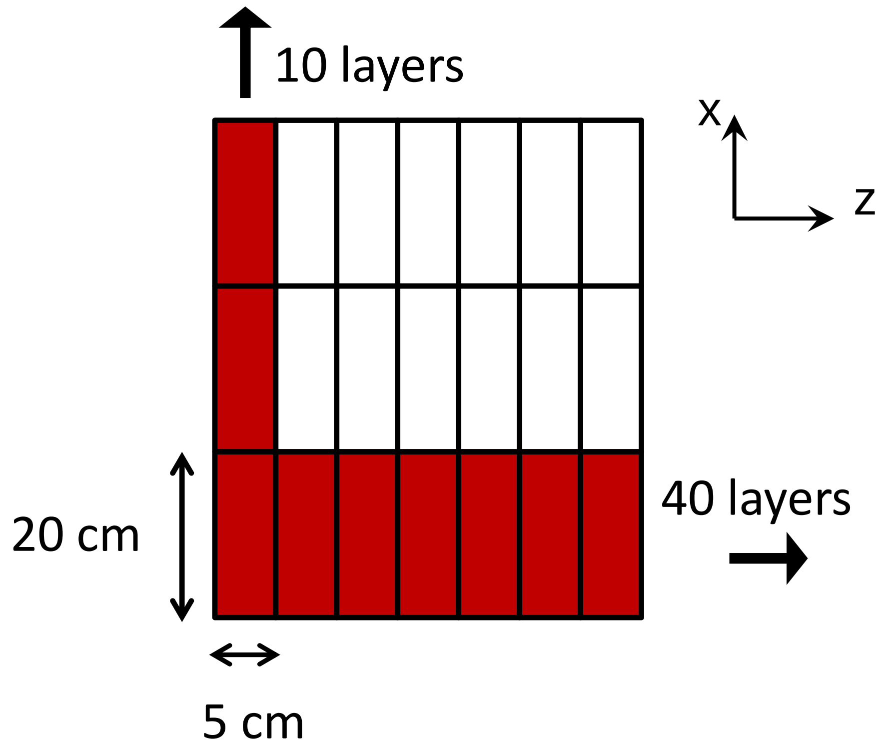

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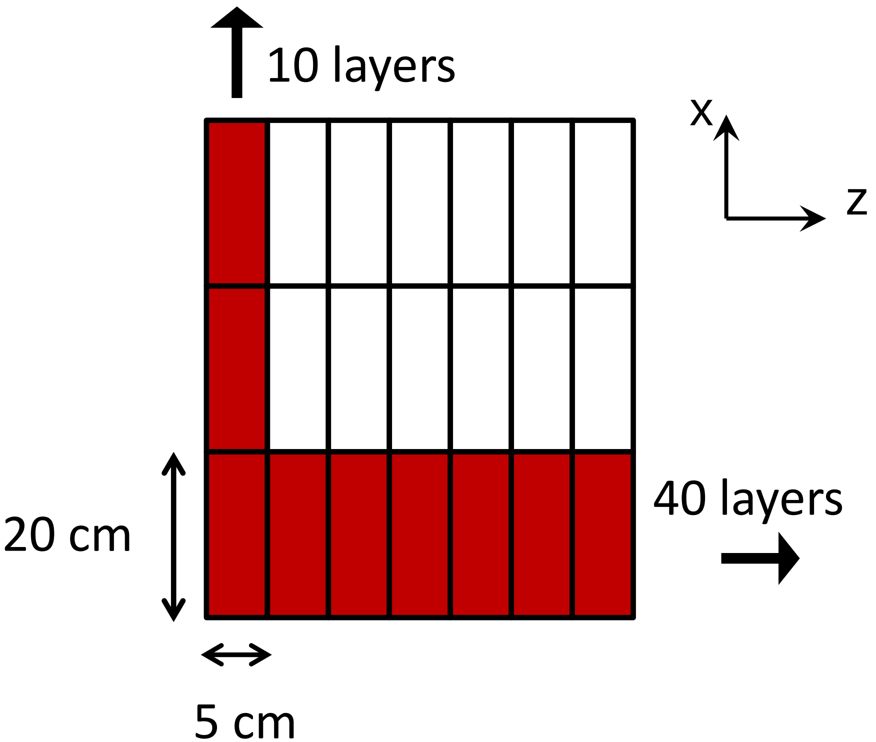
- We considered total deposited energy in these 49/400 small boxes to calculate dose.



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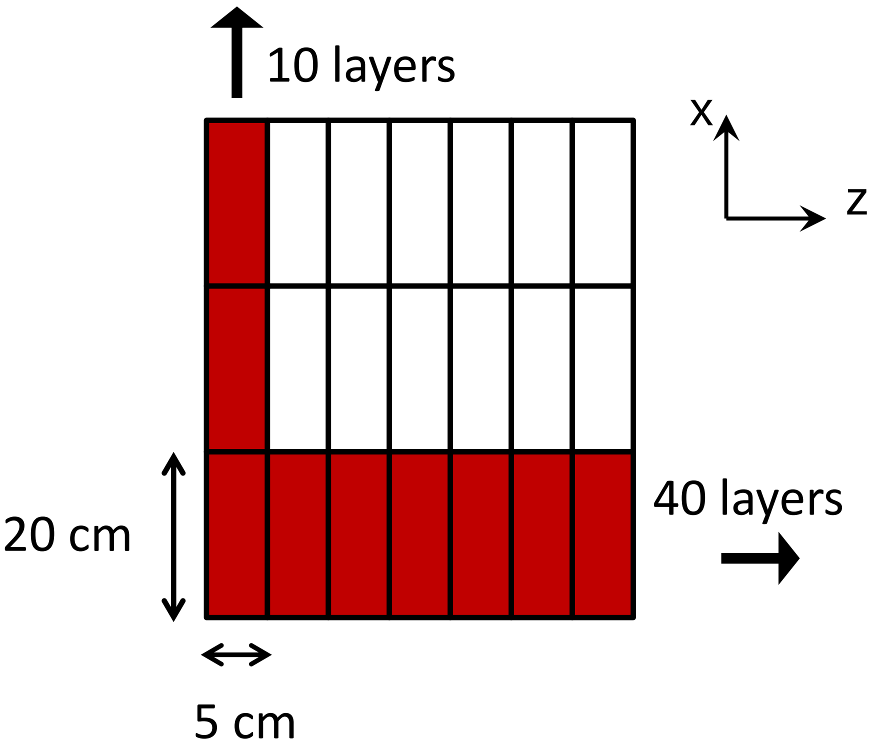
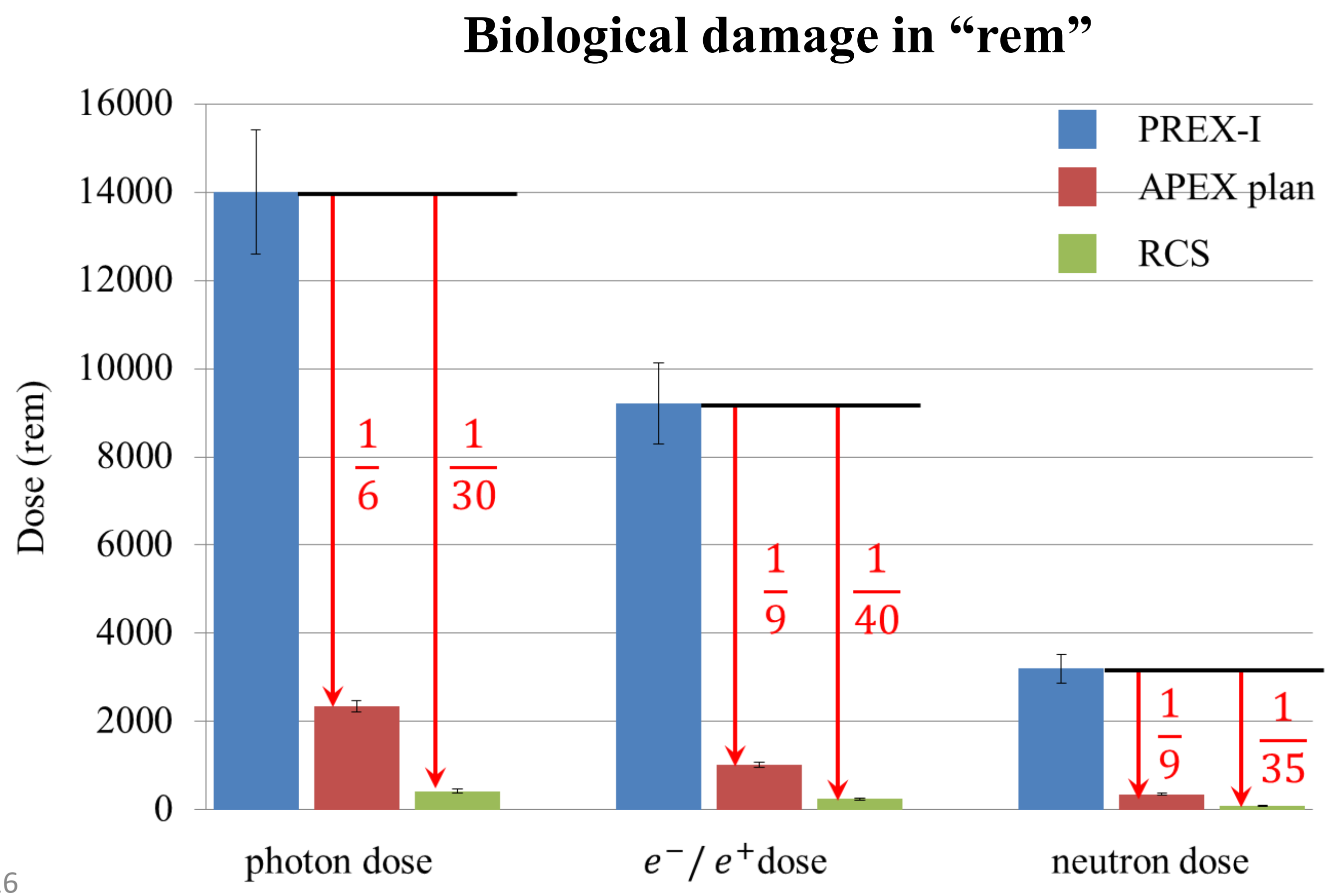


Radiation dose calculations – 8/8

- Complete dose calculation for upstream and HRS electronics area is in backup slides.
- Plot shows the total APEX dose in rem at HRS control electronics compared with PREX-I and RCS experiments.



Outline of this report

1. Experiment Safety Assessment Document (ESAD) for experimental hall A base equipment, approach - 3 slides
2. Radiation damage to electronics – 8 slides
3. Geant4 model of JLab hall A – 5 slides
4. Overview of APEX– 4 slides
5. Radiation dose calculations – 8 slides
6. Conclusions

Results of sections 3, 4 and 5

- GEANT4 simulation package was used to evaluate biological damage at HRS electronics during APEX, PREX-I and RCS experiments.

- Neutron dose rate calculations in upstream were compared with empirical data. GEANT4 simulation over predicts the biological damage dose in hall A by a factor of 2-3. Pavel has observed similar over predications in the past and RadCon agrees this conservative dose is reasonable to predict the actual dose in hall A (see backup slides).

- Total biological damage due to neutrons and electrons during APEX is about factor of 9 lower compared to PREX-I.

- Total biological damage due to photons during APEX is about factor of 6 lower compared to PREX-I.

APEX Radiation Budget

Hall: A   **RADIATION BUDGET FORM**   *page:* 1 of 1

Exp. # C12-10-009   **rev:**   **run dates:** 2016   **name of liaison:** P. Schuster

setup number			1	2	3	4	
beam	energy	GeV	1.1	2.2	3.3	4.4	*totals:*
	current	uA(CW)	50.0	100.0	120.0	90.0	
exp't target	element		C	W	W	W	
	thickness	mg/cm2	299	189	358	358	
time	run time	hours	170	166	170	314	820
	(100% eff.)	days	7.1	6.9	7.1	13.1	34.2
	installation	hours					0
	time	days	0.0	0.0	0.0	0.0	0.0
dose rate at the fence post (run time)	method 1	urem/hr	0.38	1.14	2.84	2.12	
	method 2	urem/hr					
	conservative	urem/hr	0.38	1.14	2.84	2.12	
dose per setup		urem	64	190	483	665	1401.6
% of annual dose budget		%	0.6	1.9	4.8	6.6	14.016
% of allowed dose for the total time							149.73
% of allowed dose for the run time only							149.73

If > 200%, discuss result with Physics Research EH&S officer

date form issued: March 22, 2016   *authors:* P.Degtiarenko

- Radiation budget is specified as a percentage of the Jefferson Lab design goal for dose to the public, which is 10 mrem per year.
- APEX (total over two months calendar time) % of annual dose budget is 14%.

Conclusions

Charge item 4: Are the radiation levels expected to be generated in the hall acceptable? i.e. has the impact of the radiation generated in the hall equipment and infrastructure been properly calculated and mitigated?

- Radiation levels in the hall are acceptable.
  - A detailed GEANT4 calculation has been done to evaluate radiation levels during APEX experiment. Projected down time for the experiment is **< 7 %** based on damage to electronics.
  - Radiation budget for APEX is **14%** of annual limit.
- Mitigation already implemented in hall A (replacing weak electronic items by robust ones) should reduce down time even further.

Acknowledgements

Gordon D. Cates
Bogdan Wojtsekhowski
Pavel Degtiarenko
Sergey Abrahamyan
Seamus Riordan
Vladimir Nelyubin
Kent Paschke
Rakitha S. Beminiwattha
Bryan Wright
Alan Gavalya

Backup slides

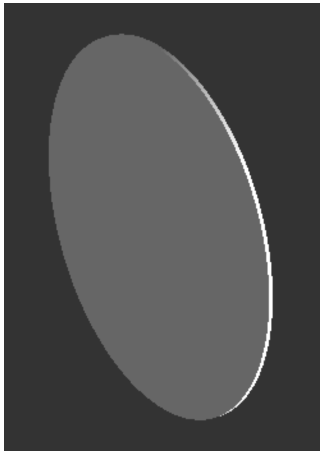
To Do list

- Calculate energy deposition in material near critical aperture and projected activation.

- Whatever the committee will suggest us to do.

Simulated Experiments - **PREX**

- PREX target is a Lead disc with thickness of 0.56 mm. (10 % rad length)

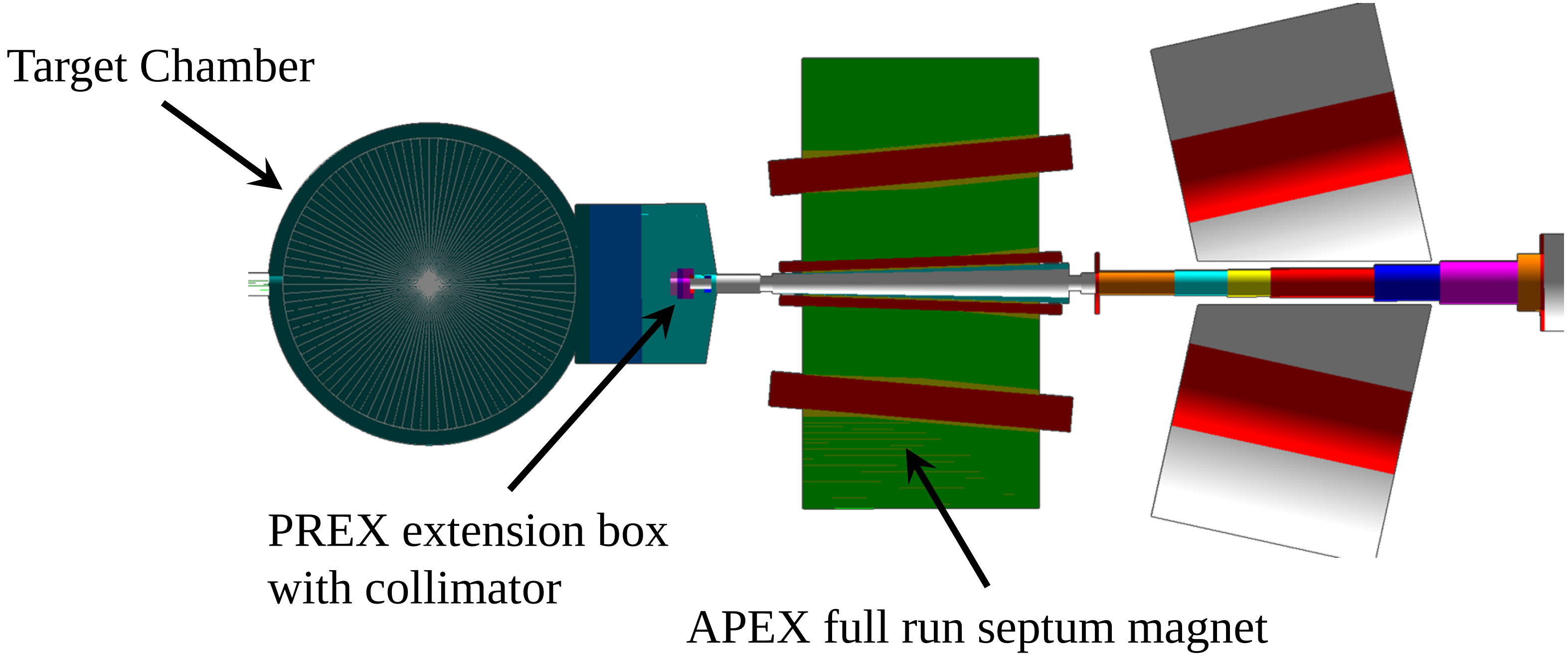


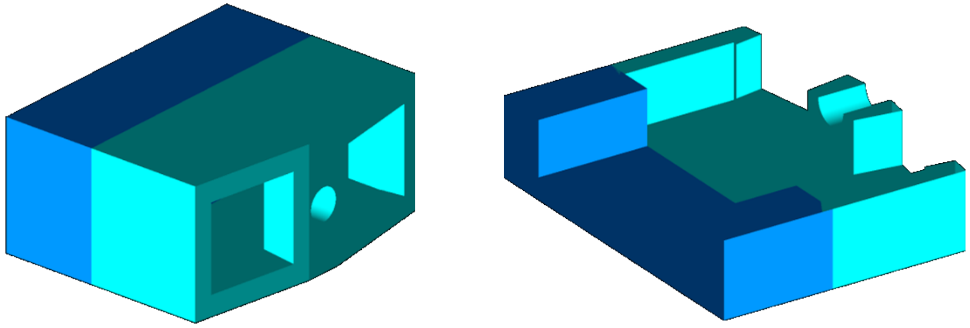
637 mg/cm^2

Beamline components used in PREX simulation

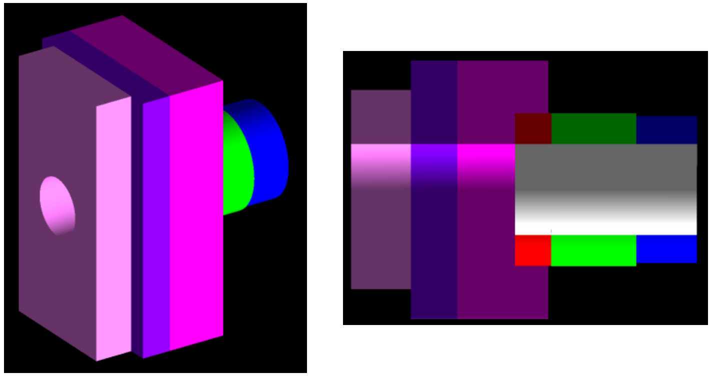
- PREX Extension Box
- PREX Collimator
- APEX Full Run Septum Magnet with PREX field map.
- Beam:1.06 GeV
- HRS : positioned at 12.5^{o} with respect to the beam direction.

Simulated Experiments - PREX





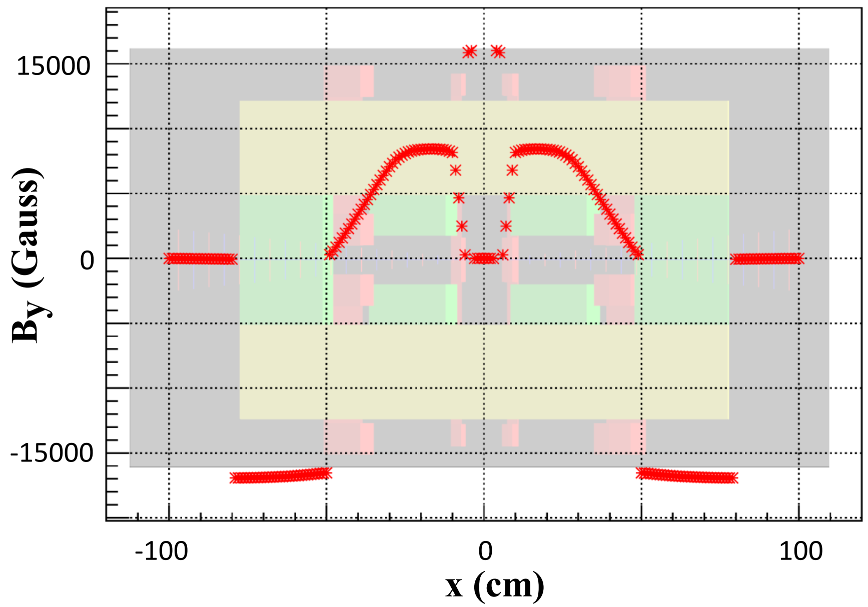
PREX extension box



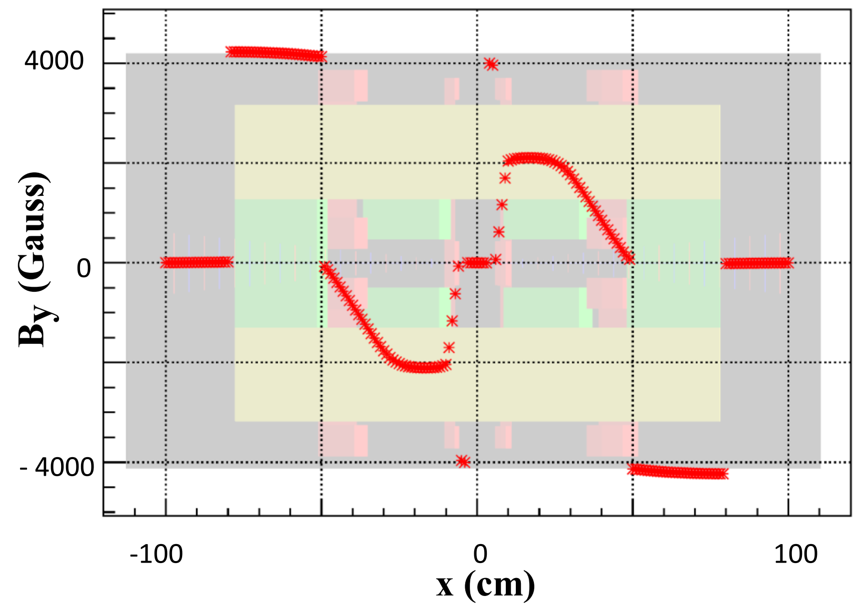
Tungsten Collimator

Simulated Experiments - PREX

TOSCA field map for APEX 4.4 GeV setting

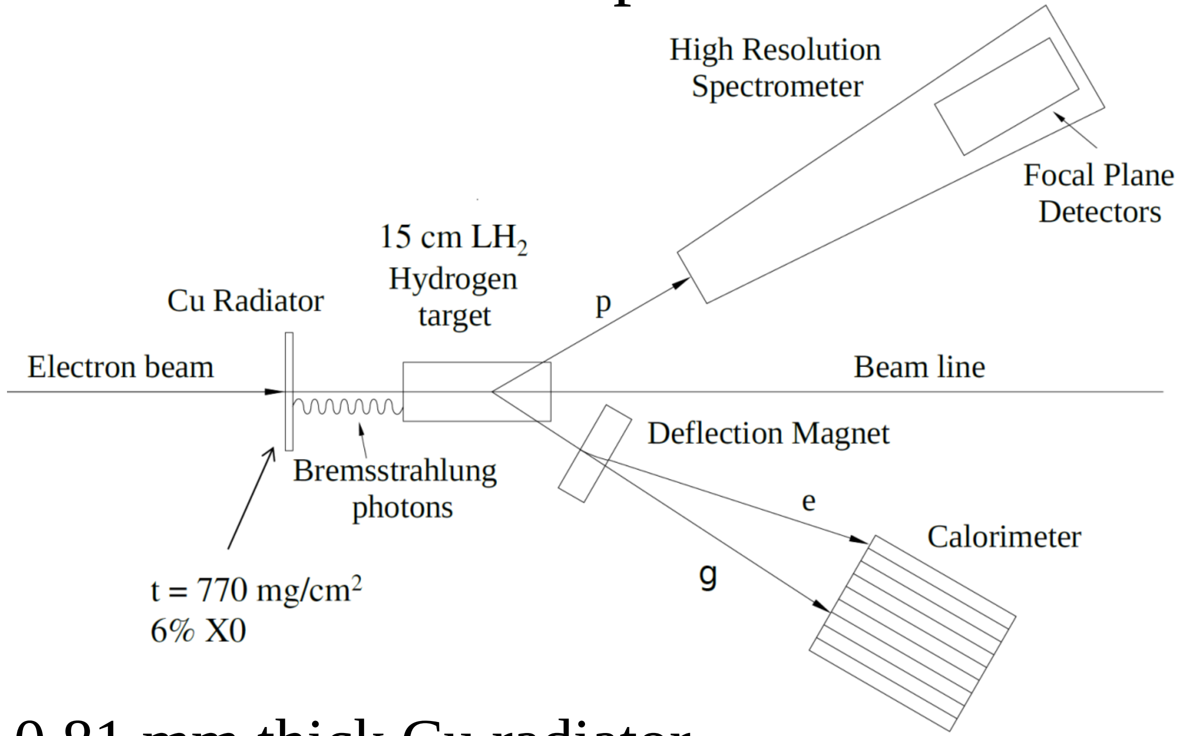


Modified TOSCA field map used for PREX-I



- APEX septum magnet was used instead of PREX septum.
- We used the same APEX TOSCA field map, but scaled down and inverted in -x side to match the PREX-I septum field.
- Figures show magnetic field along x axis (y=0, z=0).

Simulated Experiments - **RCS**



Target: 0.81 mm thick Cu radiator.

15 cm LH_2 target

Beam: 3.5 GeV

Left HRS: positioned at 19.5° with respect to the beam direction

Only Left HRS was used for the simulation.

Radiation dose rate evaluated using method 1

	Target	Particle type	Dose Rate : Upstream detector (rem / h)	Dose Rate : HRS-L detector (rem / h)
PREX – I 70 μA	Lead 10 % r.l. 567 mg / cm^2	Photons e^-/e^+ Neutrons	3.7E+00 3.8E-01 3.4E+00	3.6E+01 2.4E+01 8.4E+00
RCS, 3.481 GeV 40 μA	Copper radiator 6 % r.l. 15 cm LH_2 target	Photons e^-/e^+ Neutrons	3.0E-01 4.7E-02 3.0E-01	1.1E+00 6.3E-01 2.4E-01
APEX, 1.1 GeV 50 μA	Carbon 0.7 % r.l. 300 mg / cm^2	Photons e^-/e^+ Neutrons	5.2E-02 6.2E-03 6.6E-02	3.9E-01 2.3E-01 6.4E-02
APEX, 2.2 GeV 100 μA	Tungsten 2.8 % r.l. 190 mg / cm^2	Photons e^-/e^+ Neutrons	2.3E-01 3.6E-02 3.9E-01	3.1E+00 1.4E+00 3.8E-01
APEX, 3.3 GeV 120 μA	Tungsten 5.3 % r.l. 360 mg / cm^2	Photons e^-/e^+ Neutrons	4.6E-01 1.2E-01 8.5E-01	5.8E+00 2.7E+00 7.8E-01
APEX, 4.4 GeV 90 μA	Tungsten 5.3 % r.l. 360 mg / cm^2	Photons e^-/e^+ Neutrons	2.7E-01 1.0E-01 5.6E-01	3.5E+00 1.4E+00 6.2E-01

Radiation dose evaluated using method 1

	Days	Particle type	Dose : Upstream detector (rem)	Dose : HRS-L detector (rem)
PREX – I 70 μA	16 effective days	Photons e^-/ e^+ Neutrons	1.4E+03 1.5E+02 1.3E+03	1.4E+04 9.2E+03 3.2E+03
RCS, 3.481 GeV 40 μA	16 effective days	Photons e^-/ e^+ Neutrons	1.2E+02 1.8E+01 1.2E+02	4.2E+02 2.4E+02 9.2E+01
APEX, 1.1 GeV 50 μA	6 PAC days	Photons e^-/ e^+ Neutrons	7.5E+00 8.9E-01 9.5E+00	5.6E+01 3.3E+01 9.2E+00
APEX, 2.2 GeV 100 μA	6 PAC days	Photons e^-/ e^+ Neutrons	3.3E+01 5.2E+00 5.6E+01	4.5E+02 2.0E+02 5.5E+01
APEX, 3.3 GeV 120 μA	6 PAC days	Photons e^-/ e^+ Neutrons	6.6E+01 1.7E+01 1.2E+02	8.4E+02 3.9E+02 1.1E+02
APEX, 4.4 GeV 90 μA	12 PAC days	Photons e^-/ e^+ Neutrons	7.8E+01 2.9E+01 1.6E+02	1.0E+03 4.0E+02 1.8E+02

1 MeV neutron equivalent fluece at HRS control electronics

	Days	Particle type	1 MeV neutron equivalent fluence rate $(n_{eq}\ cm^{-2}\ s^{-1})$	Total 1 MeV neutron fluence $(n_{eq}\ cm^{-2})$
PREX-I, 1.06 GeV 70 μA 10 % r.l. Lead	16 effective days	neutrons e^-/e^+ photons	1.8E+05 6.9E+04 8.7E+04	**4.6E+11**
RCS, 3.481 GeV 40 μA	16 effective days	neutrons e^-/e^+ photons	5.0E+03 2.1E+03 1.0E+03	**1.1E+10**
APEX, 1.1 GeV 50 μA 0.7 % r.l. Carbon	6 PAC days	neutrons e^-/e^+ photons	1.0E+03 5.9E+02 7.8E+02	**1.2E+09**
APEX, 2.2 GeV 100 μA 2.8 % r.l. Tungsten	6 PAC days	neutrons e^-/e^+ photons	9.2E+03 3.7E+03 1.1E+04	**1.2E+10**
APEX, 3.3 GeV 120 μA 5.3 % r.l. Tungsten	6 PAC days	neutrons e^-/e^+ photons	1.9E+04 6.4E+03 2.5E+04	**2.6E+10**
APEX, 4.4 GeV 90 μA 5.3 % r.l. Tungsten	12 PAC days	neutrons e^-/e^+ photons	1.1E+04 3.7E+03 1.2E+04	**2.8E+10**

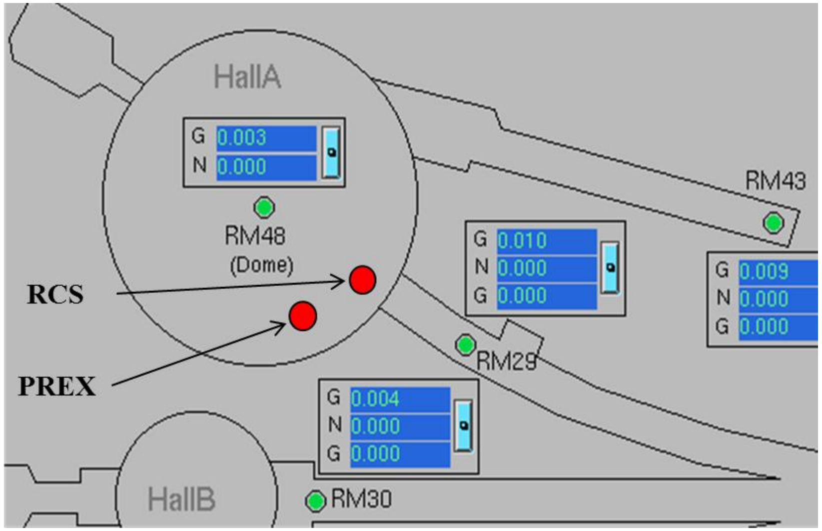
Calculated dose rates for previous experiments - 1/3

- **Available RadCon neutron dose rate measurements are in units of Biological Damage (rem).**

- We simulated PREX-I and RCS experiments to evaluate neutron dose rates in hall A upstream and compared with empirical data.
  Details of the calculation will be discussed later.

Canberra NP-100B
BF_3 proportional counter

Sensitive energy range: 0.025 eV – 15 MeV



Positions of the detectors during measurement

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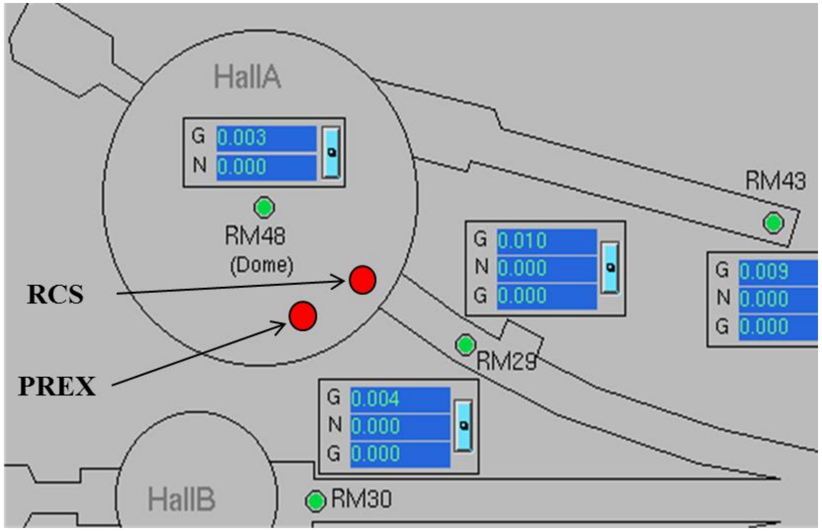
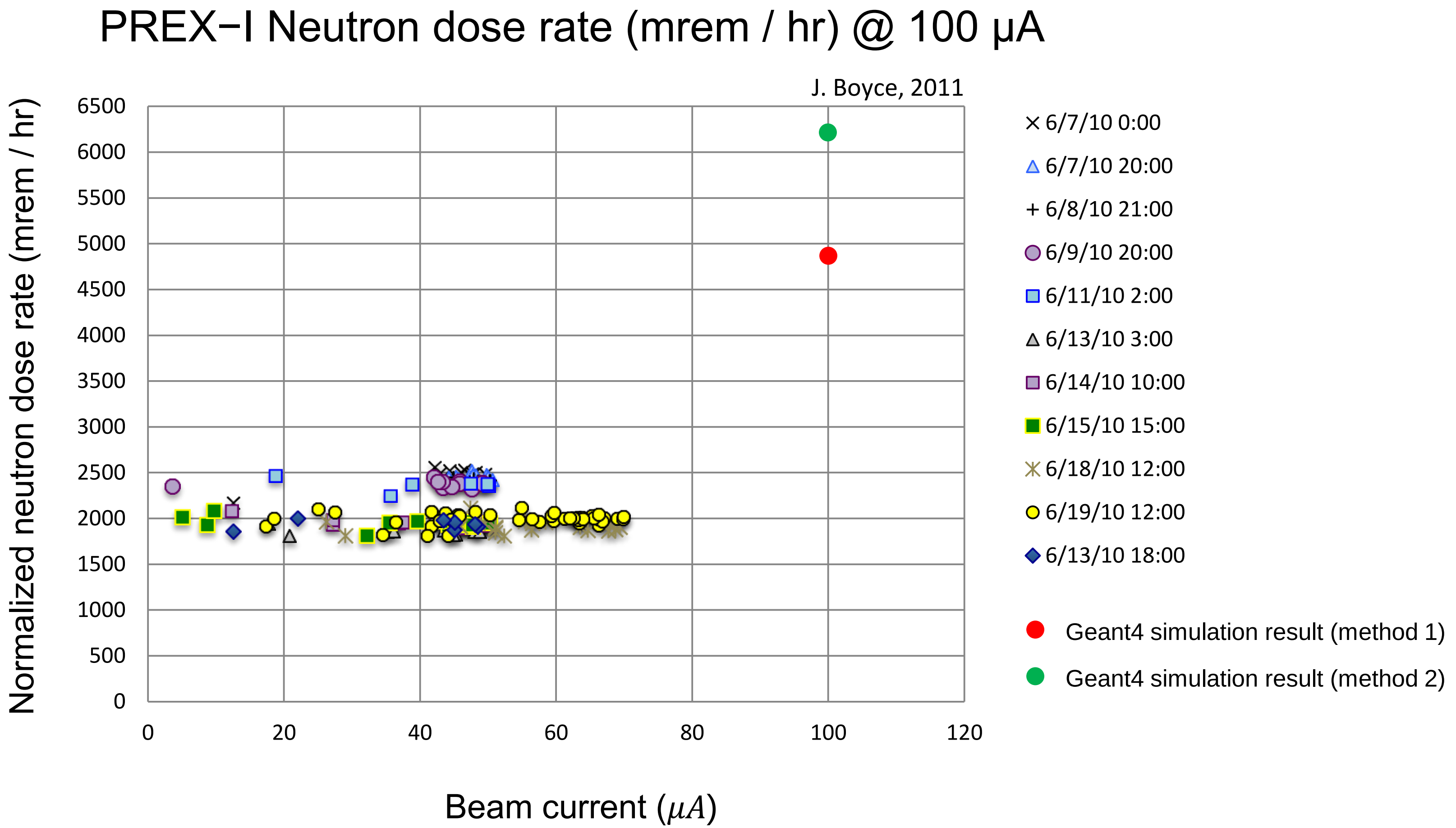


Positions of the detectors during measurement

Calculated dose rates for previous experiments - 2/3

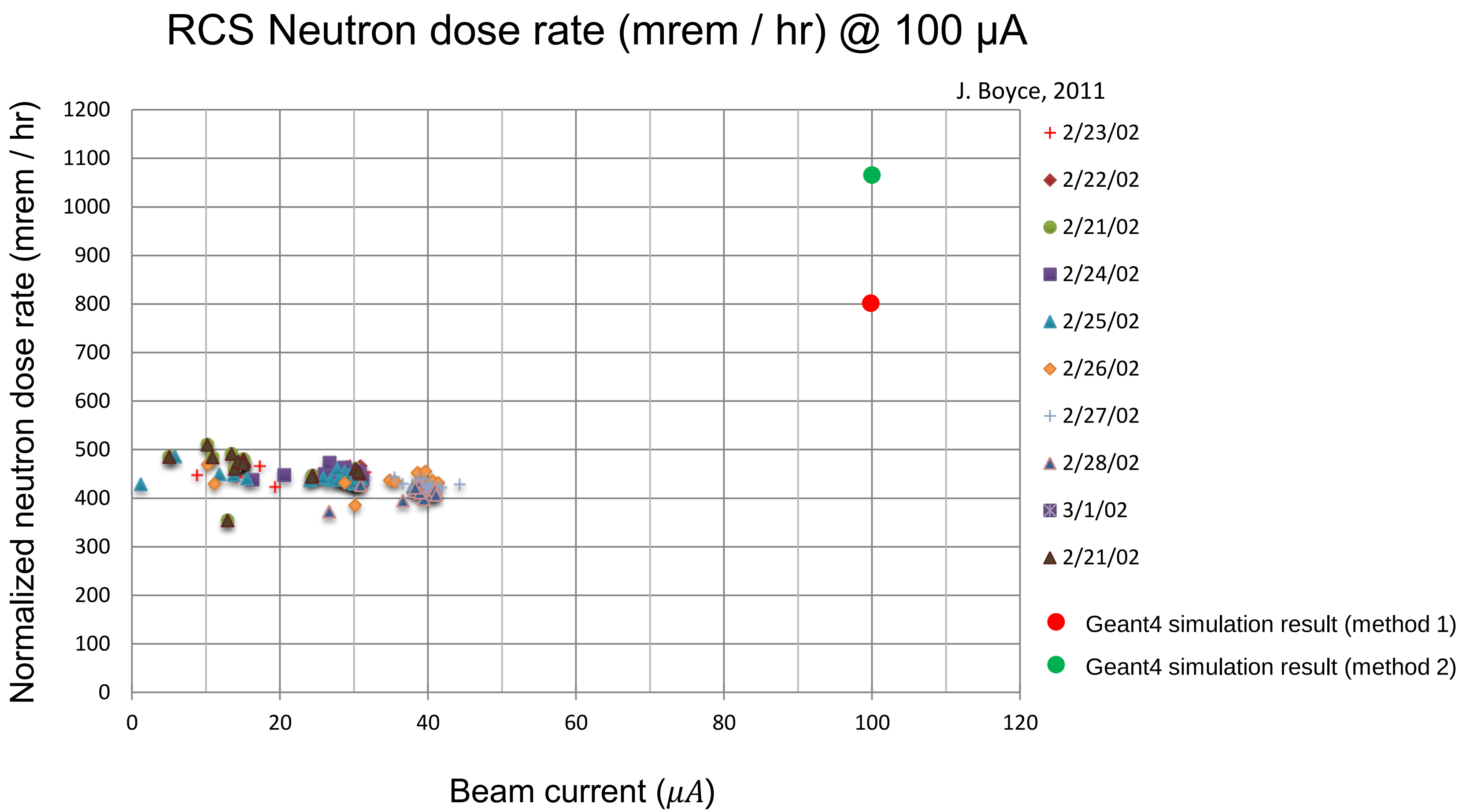


Average measured dose rate: 2080 mrem / hr at 100 μA

Geant4 simulation dose rate (method 1): 4800 mrem / hr at 100 μA

Geant4 simulation dose rate (method 2): 6200 mrem / hr at 100 μA

Calculated dose rates for previous experiments - 3/3



Average measured dose rate: 440 mrem / hr at 100 μA

Geant4 simulation dose rate (method 1): 800 mrem / hr at 100 μA

Geant4 simulation dose rate (method 2): 1060 mrem / hr at 100 μA

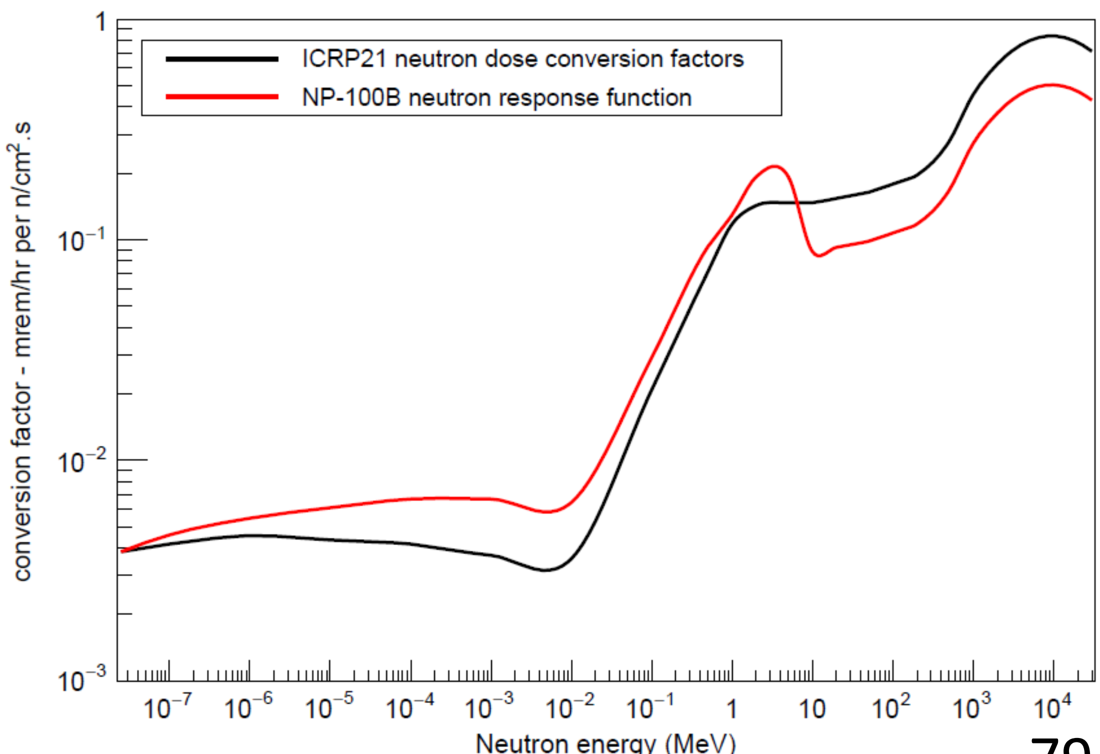
Radiation dose rate/dose evaluated using method 2

- JLab neutron monitor (Canberra NP-100B) has an Anderson-Braun moderator which makes its energy response closer to fluence-to-dose equivalent conversion factor curve.

- International Commission on Radiological Protection (ICRP) publication 21 includes conversion coefficients for neutron fluence to equivalent dose in rem (black curve in the plot)

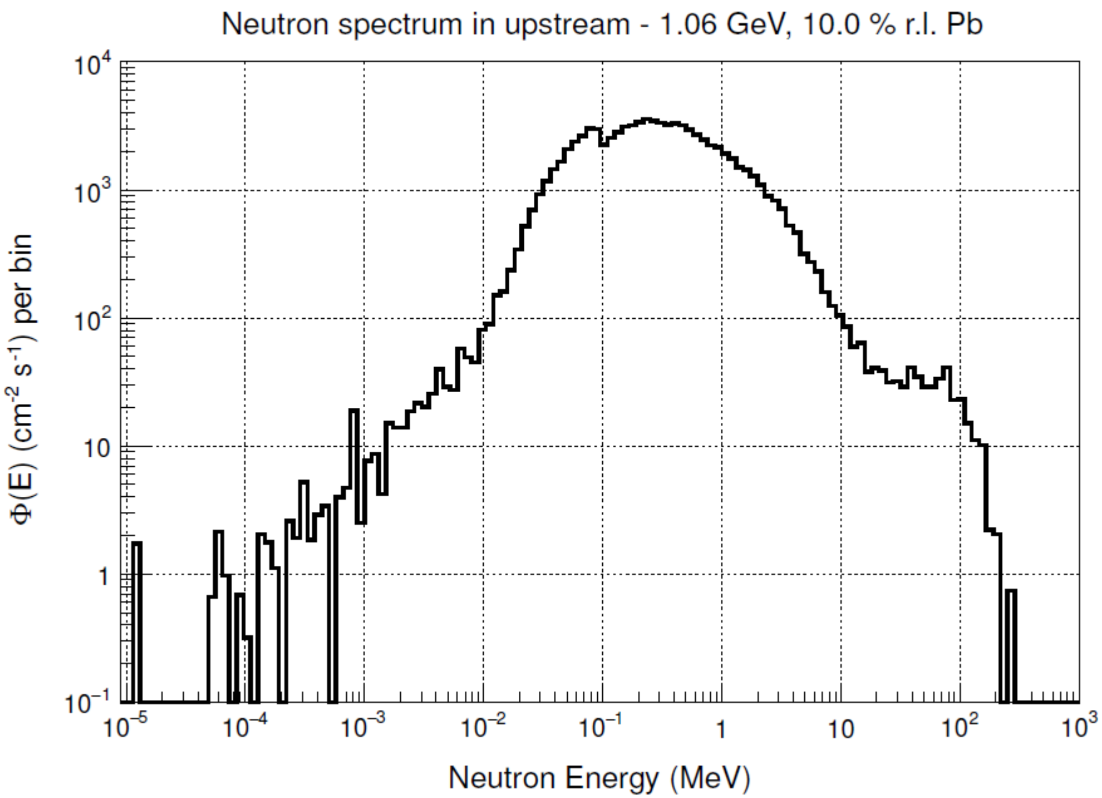
- Canberra claims the NP-100B neutron response follows the red curve shown in the plot.

Biological damage conversion coefficients



Radiation dose rate evaluated using method 2

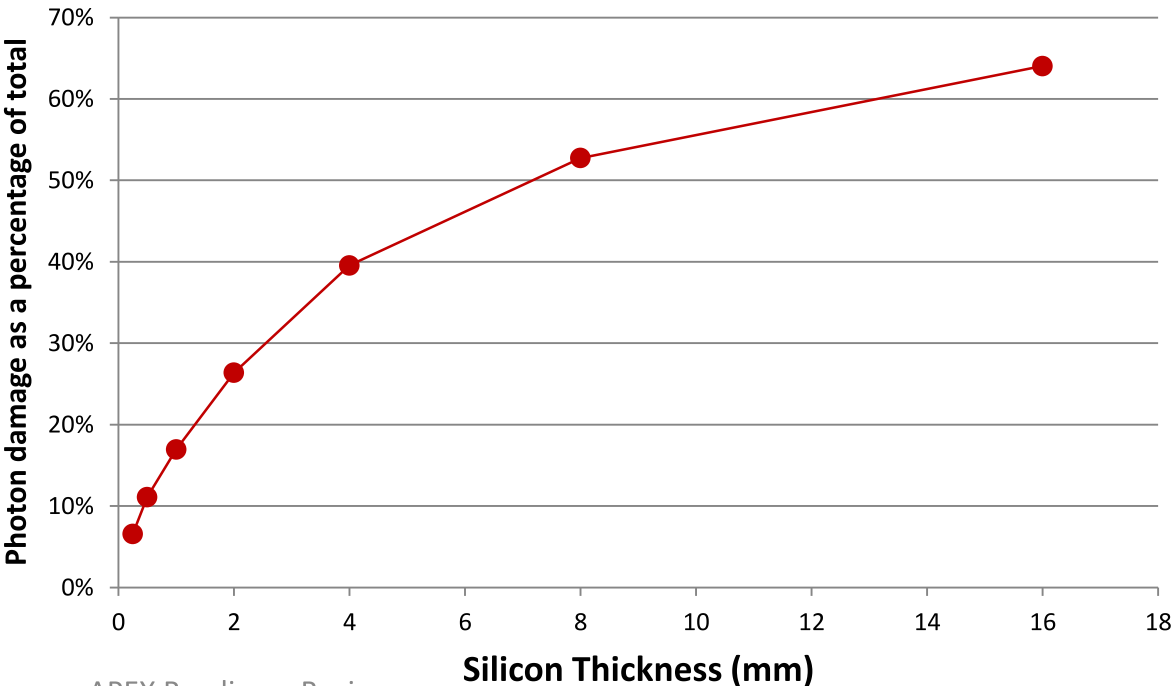
- Figure shows neutron spectrum in upstream detector during PREX-I experiment (simulation).
- We can use the detector response curve (red line) in the previous slide folded with this spectrum to calculate the neutron dose rate.



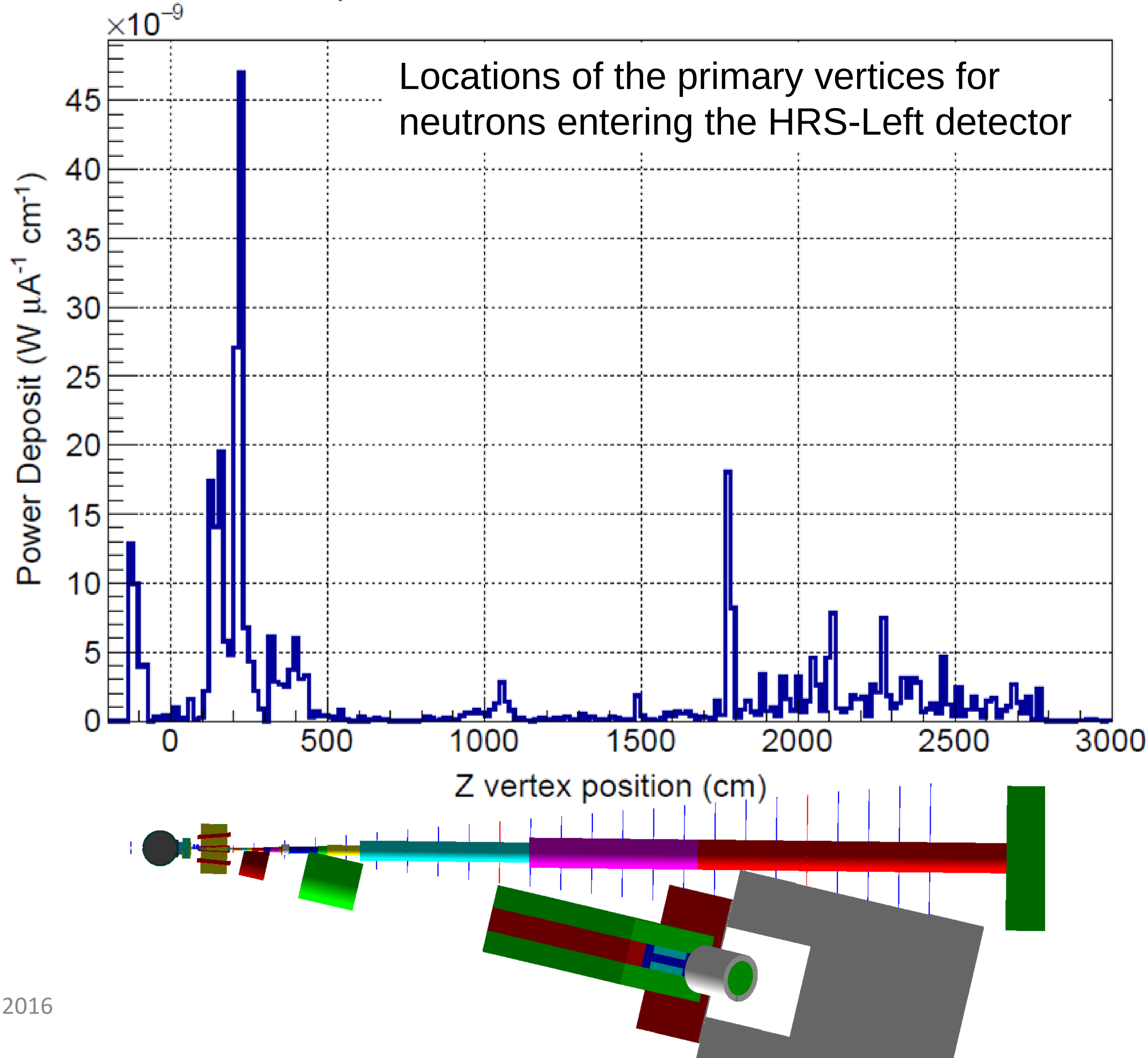
- We used this second method to evaluate only neutron dose.

Evaluate electronics damage by photons

- No direct damage curves were available for Silicon photon damage.
- Photon damage occurs due to electrons and positrons generated inside the semiconductor device due to photon flux.
- Photon spectrum at HRS-left detector was incident on a **5 mm** thick Silicon slab and evaluated $e^{-}/\ e^{+}$damage using existing damage curves. This gives us photon damage in silicon. But this value changes with Silicon thickness.
- Plot shows you how photon Silicon damage as a percentage of total Silicon damage (electron, photon and neutron) changes as a function of Silicon thickness for APEX 3 GeV photon spectrum.



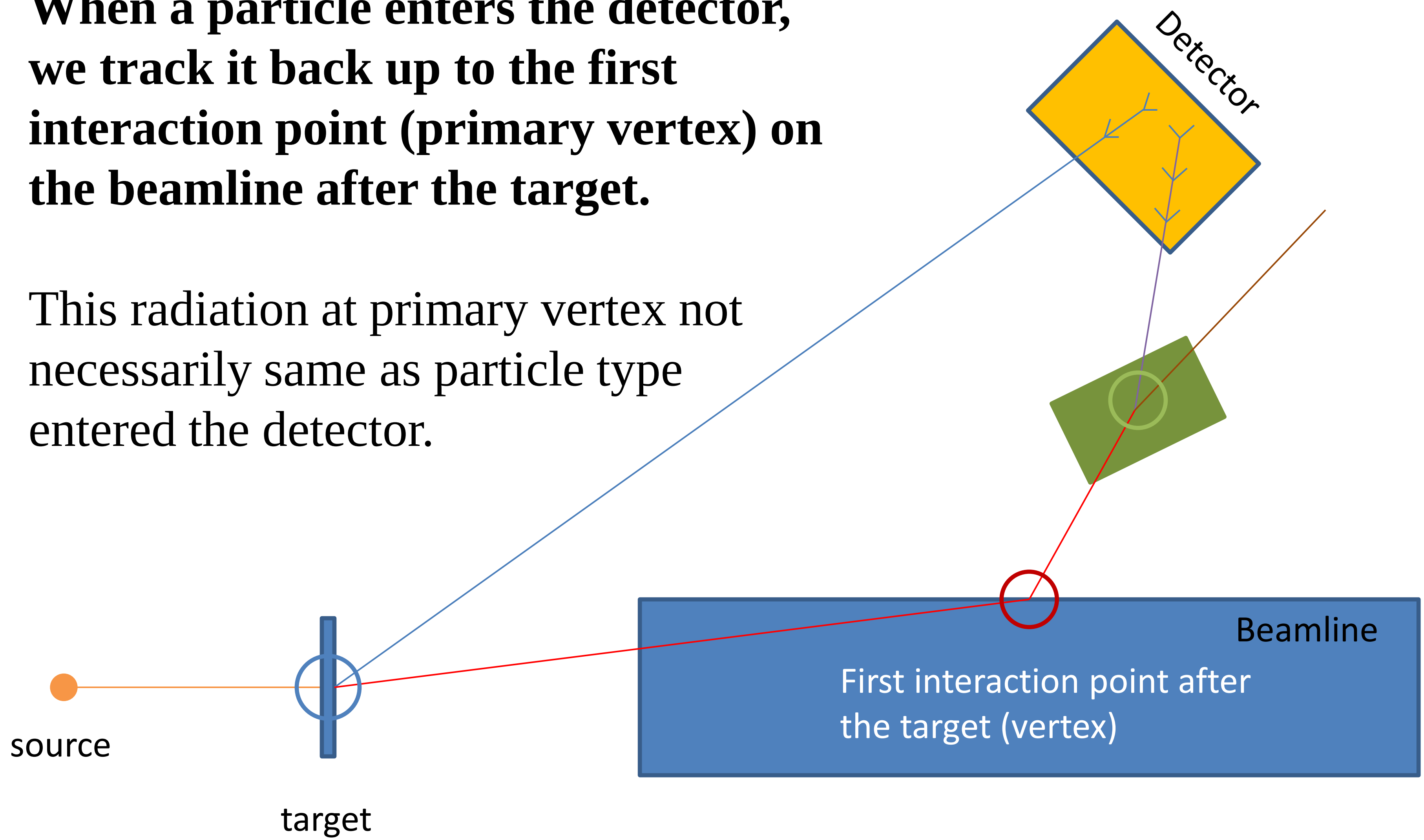
Sources of radiation



Sources of radiation - 1/6

- **When a particle enters the detector, we track it back up to the first interaction point (primary vertex) on the beamline after the target.**

- This radiation at primary vertex not necessarily same as particle type entered the detector.



Sources of radiation - 1/6

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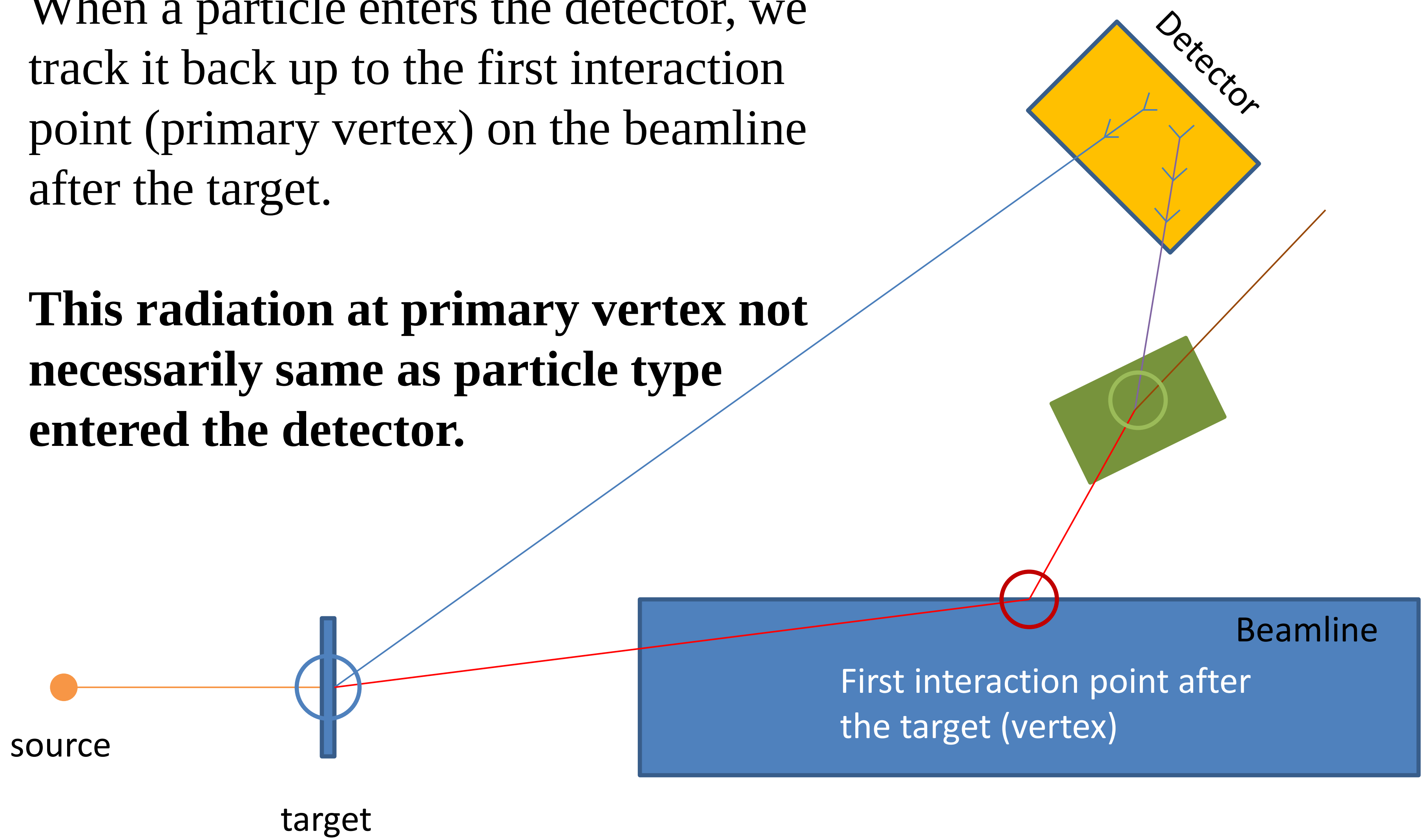
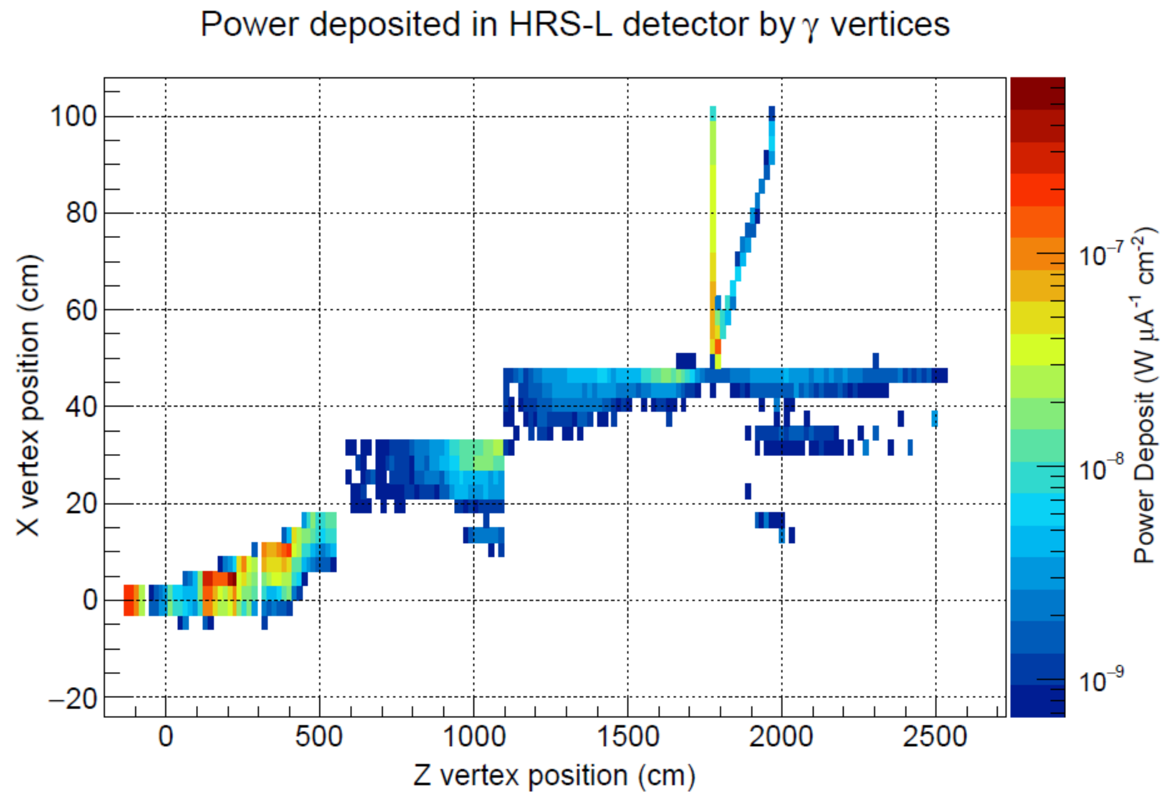


Sources of radiation – 2/6

- **X and Y axes on the plot correspond to Z and X coordinates of the "primary vertices" on the beamline.**

- Each pixel represents a particular point on the beamline, and its color encodes the deposition of power in the HRS electronics region from events that originated at that point.



Sources of radiation – 2/6

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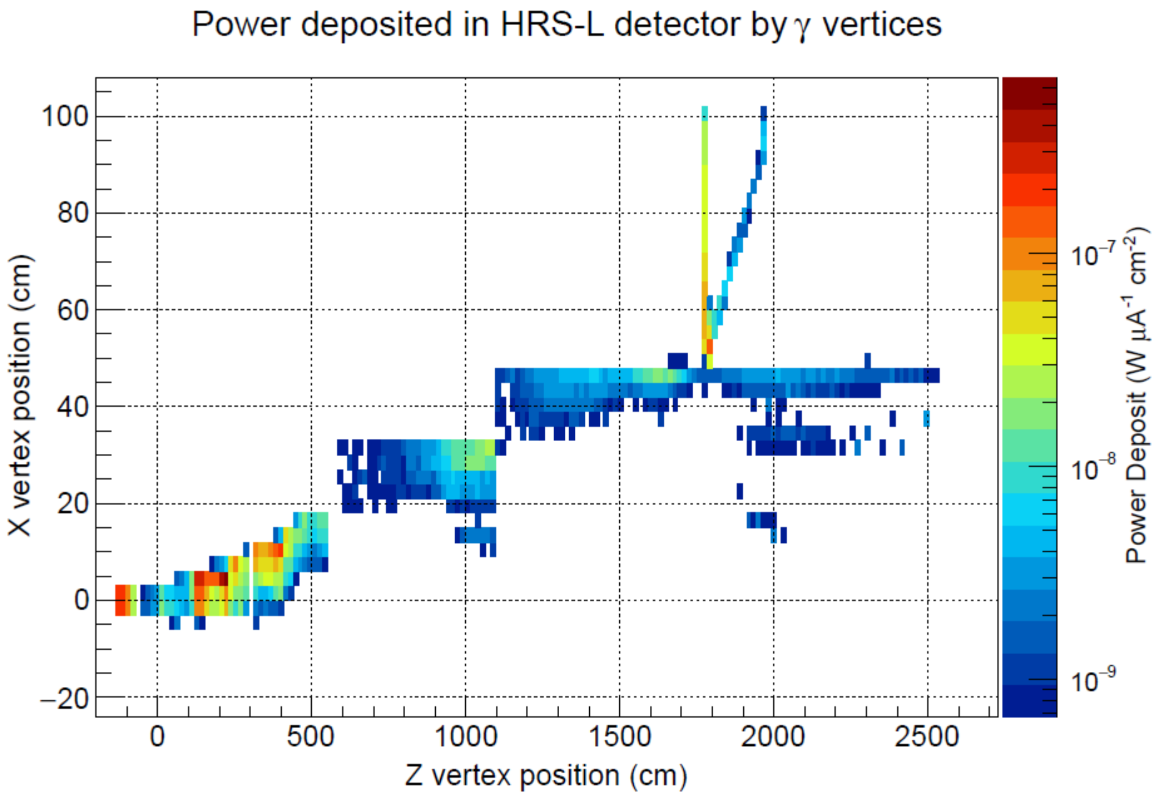
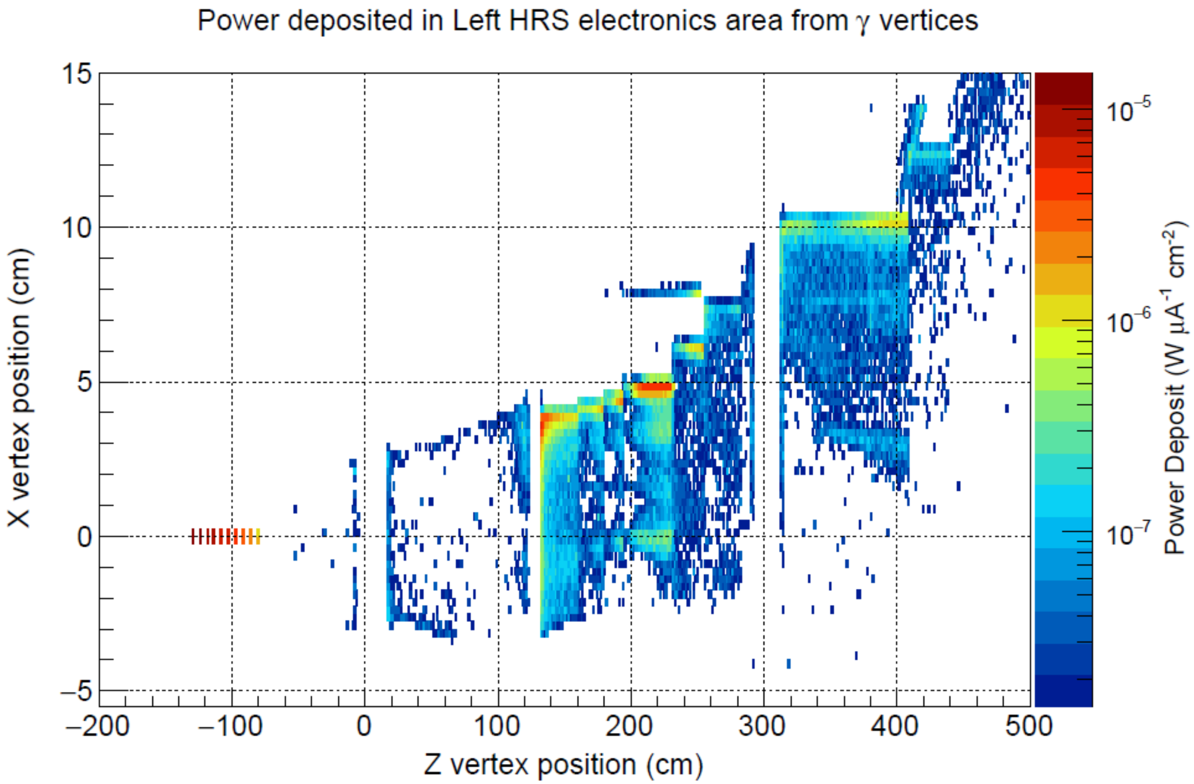


Sources of radiation – 3/6

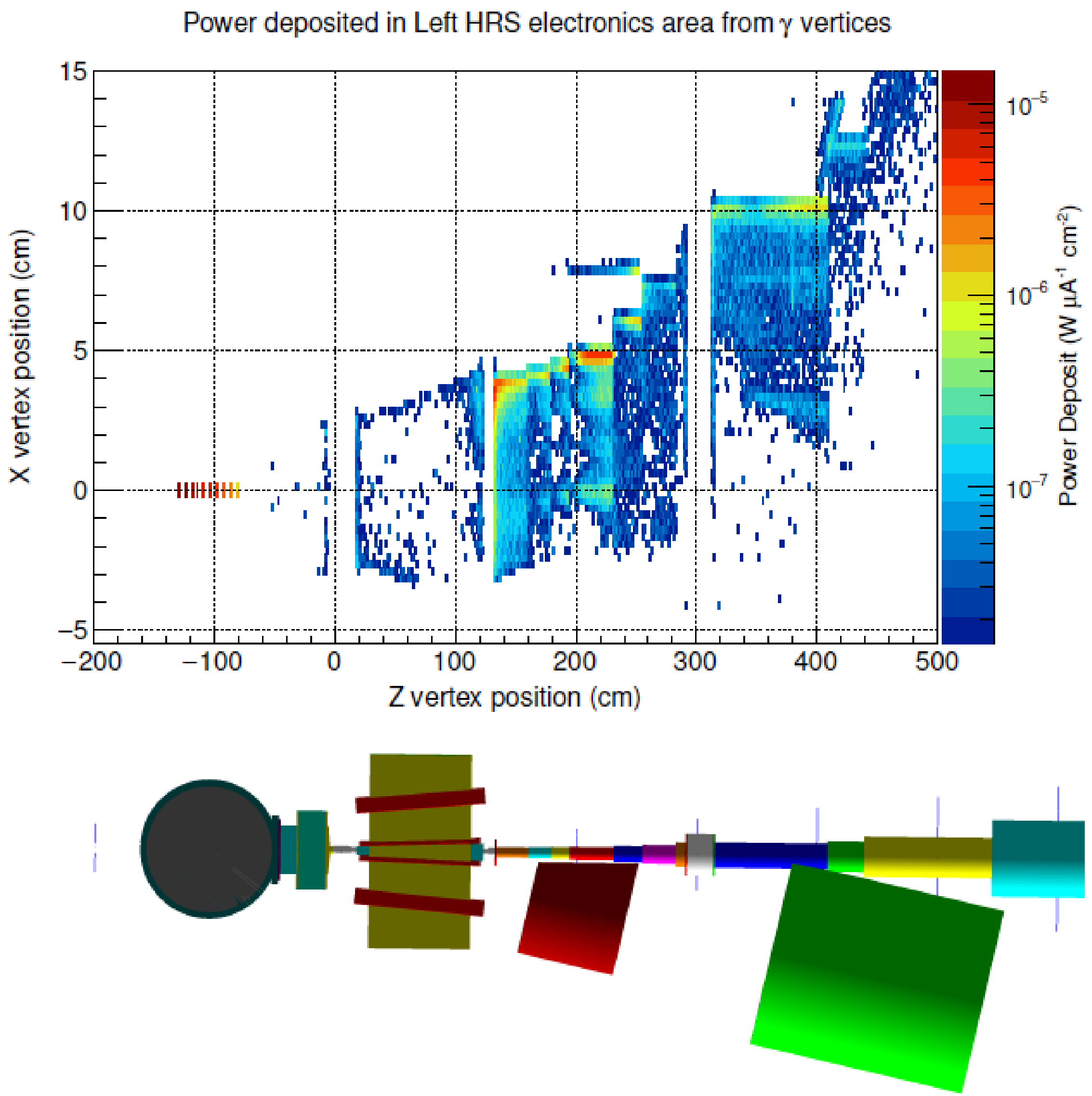
- X and Y axes on the plot correspond to Z and X coordinates of the "primary vertices" on the beamline.
- Each pixel represents a particular point on the beamline, and its color encodes the deposition of power in the HRS electronics region from events that originated at that point.

The plot is zoomed in to see the beamline components closer to the target.



Sources of radiation – 4/6

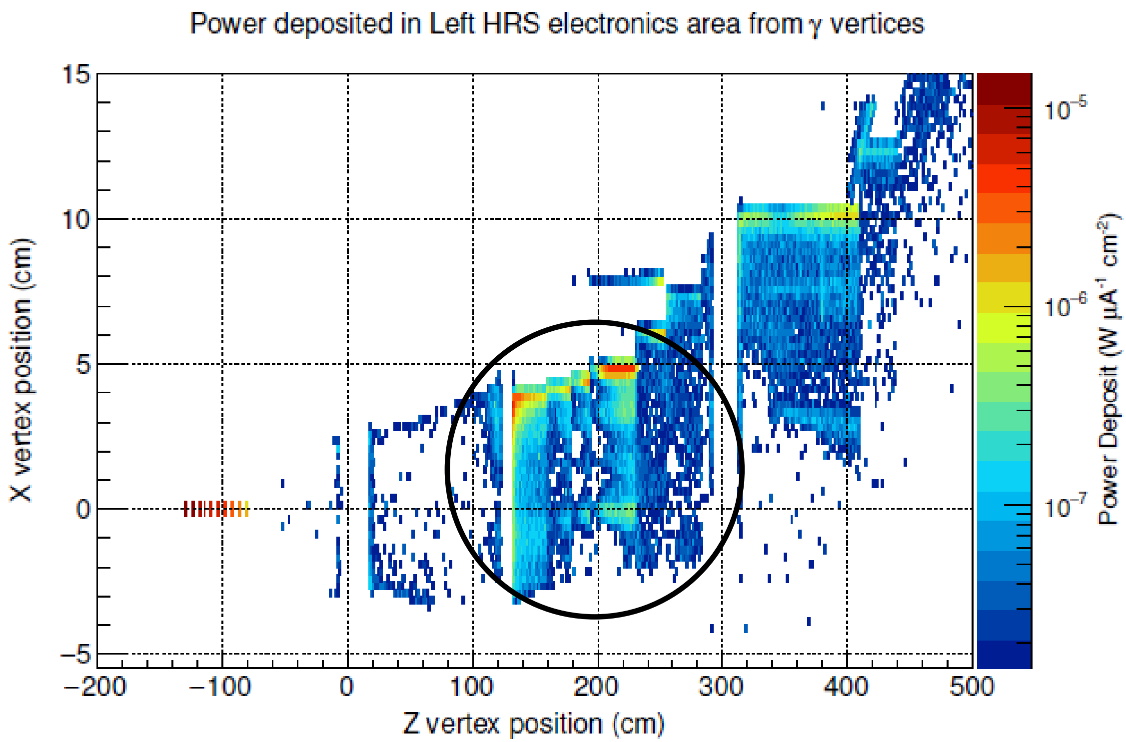
- **In the lower portion of the figure is a drawing generated by GEANT4, that shows elements of the APEX experimental setup near the region of interest.**

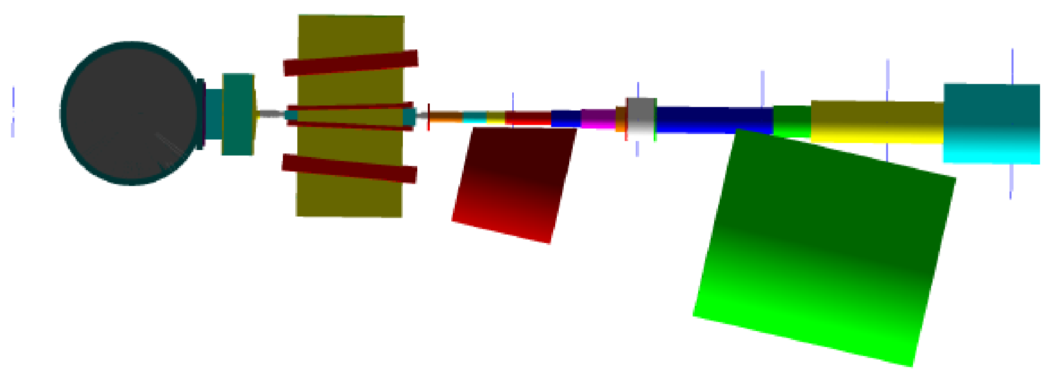


Sources of radiation – 4/6

- In the lower portion of the figure is a drawing generated by GEANT4, that shows elements of the APEX experimental setup near the region of interest.

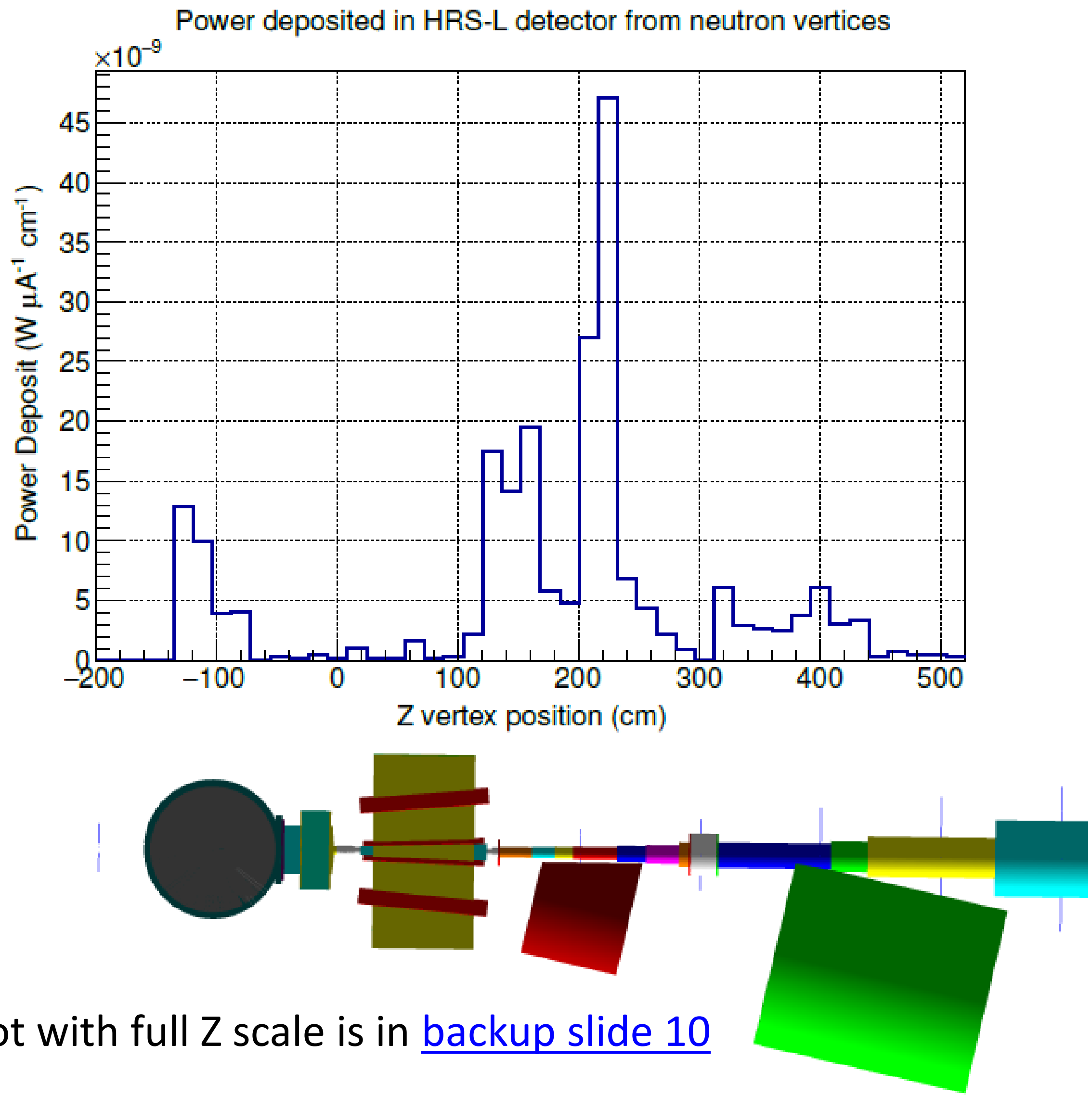
- **Most of the radiation is produced in the area circled in the plot.**





Sources of radiation – 5/6

- In the lower portion of the figure is a drawing generated by GEANT4, that shows elements of the APEX experimental setup near the region of interest.
- Most of the radiation is produced in the area circled in the plot.
- **A 1D plot allows to see quantitatively the importance of different locations. In this plot Y axis is the deposited power.**

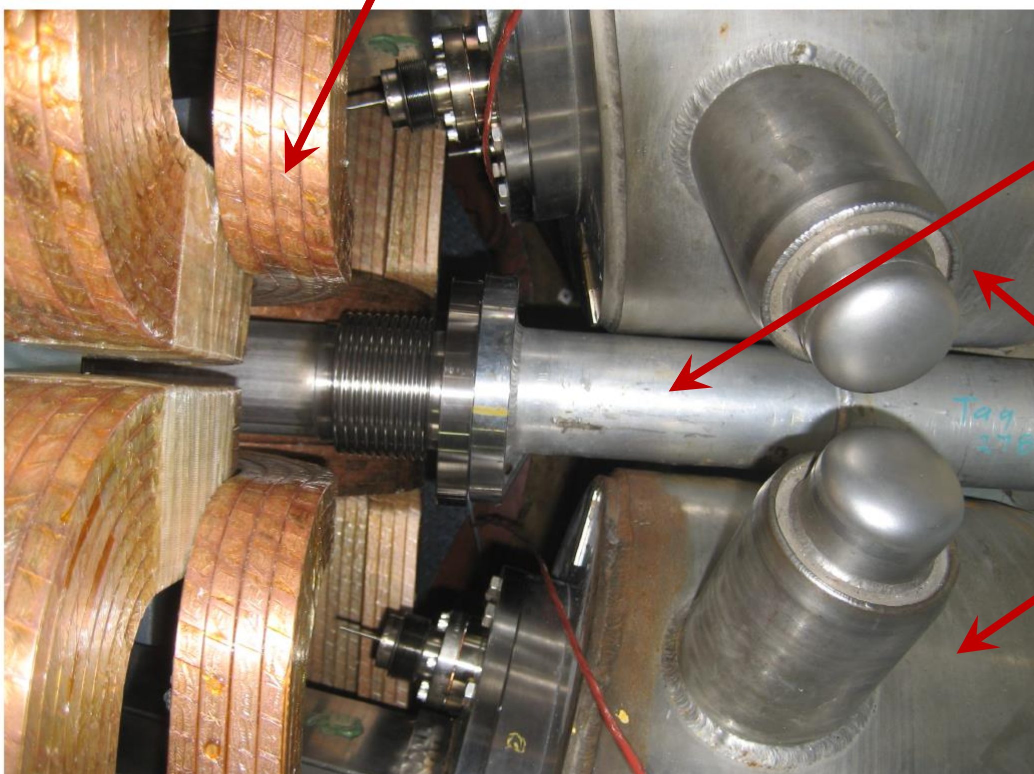


Plot with full Z scale is in [backup slide 10]

Sources of radiation – 6/6

Telescopic beampipe shown in the picture is the ideal location need to be shielded to lower the radiation in HRS control electronics.

Coils of the Septum Magnet



Telescopic section of the beam line which produces lot of radiation sources.

Q1 magnets

B. Wojtsekhowski, APEX14