GEANT4 Simulation of APEX Background Radiation and Shielding

Maduka Kaluarachchi

University of Virginia

The A Prime EXperiment

Standard Model
g $W^{\pm}, Z$ γ

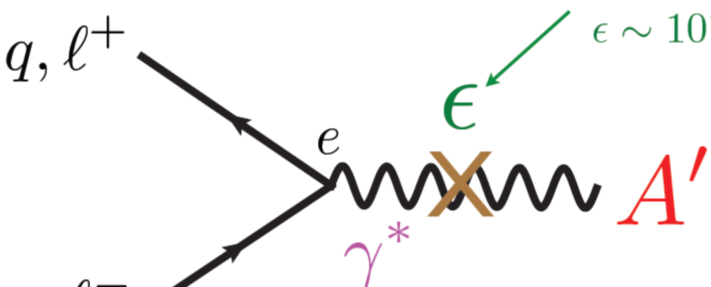
?

Dark Sector
forces + particles
dark matter?

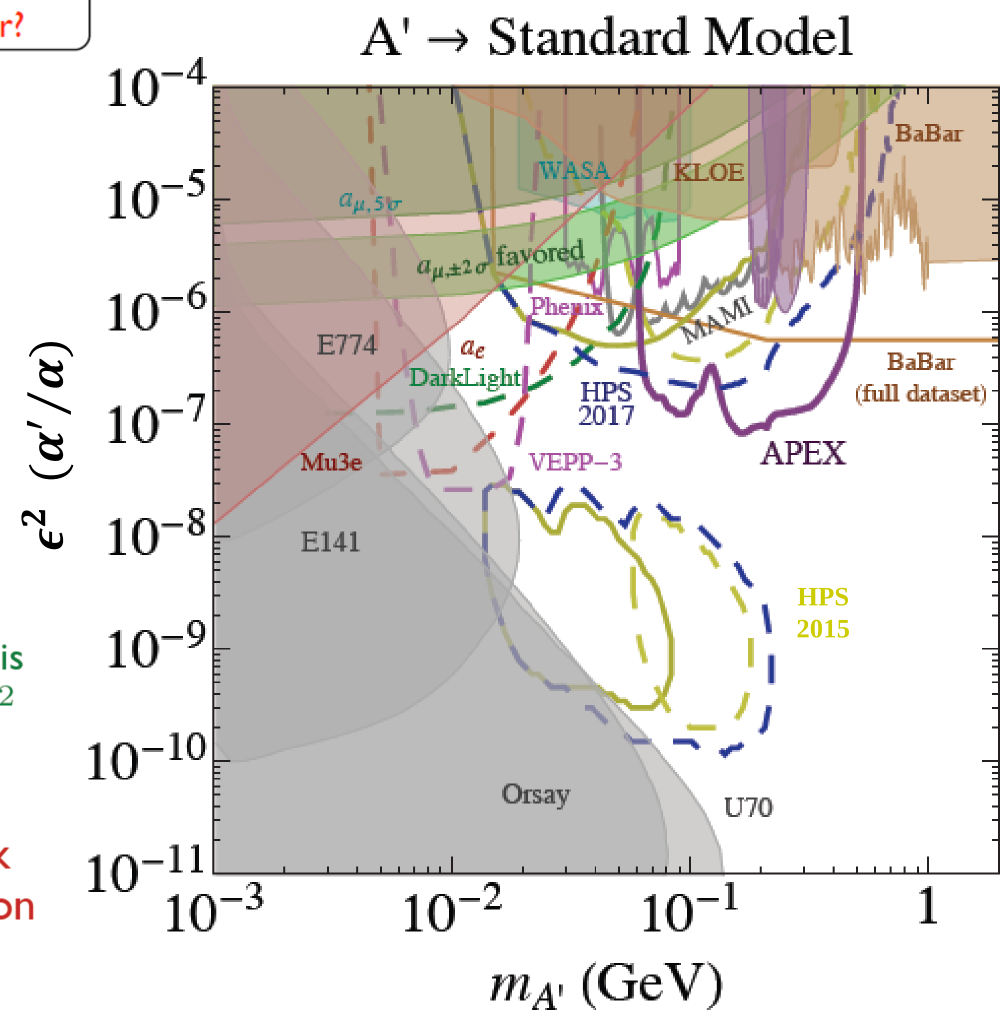
APEX built to probe the
dark photon portal

A' couples very weakly to quarks and charged leptons

a motivated target is
$\epsilon \sim 10^{-5} - 10^{-2}$



dark
photon



Rouven Essig, 2014 APEX Collaboration Meeting, JLab

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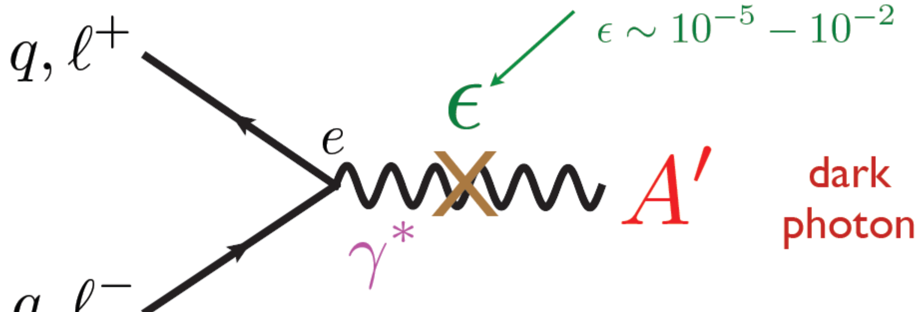
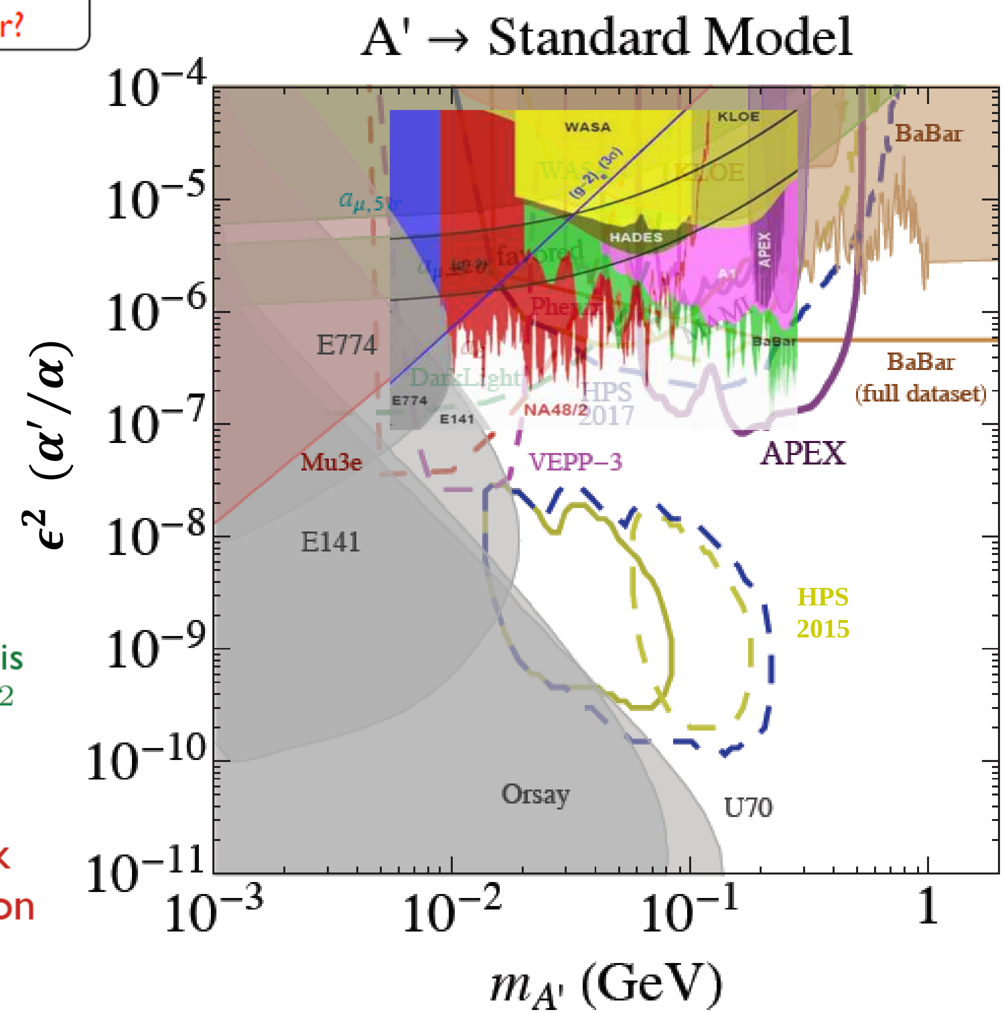


http://arxiv.org/abs/1504.00607



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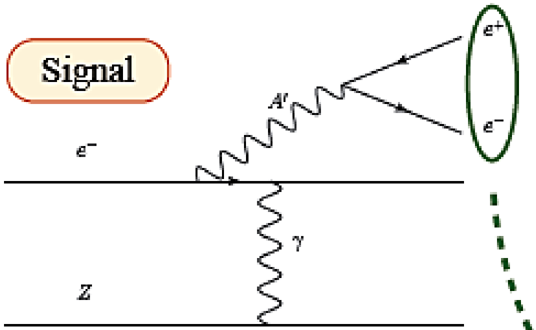
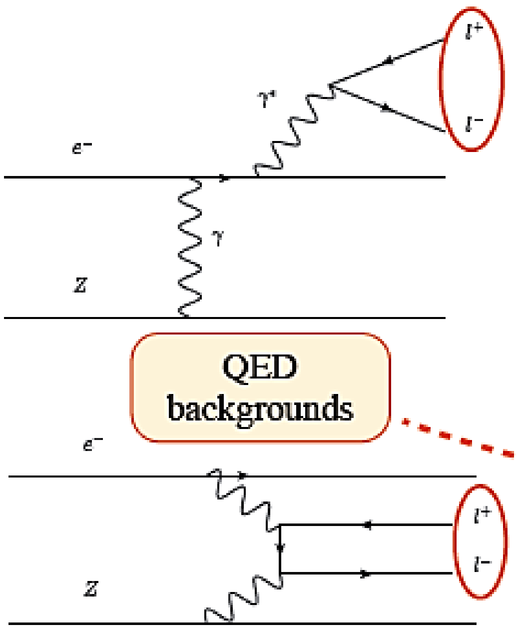
The A Prime EXperiment

Direct production of A' at JLab

- Produced via high energy e⁻ beam incident on fixed high-Z (W) target
- Decays to e^+e^- pair

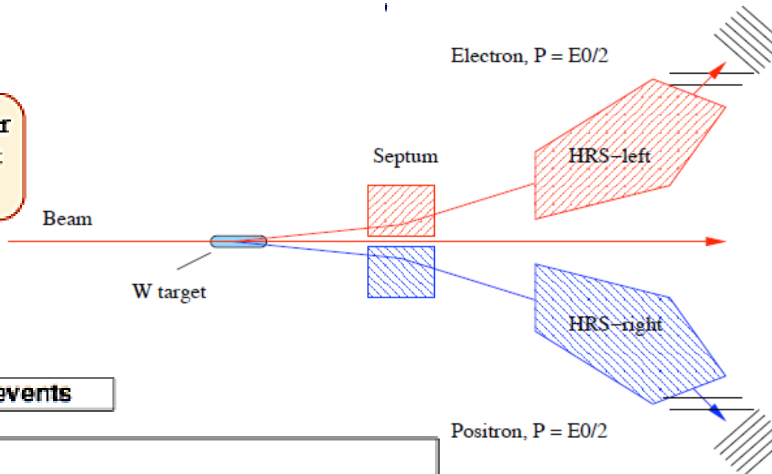
Signal

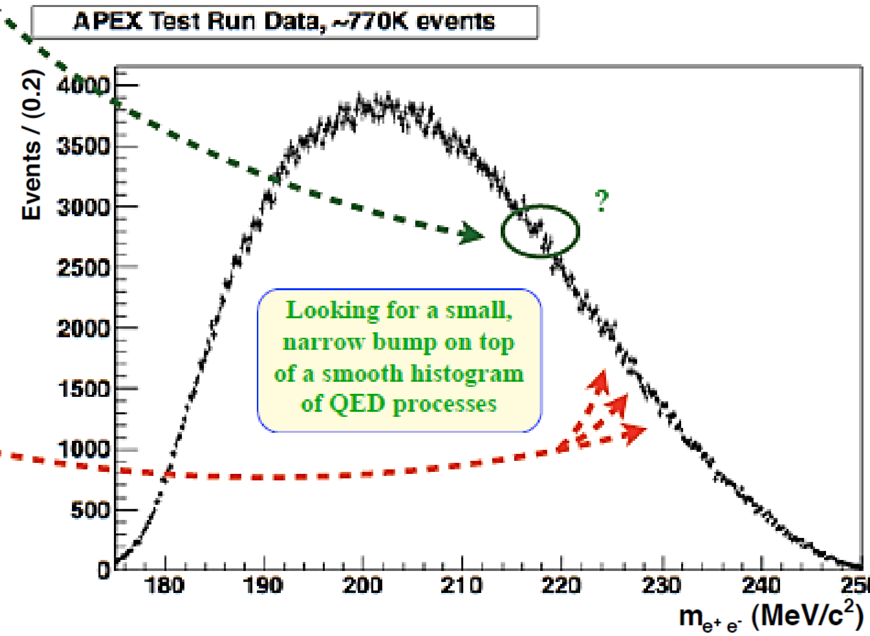




QED backgrounds

Dipole septum magnets allow for detection of e^+e^- produced at small angles



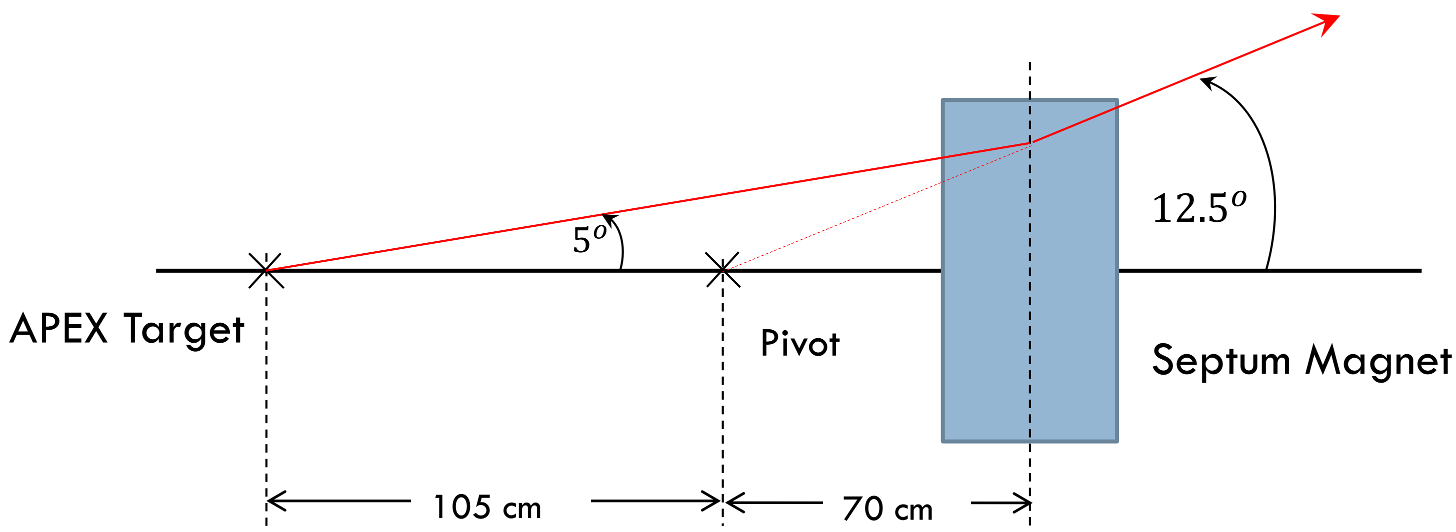


Looking for a small, narrow bump on top of a smooth histogram of QED processes; excellent mass resolution required

James Beacham, DHF - Messina, Italy, September 2014

APEX Run plan

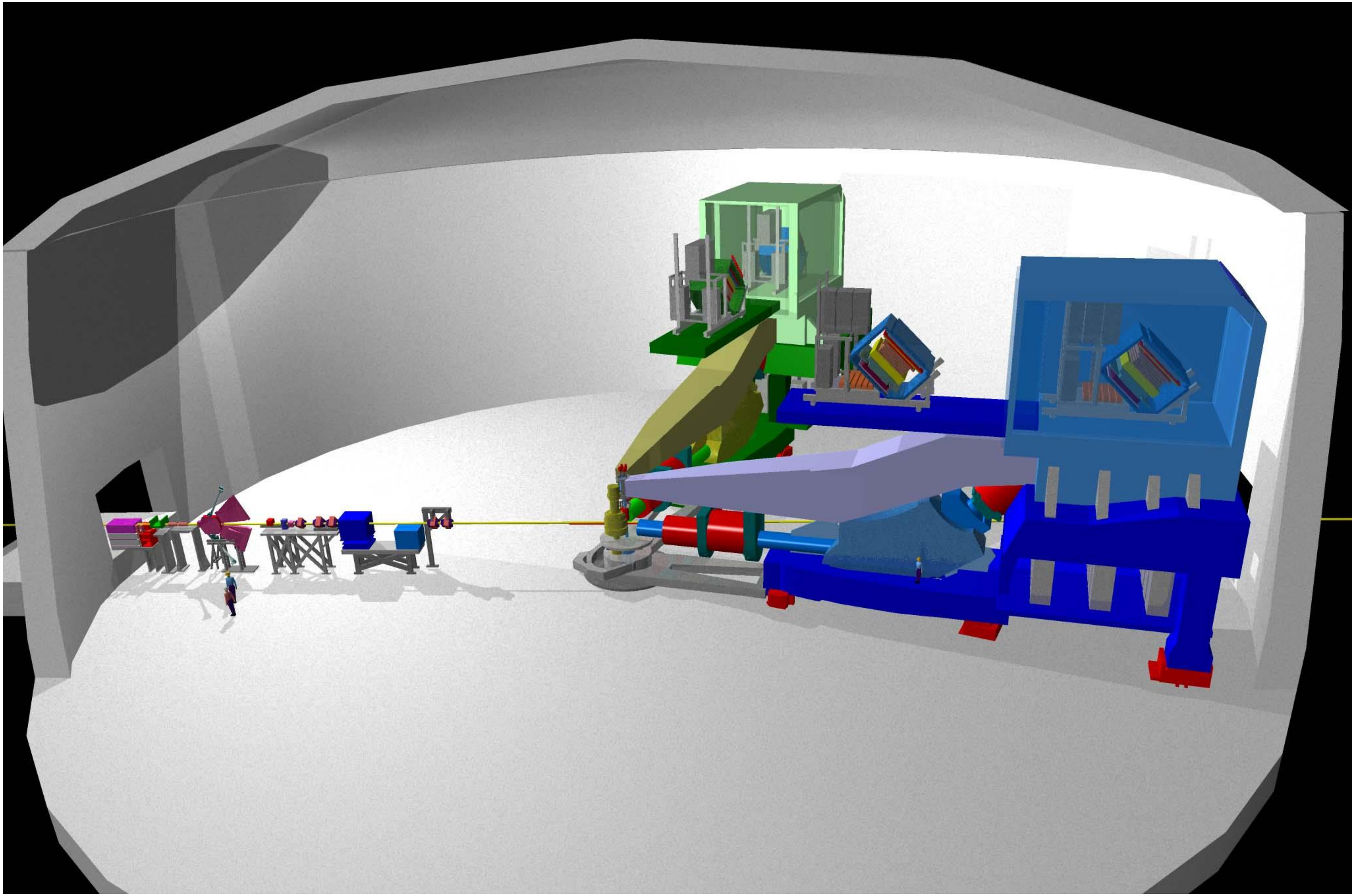
	A	B	C	D
Target	Tungsten $4\%\ X_0$	Tungsten $8\%\ X_0$	Carbon $0.7\%\ X_0$	Tungsten $8\%\ X_0$
Beam Energy	2.2 GeV	4.4 GeV	1.1 GeV	3.3 GeV
High Resolution Spectrometer (HRS) position	Central Angle - 12.5^o			
New equipment in the beam line	1) Septum Magnet 2) APEX Extension Box			



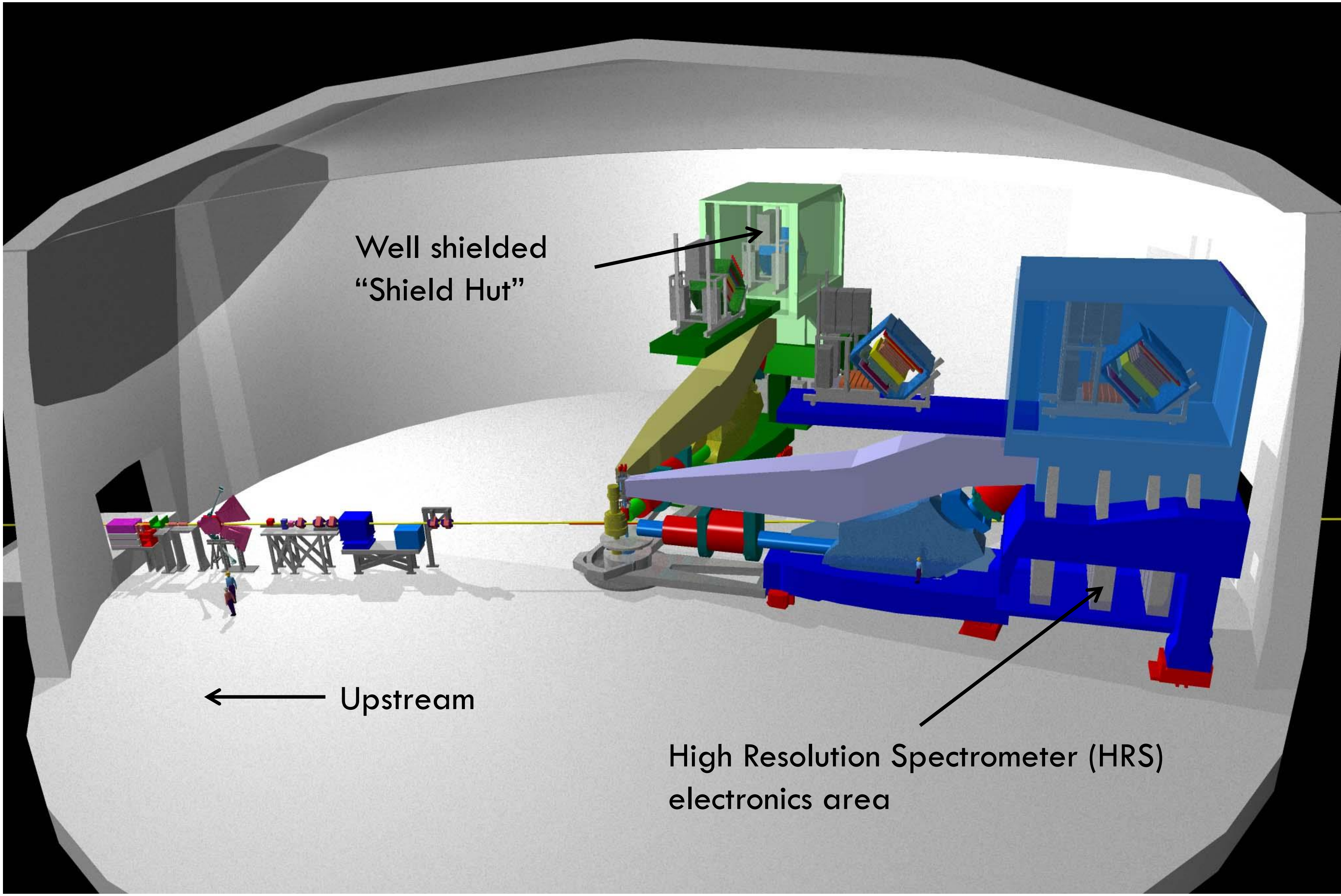
APEX challenges

- High dose rates due to high Z target and equipment used in APEX.
- Radiation damage to electronics in the hall.
  - **Physical effects**, i.e. the displacement of atoms within a crystal.
  - **Chemical effects**. i.e. breaking of existing chemical bonds and/or the formation of new bonds.
  - **Ionization effects**. produces electrical paths that allow an electric charge to break down isolations and potential barriers.
- Important to do a complete radiation analysis before proceed with the actual experiment.

JLab Hall A Setup



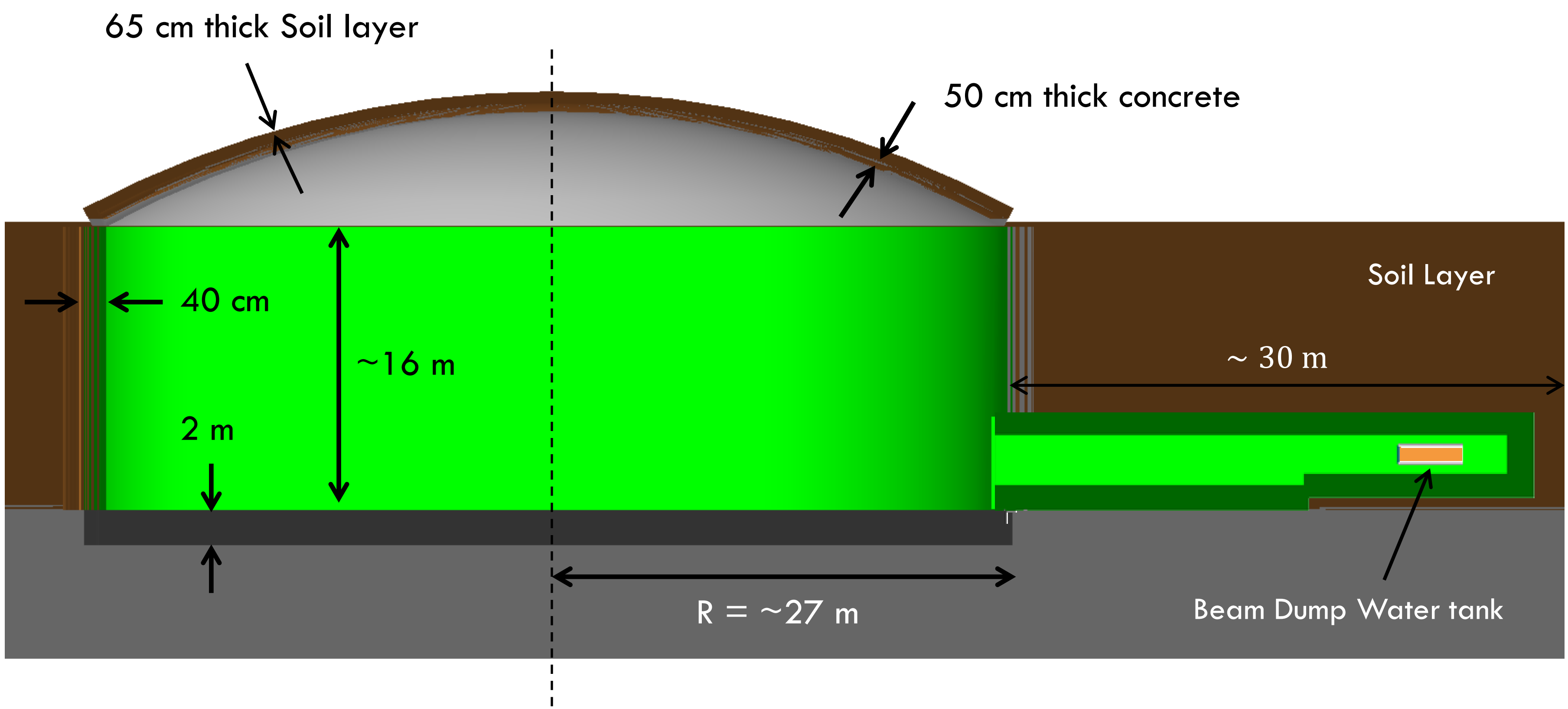
JLab Hall A Setup



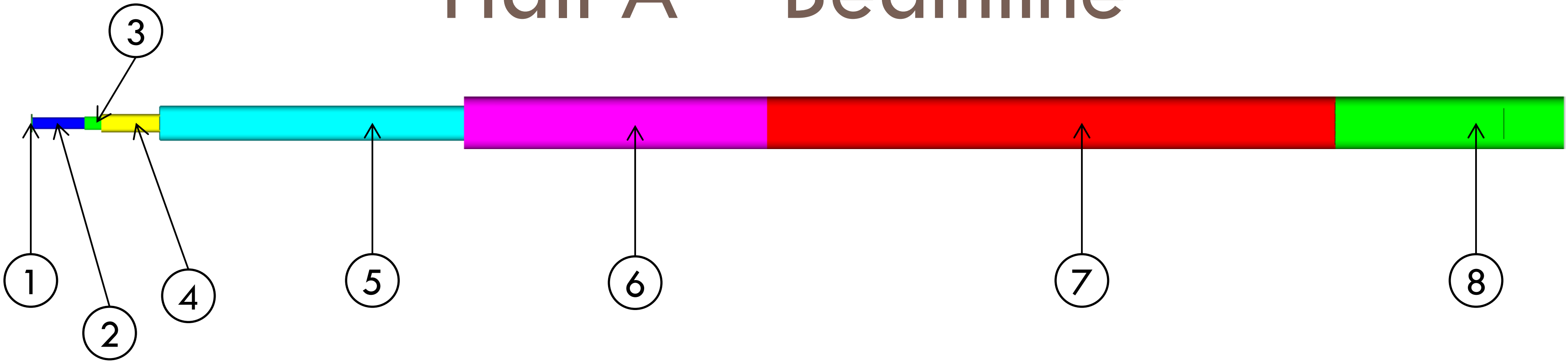
GEometry ANd Tracking

- GEANT4 is a toolkit for the simulation of the passage of particles through matter.
- Developed and maintained by GEANT4 Collaboration (http://www.cern.ch/geant4)
- Often used in physics as well as space science.

GEANT4 model of Hall A

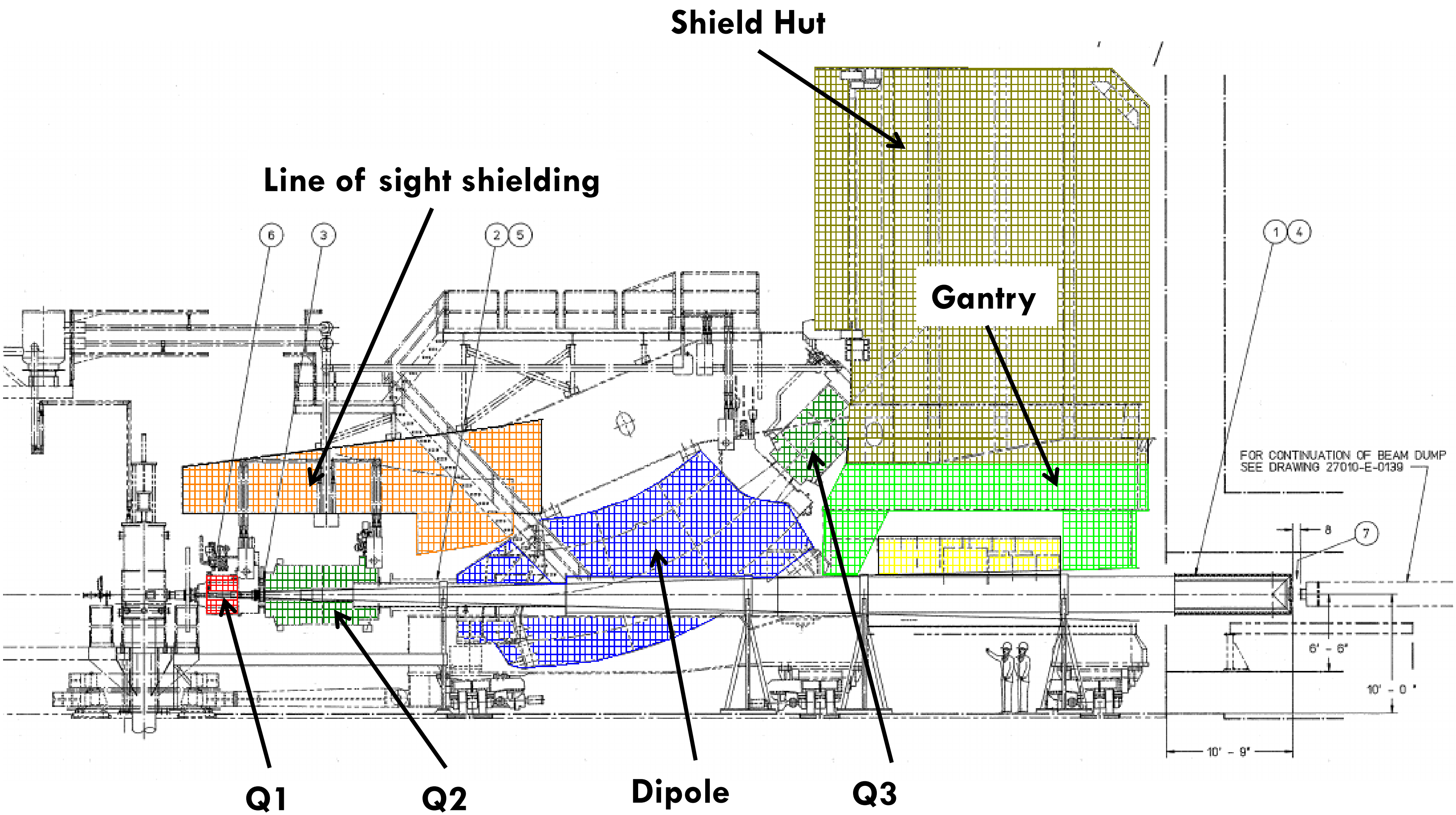


Hall A – Beamline

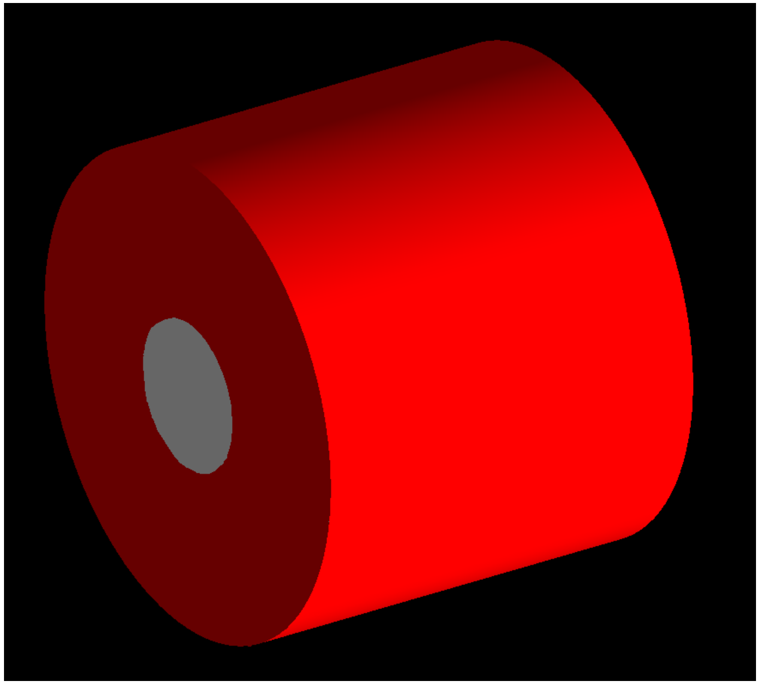


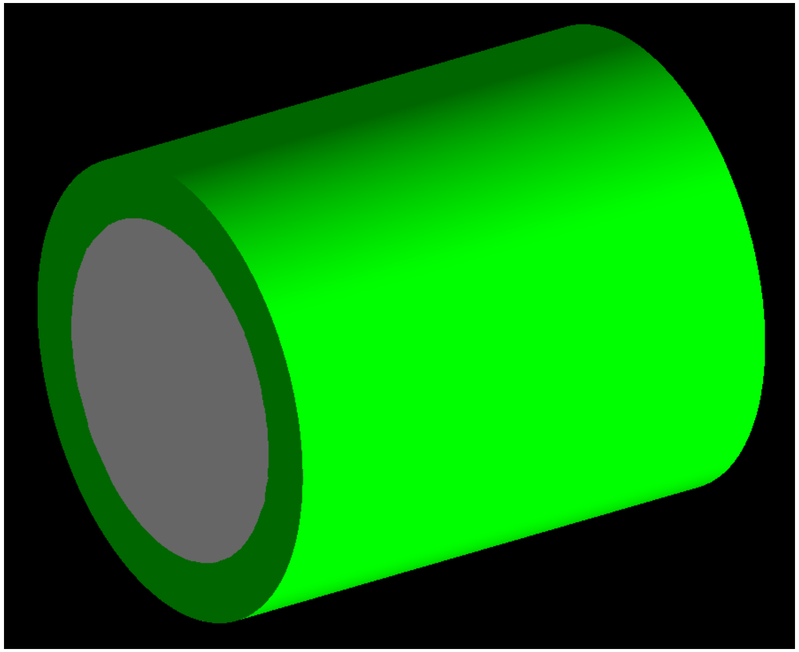
	ID (inches)	OD (inches)	Length (inches)	Density of aluminum wall (g/cm^3)
1	8.02	13.5	0.75	2.699
2	8.0	8.25	36.875	2.699
3	9.75	10.0	12.0	2.699
4	12.0	13.0	41.8125	0.3761
5	24.0	25.0	217.0	0.3718
6	36.0	38.0	216.375	0.2124
7	36.0	38.0	405.1875	0.2124
8	36.0	38.0	120.4375	0.2124

Description of HRS



Q1, Q2 Magnets

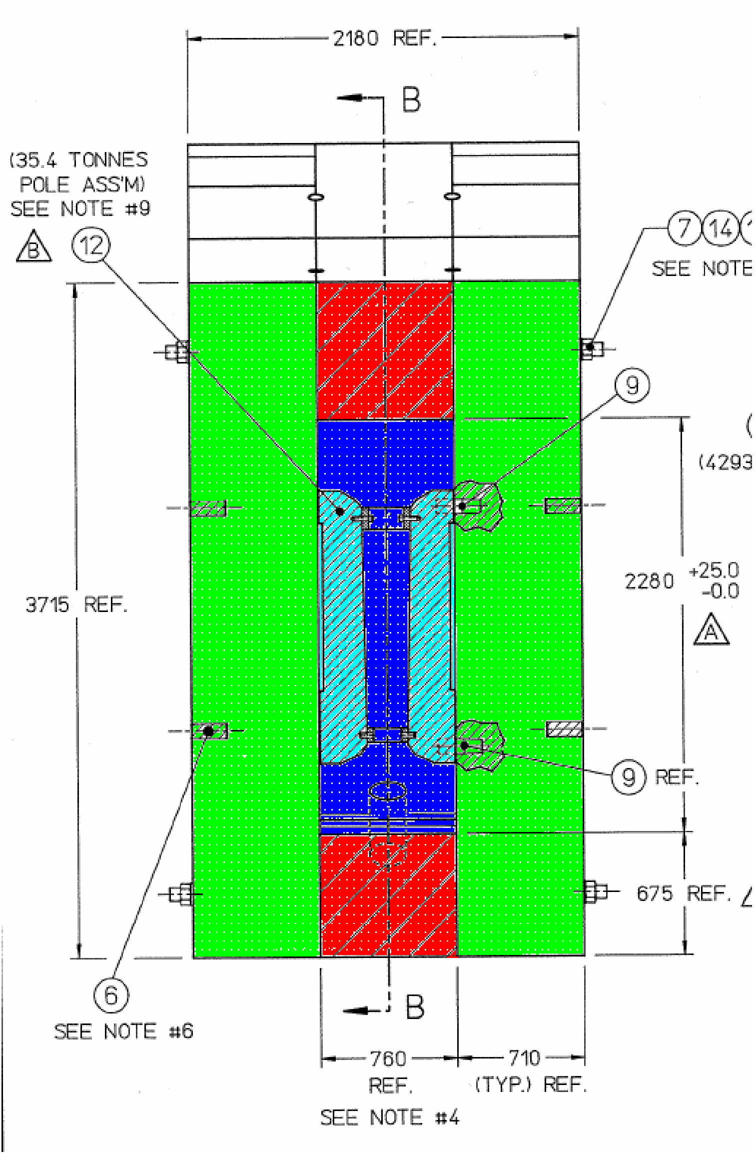


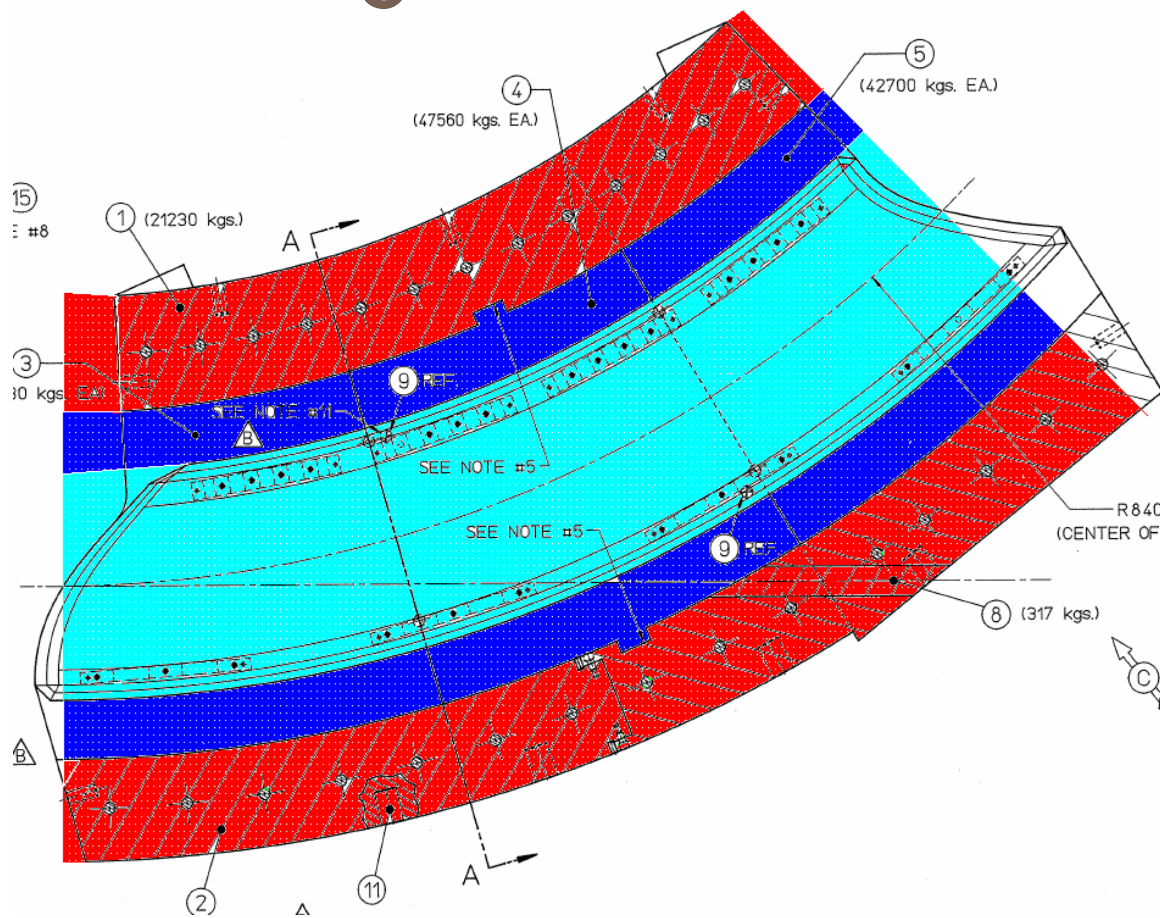


Iron
Vacuum

Iron
Vacuum

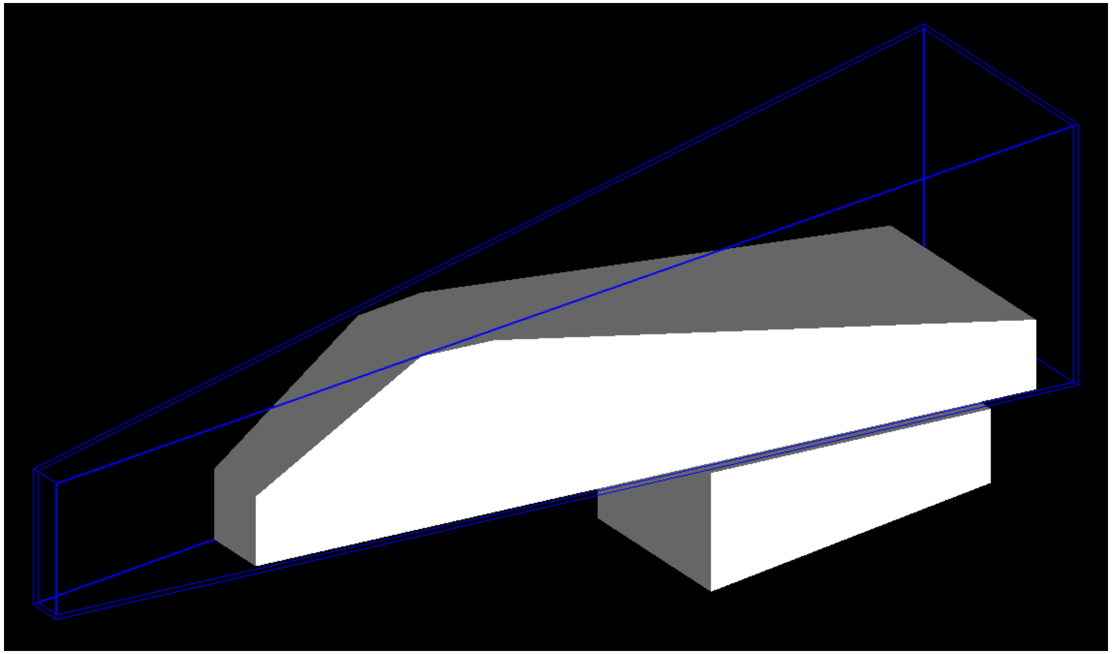
Dipole Magnet

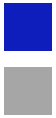




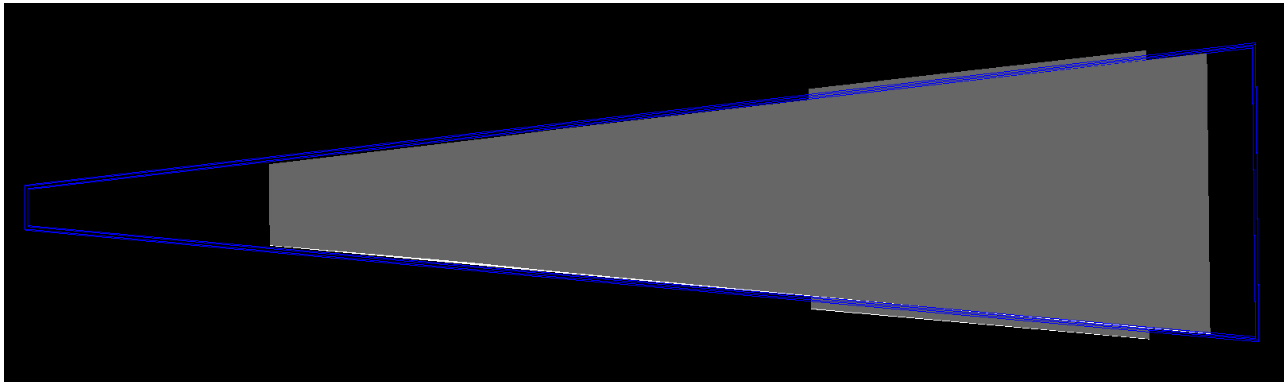
- Dipole Iron Assembly
- Dipole Iron Yoke
- Vacuum gap
- Iron Poles

Line of sight shielding



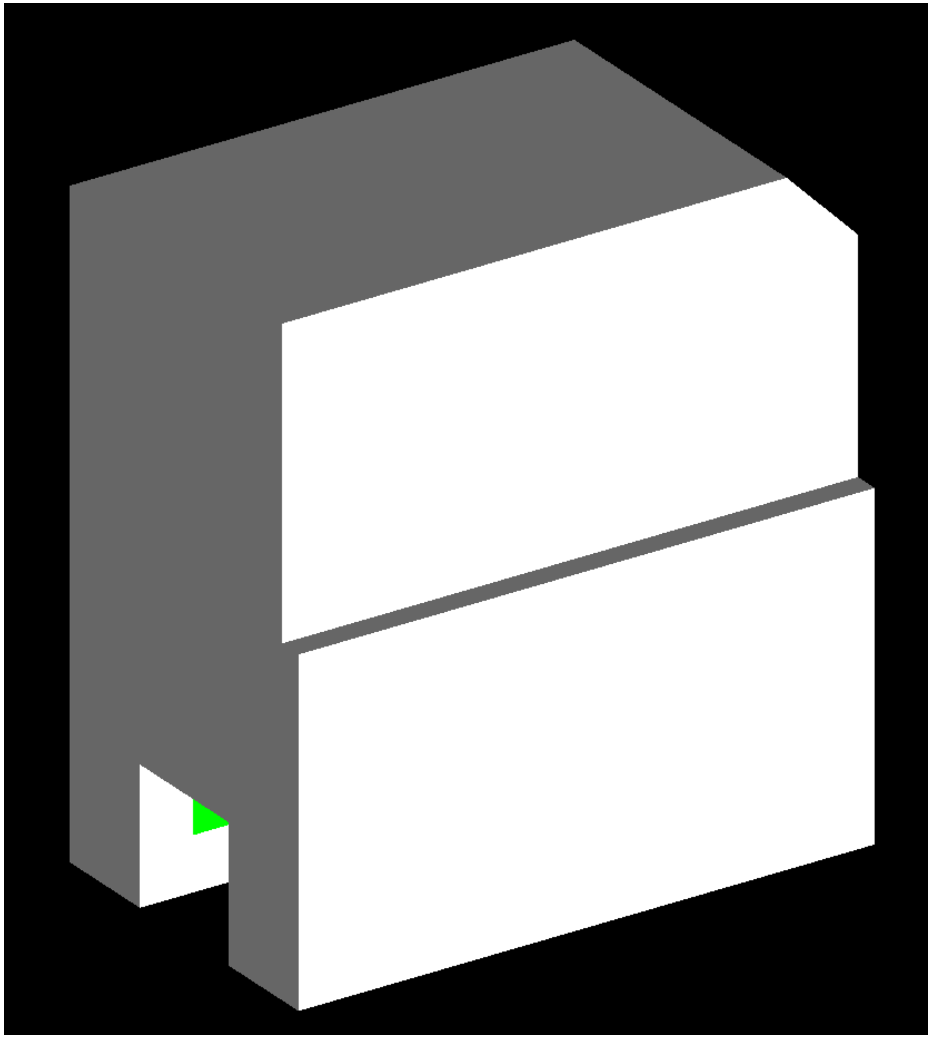


Steel frame
Concrete structure

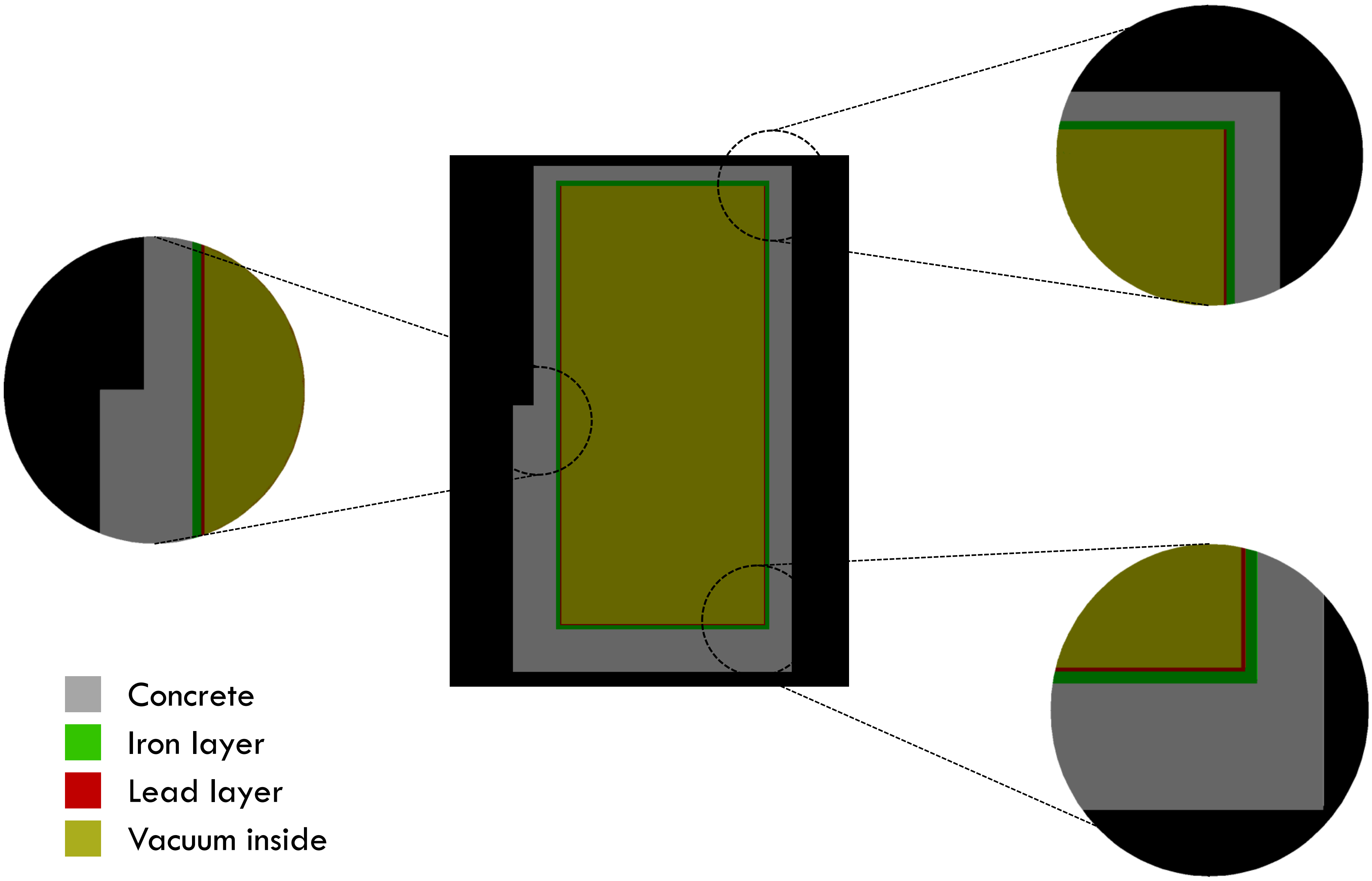


Top View

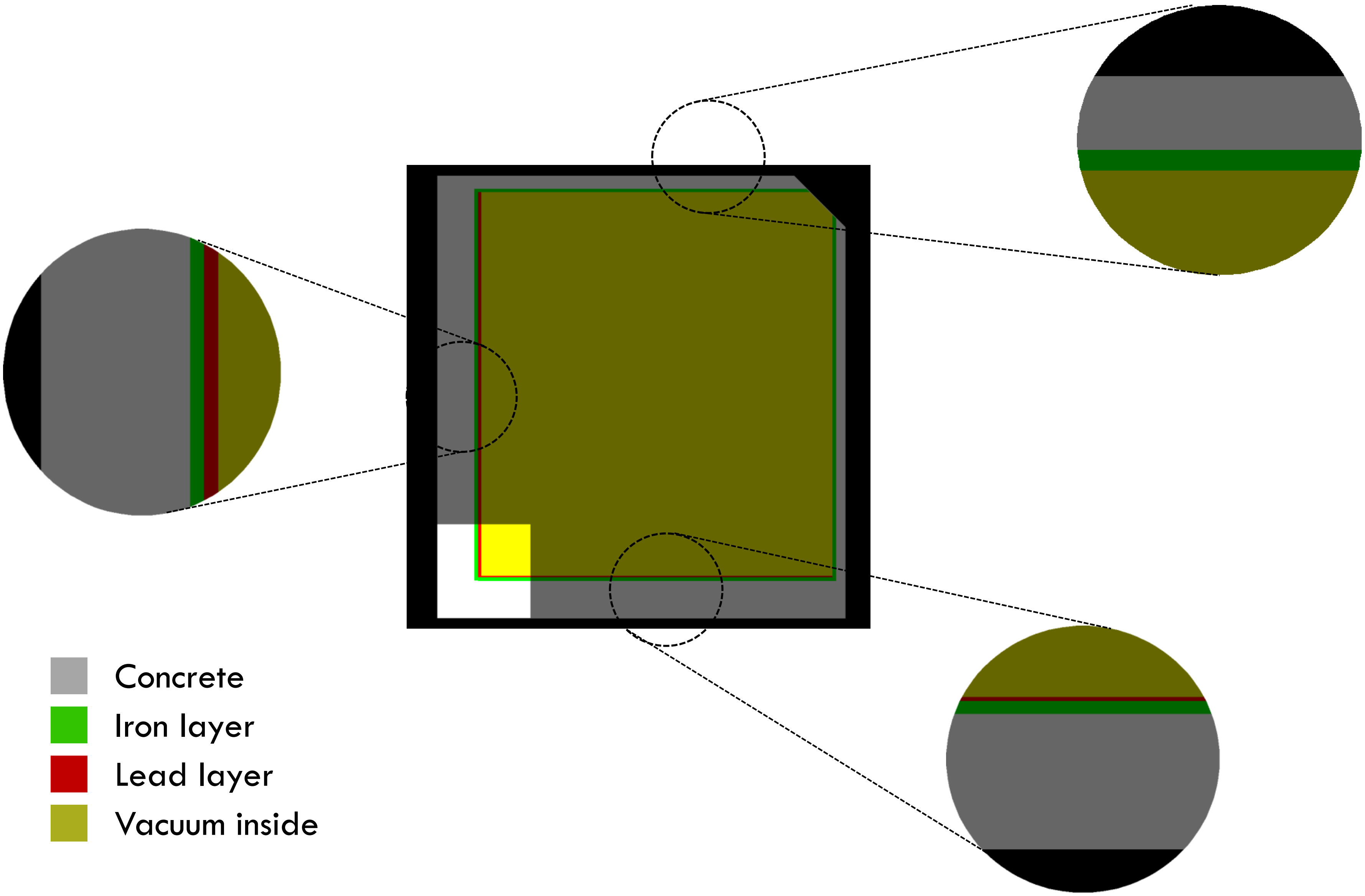
HRS Shield Hut



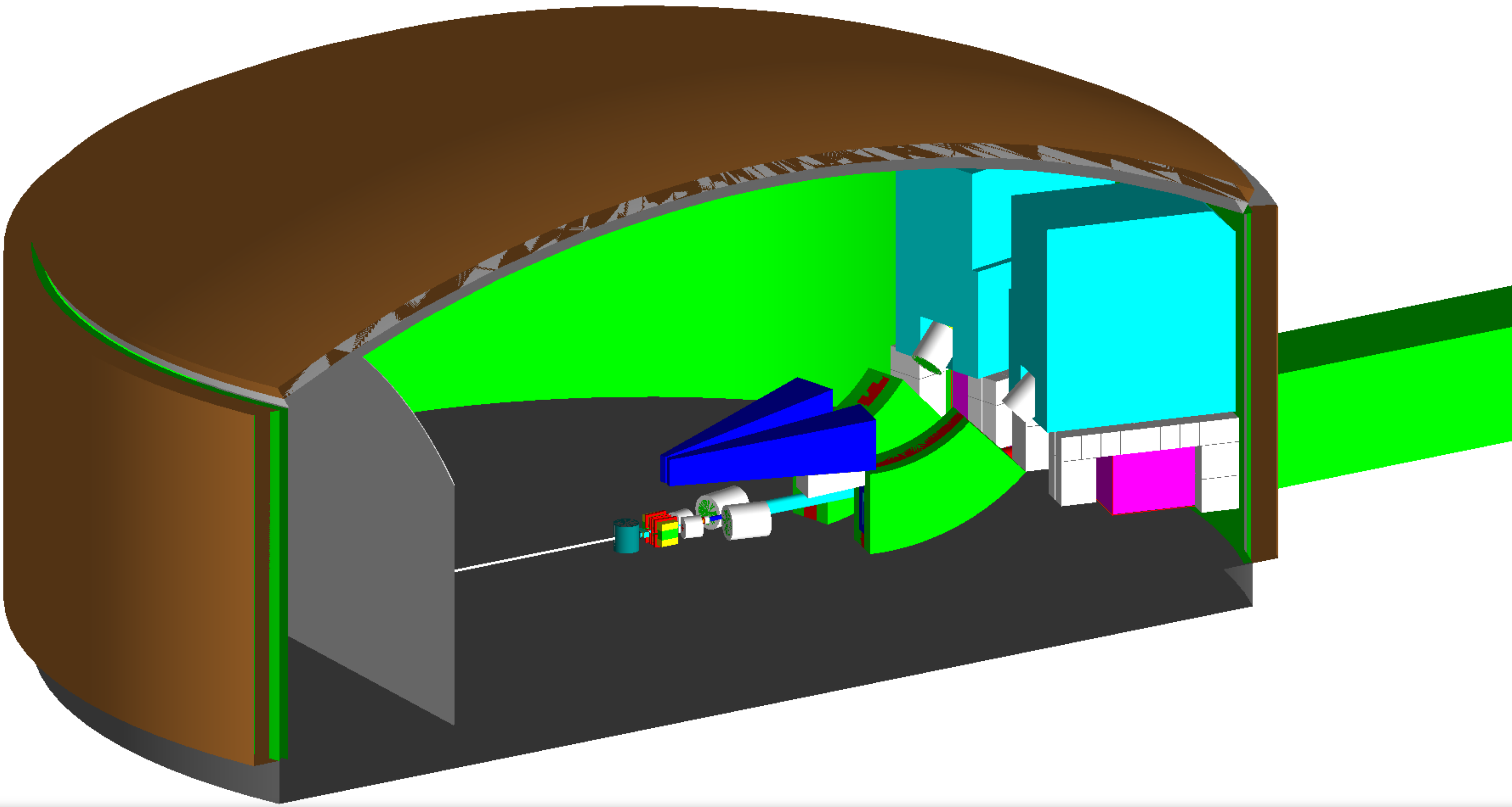
HRS Shield Hut – Front View



HRS Shield Hut – Side View



GEANT4 model of Hall A



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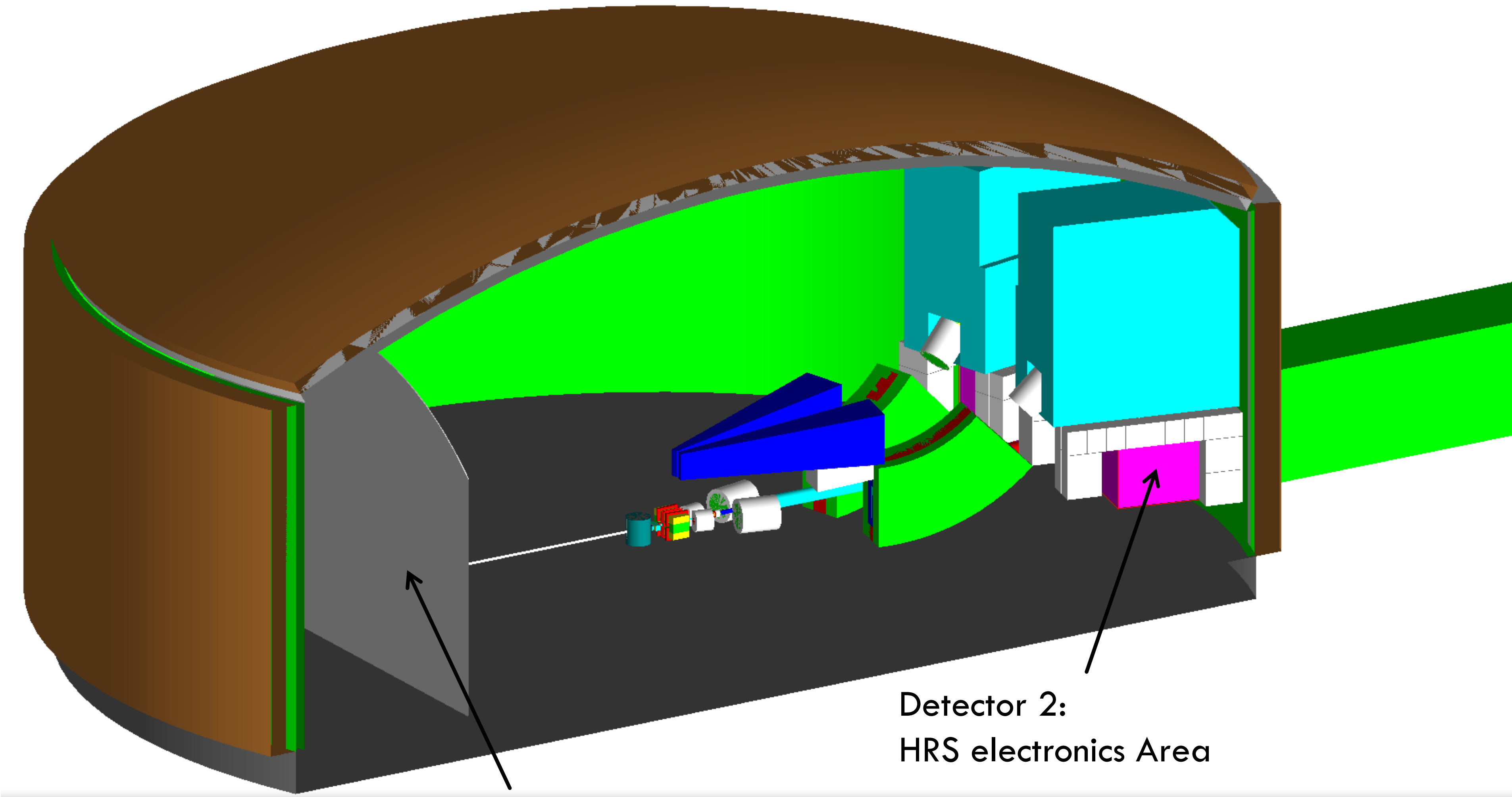

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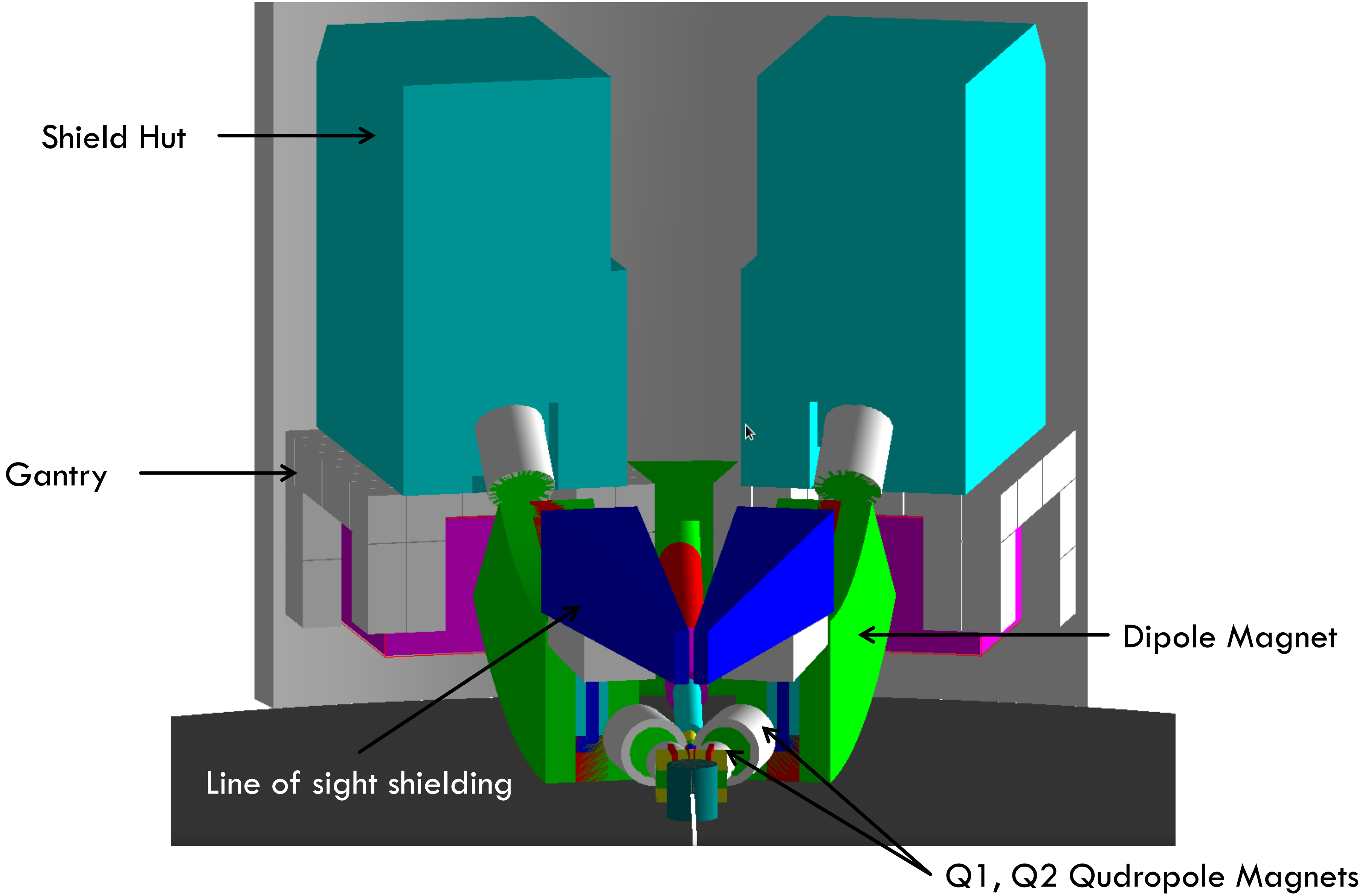
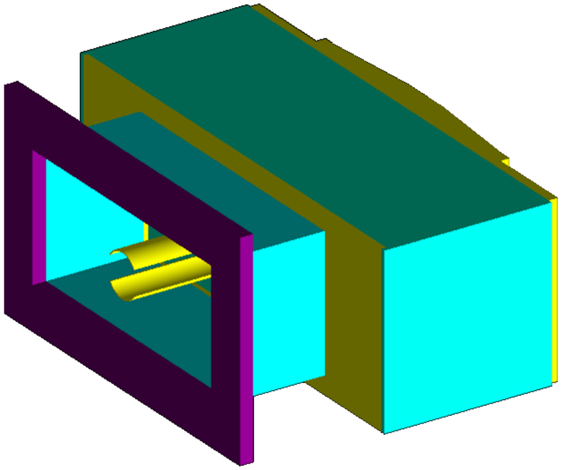
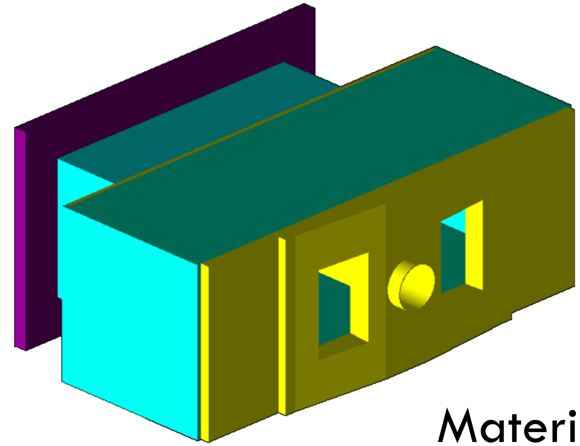
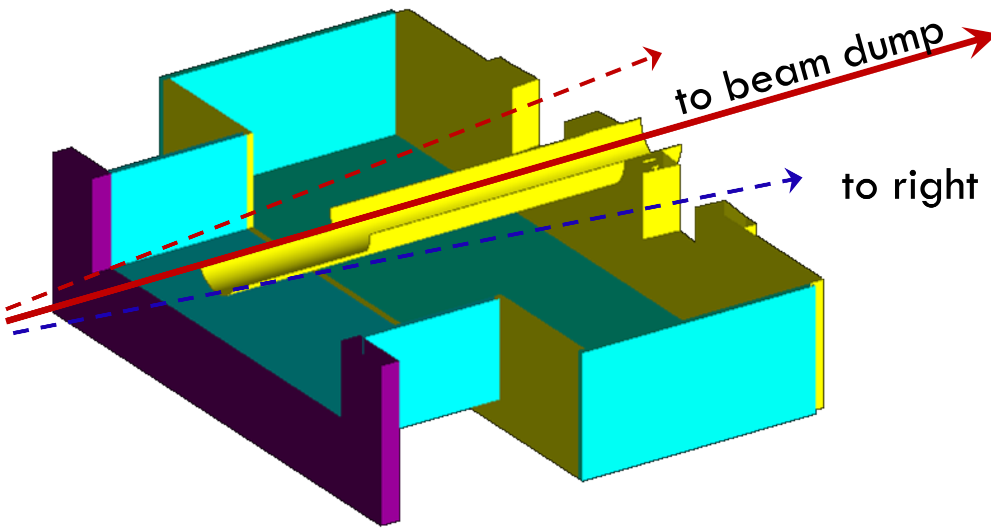


APEX Extension Box

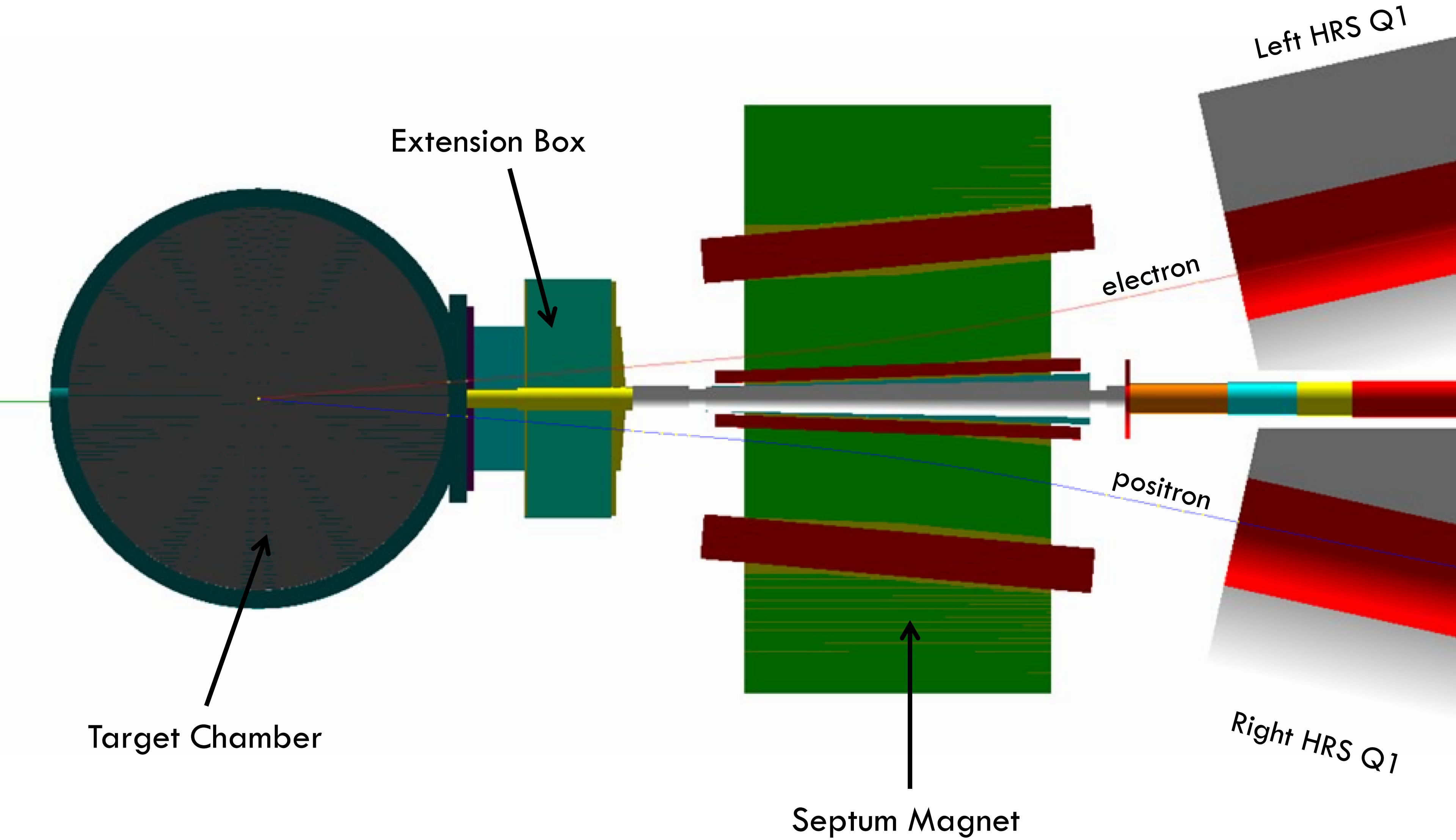




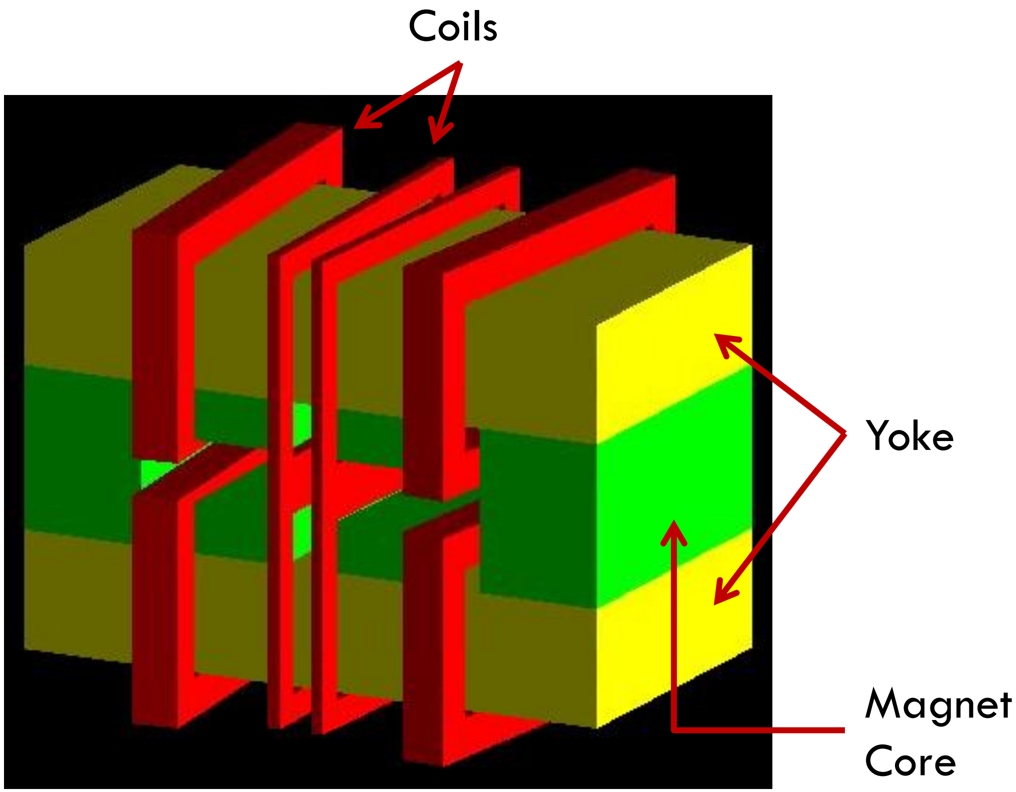
Material: Iron



Beam line – Top view

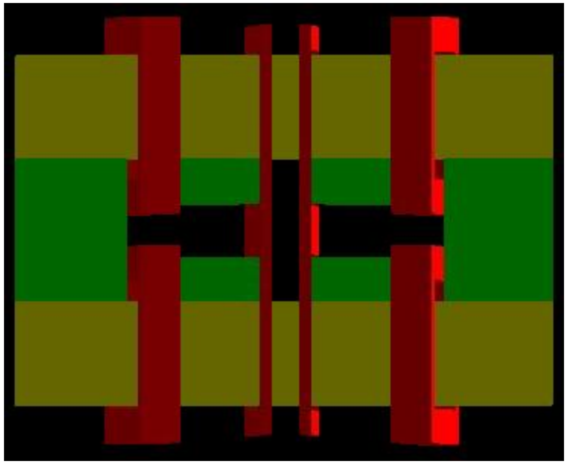


Septum Magnet

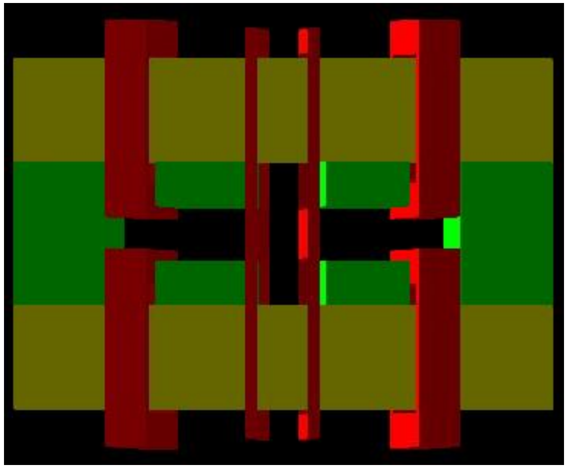


Material: Iron and Copper

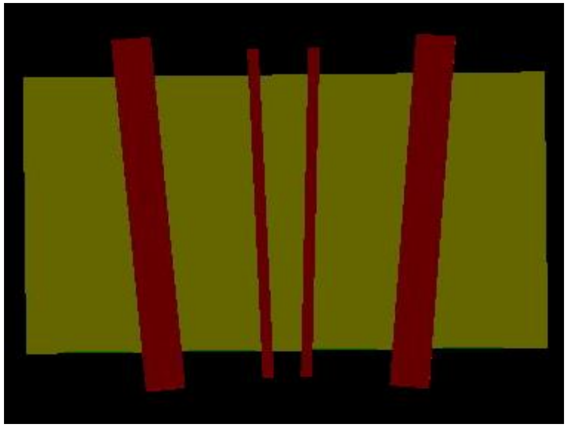
Back



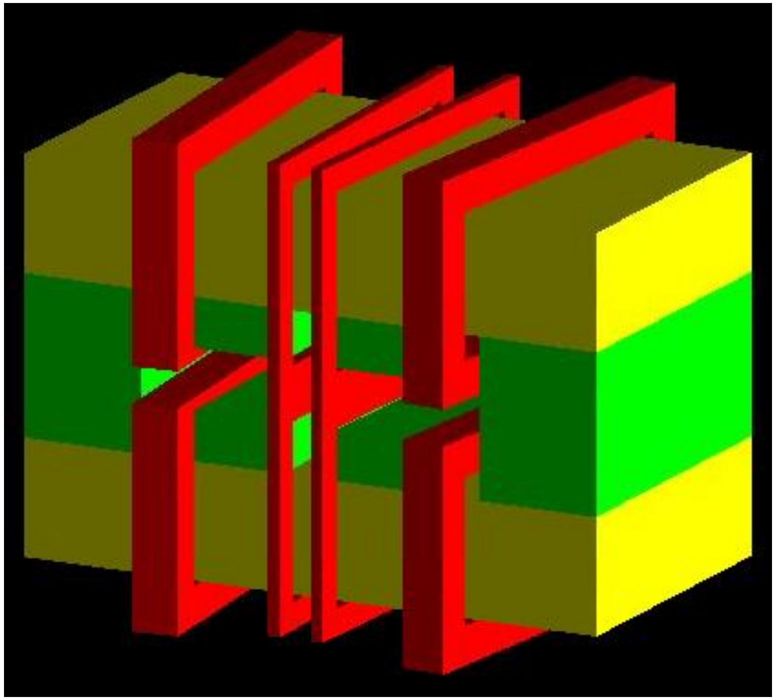
Front



Top



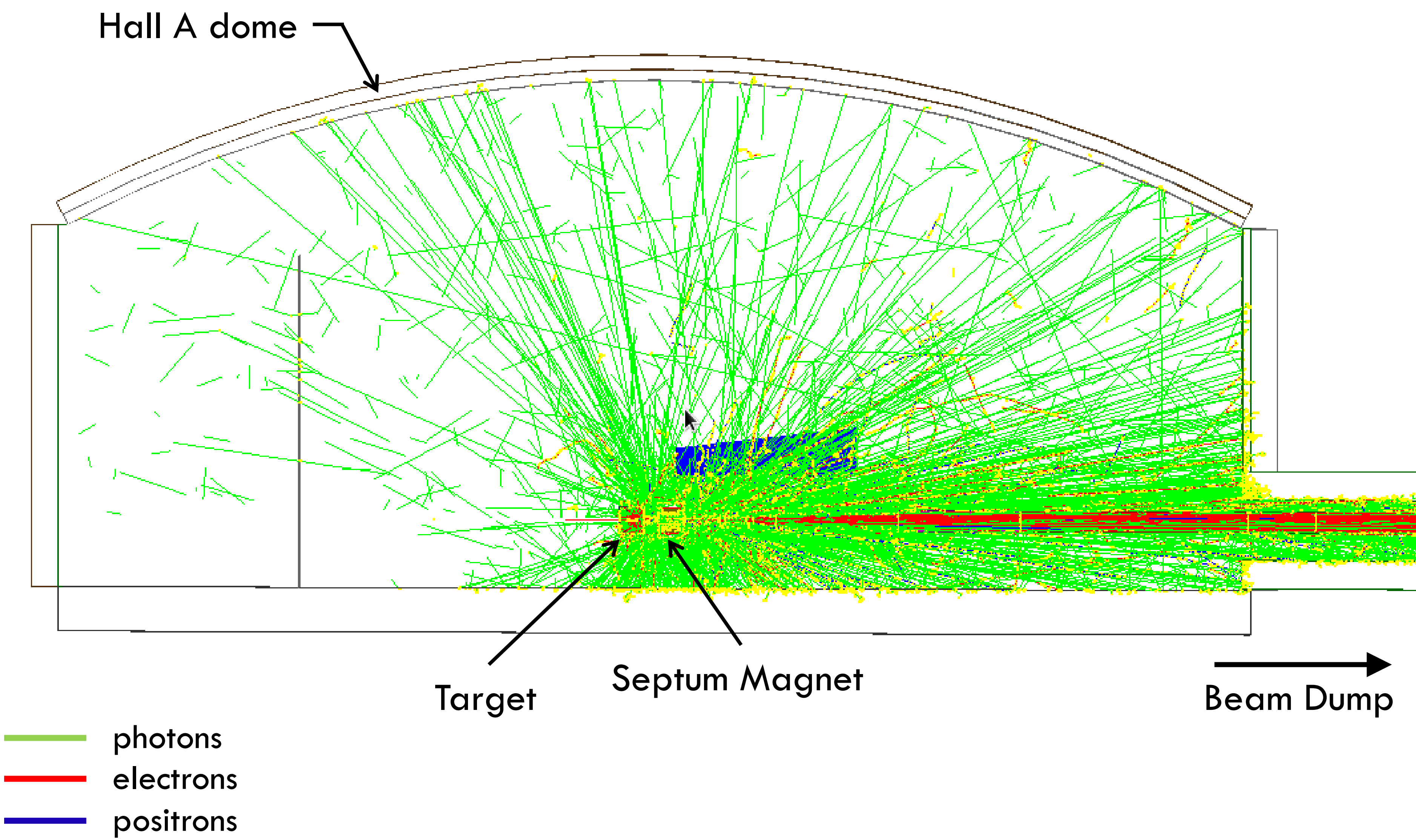
Septum Magnet



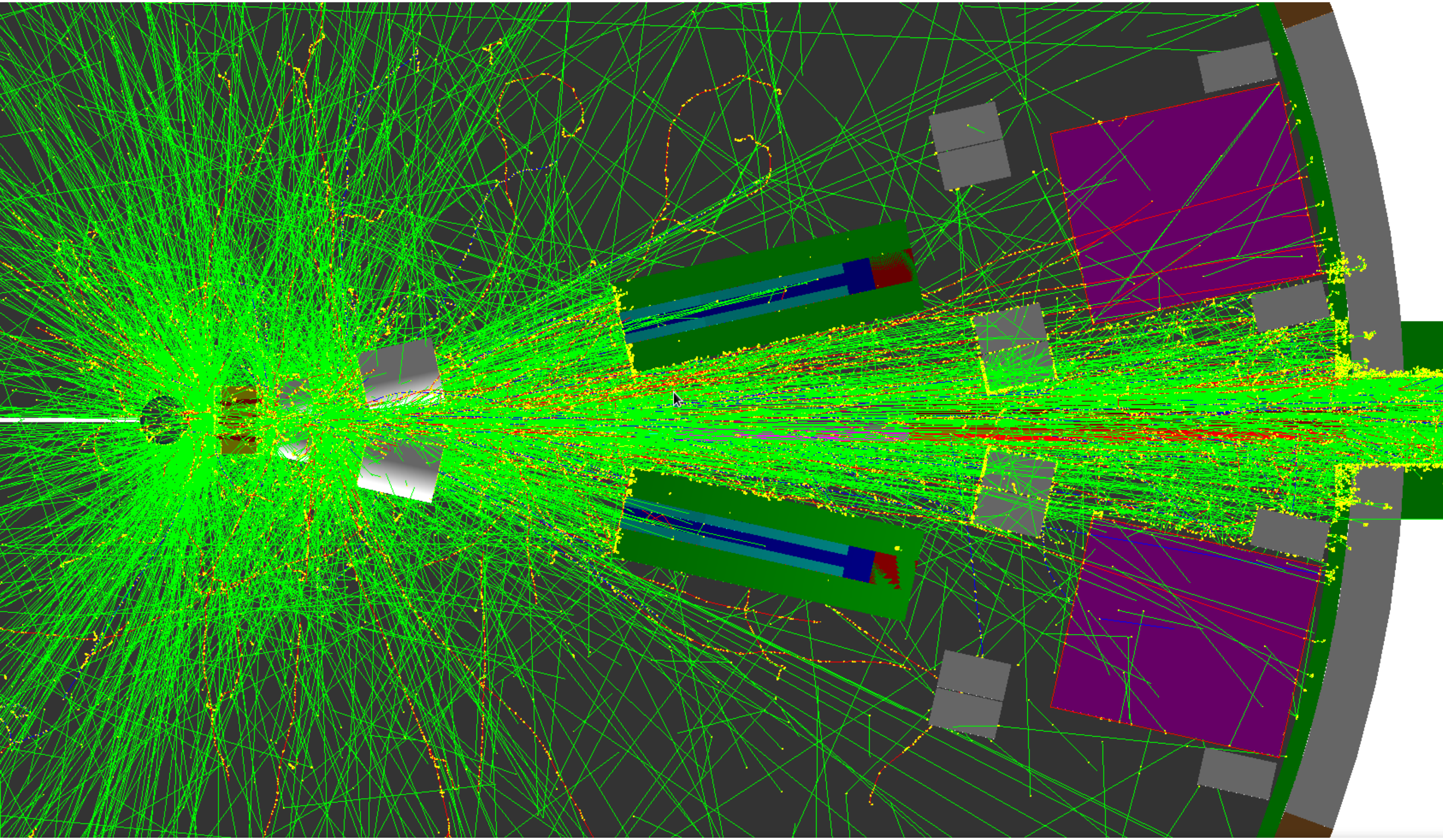
GEANT4 description

Actual magnet located at JLab

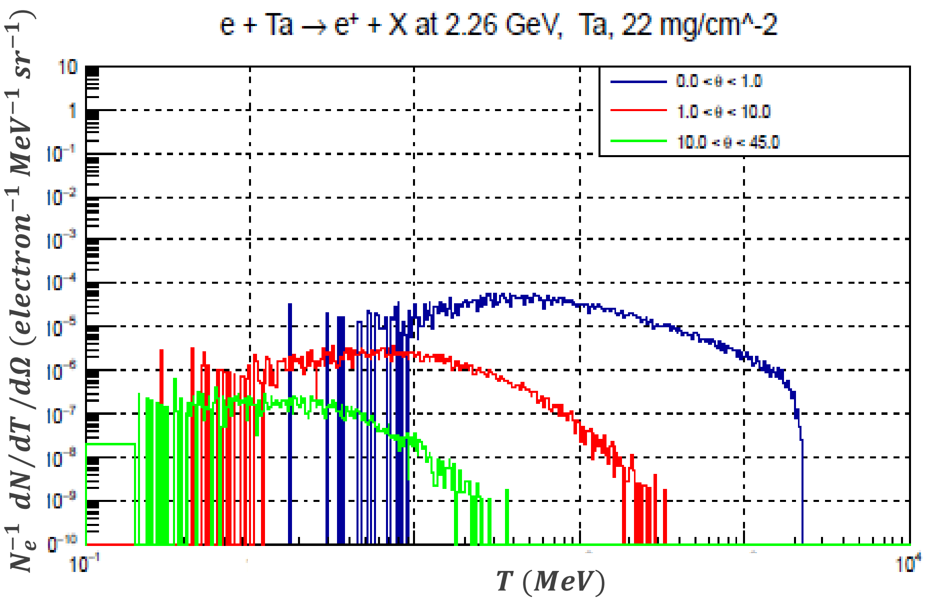
APEX Radiation Backgrounds in the Hall

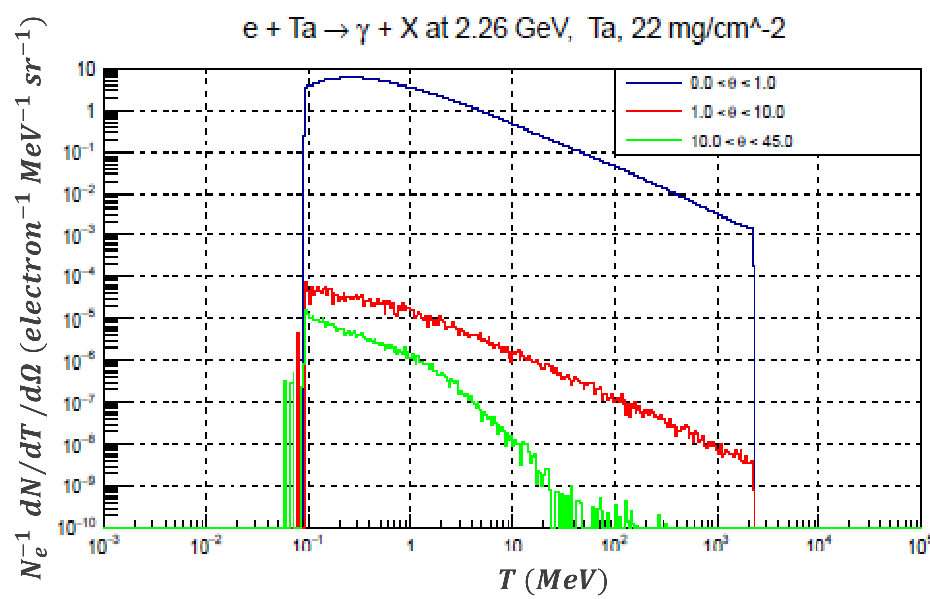


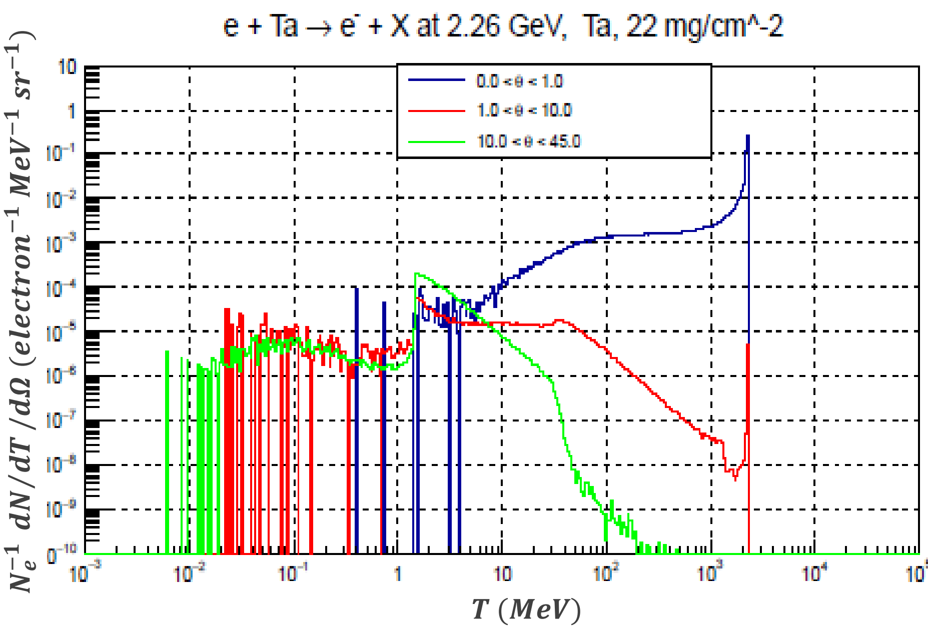
APEX Radiation Backgrounds in the Hall

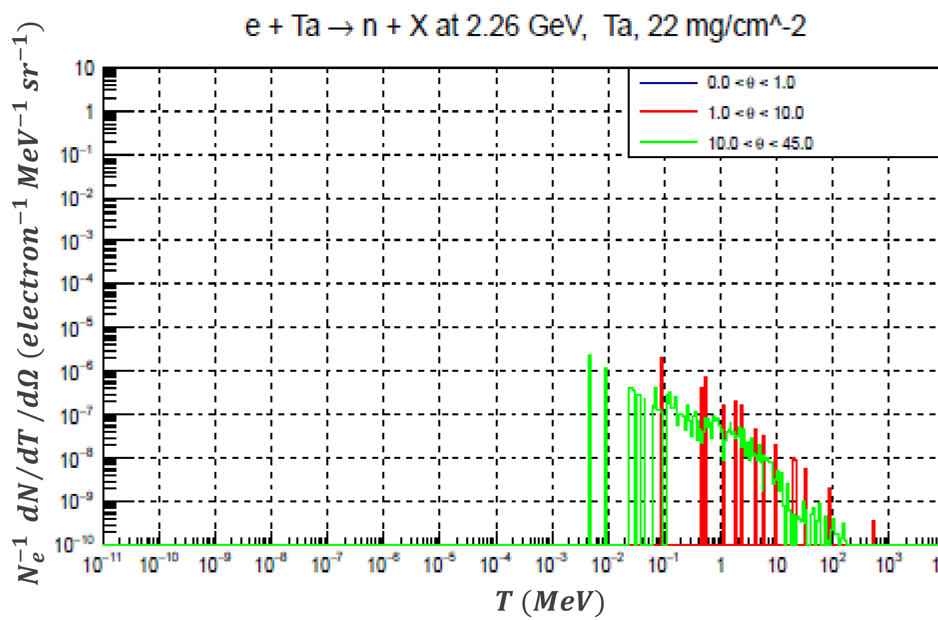


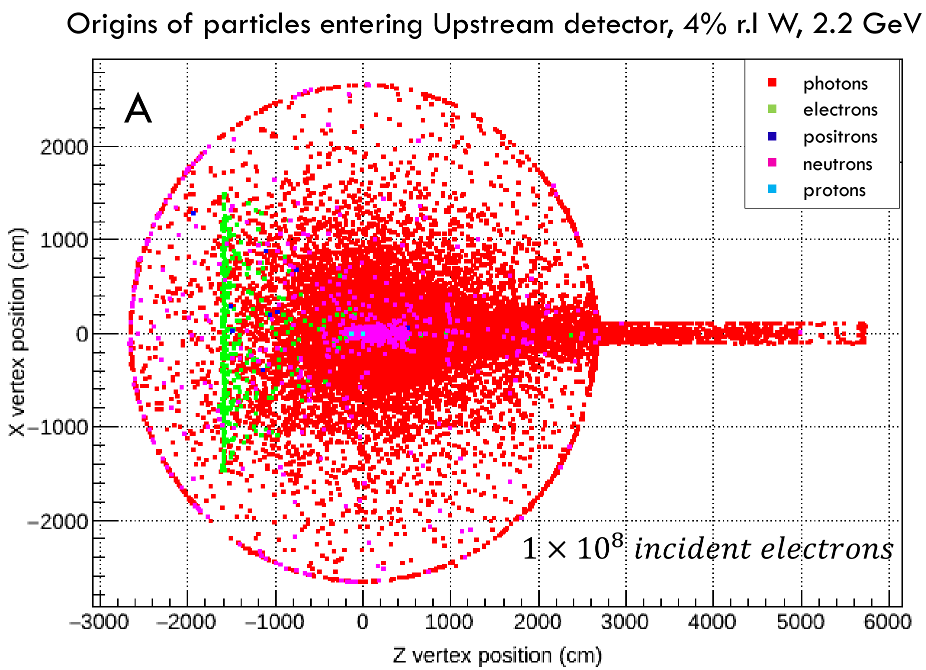
Particle yield from APEX test run



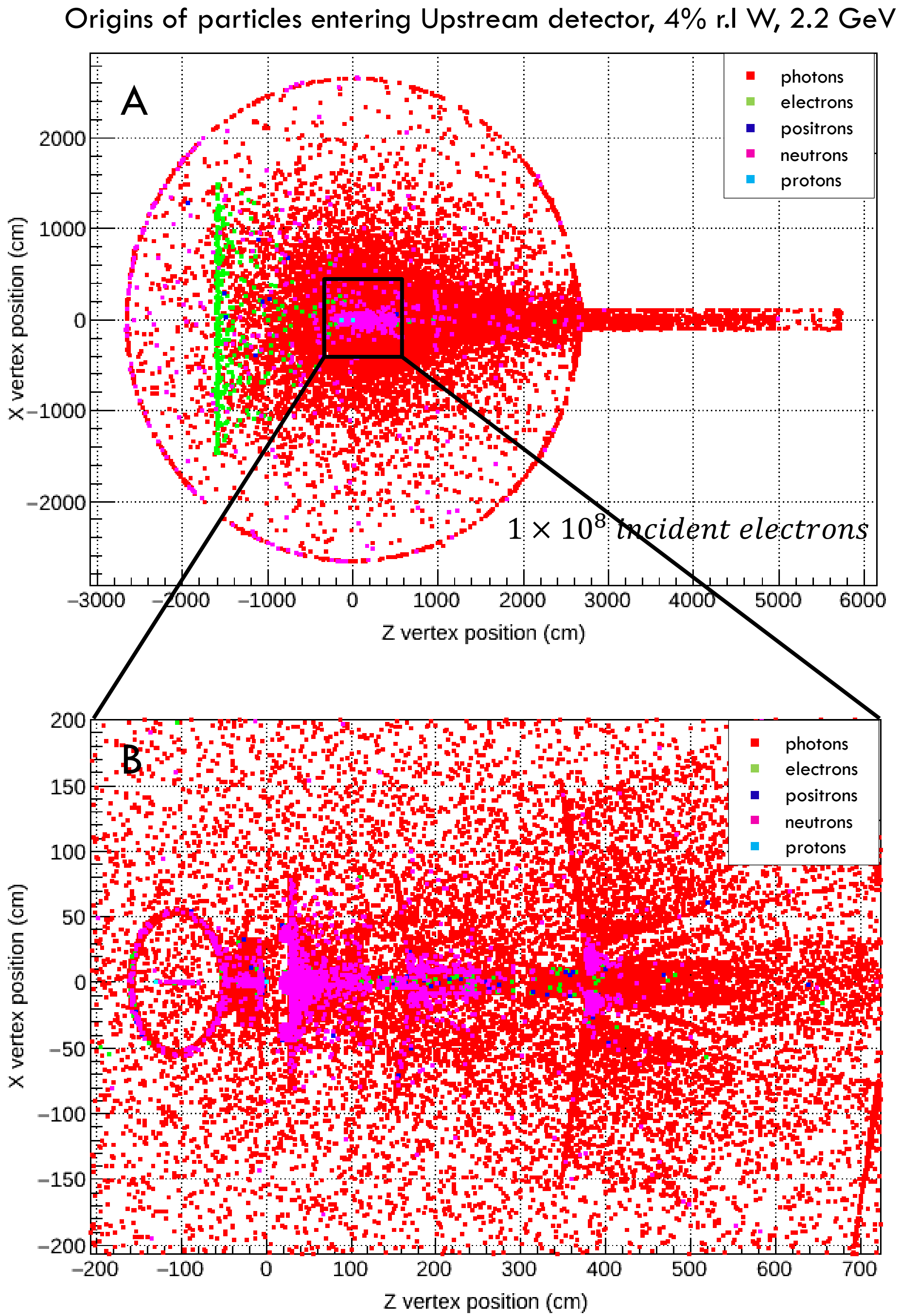








- X and Z coordinates of the origins of particles entered detector.



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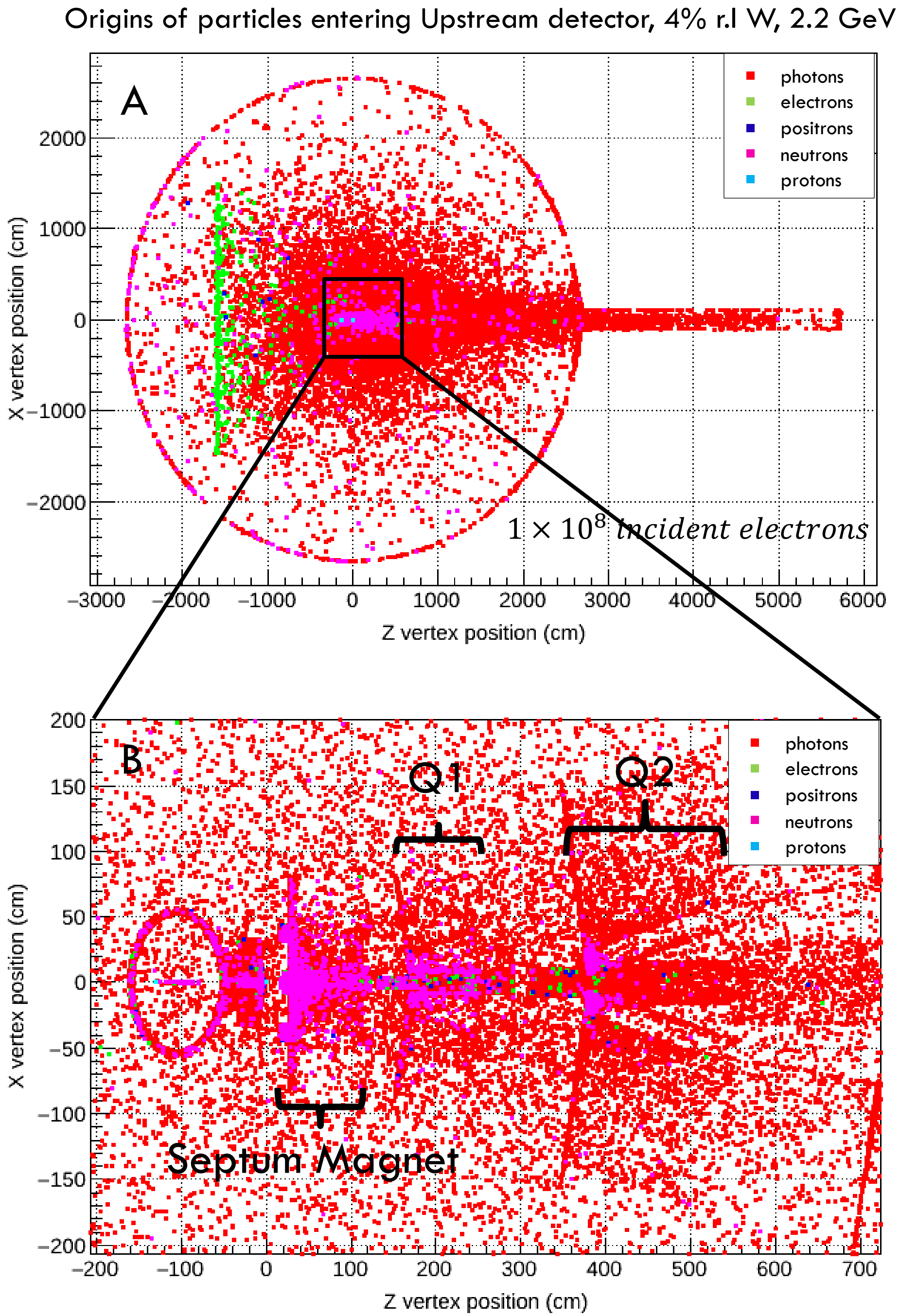

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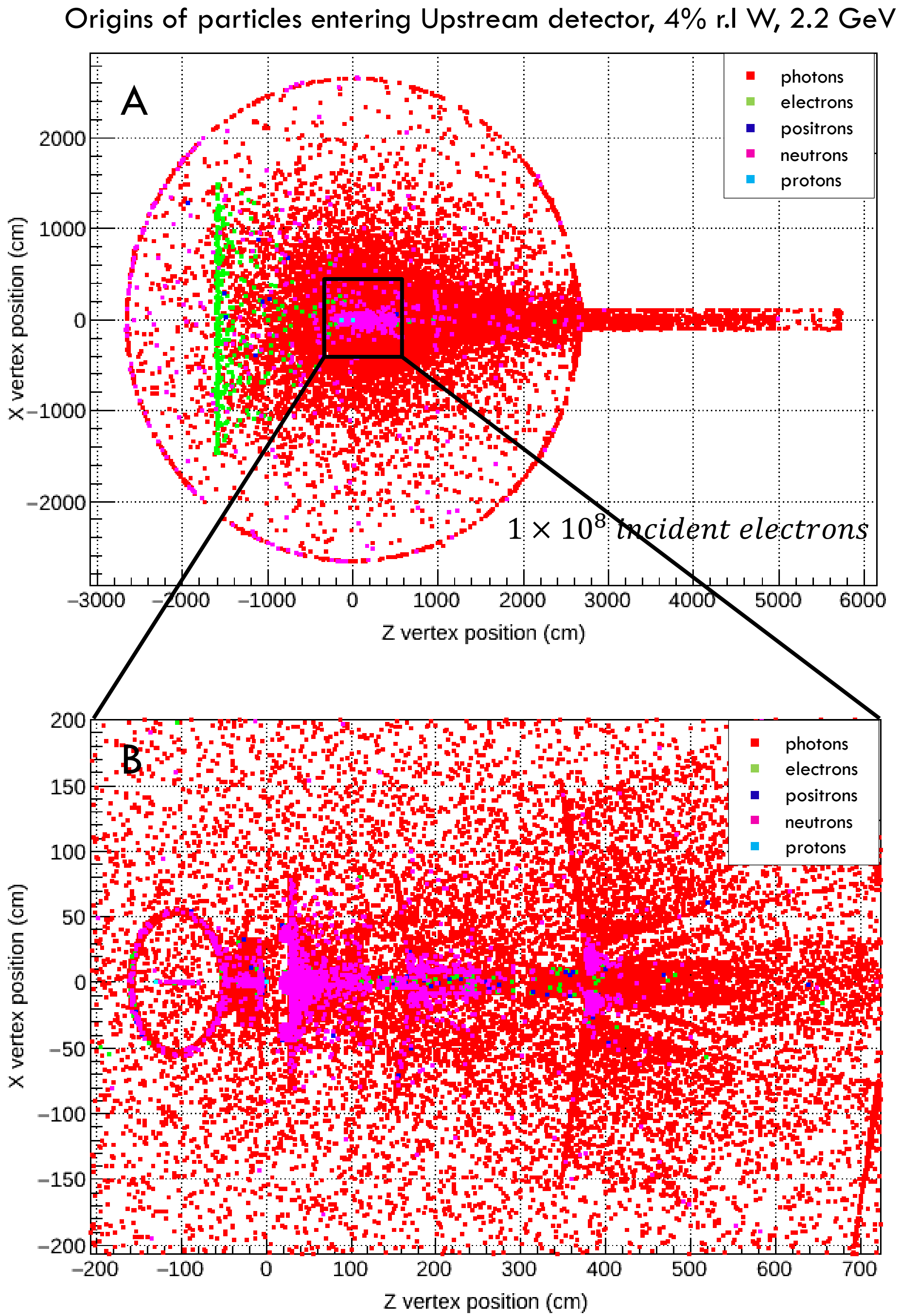

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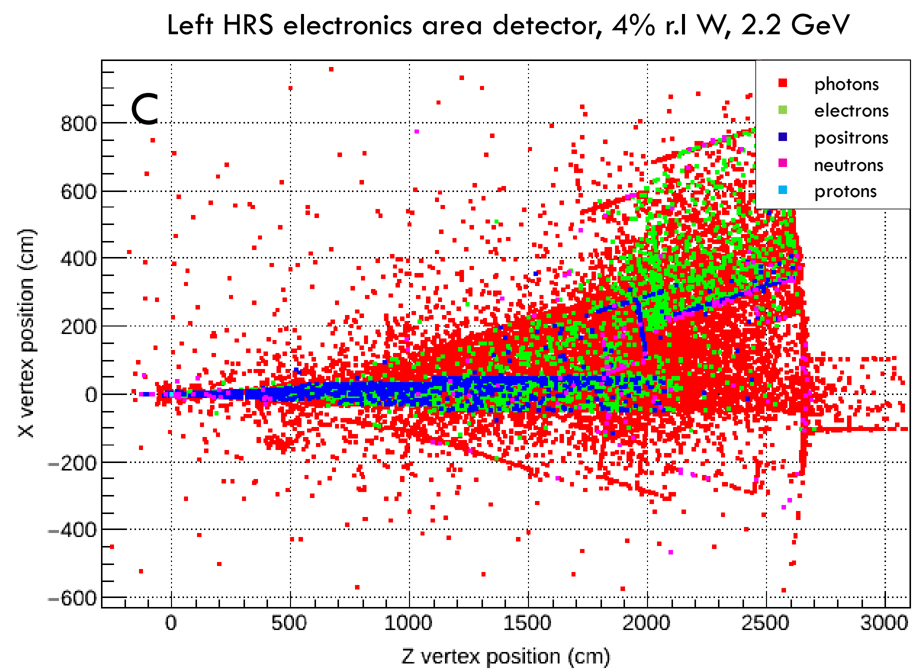
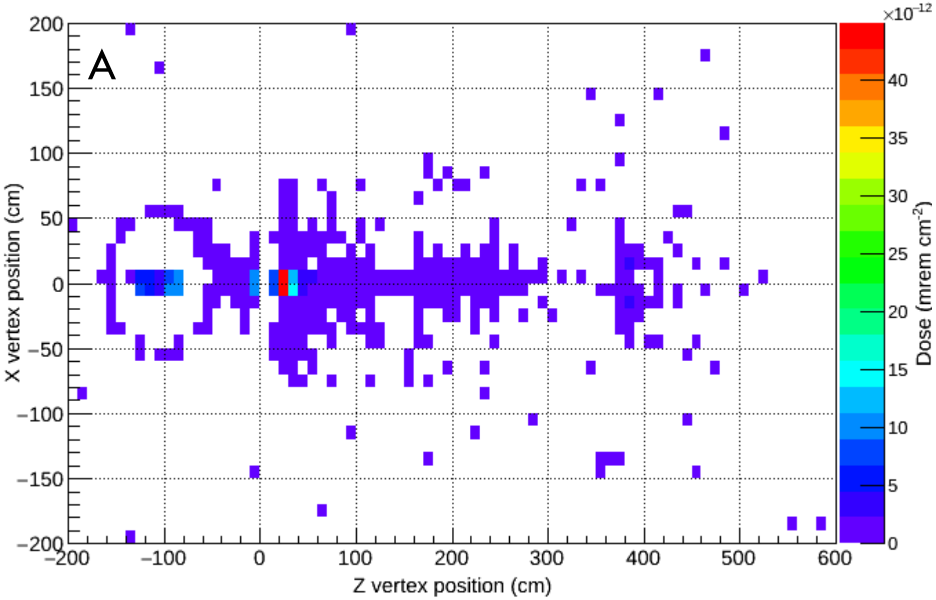
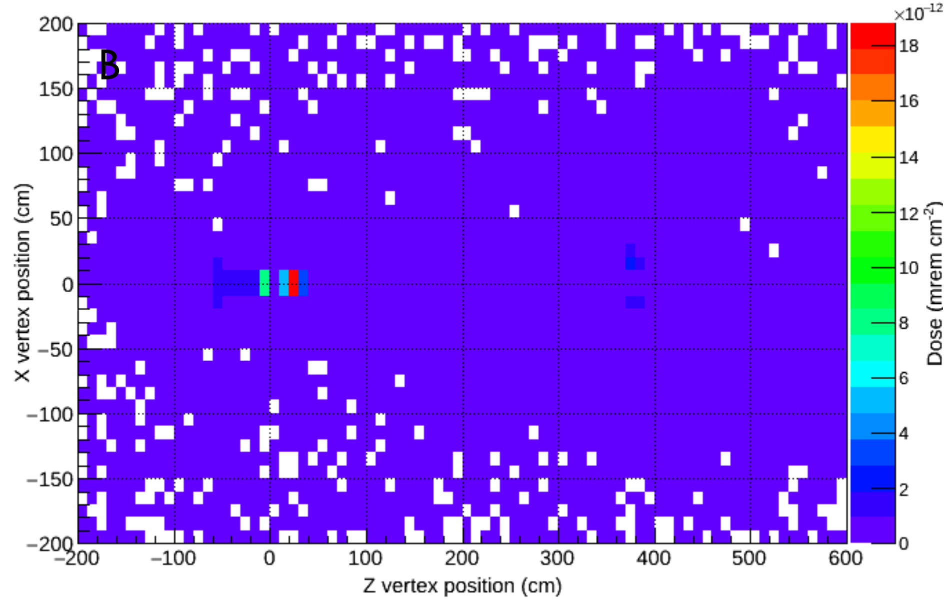


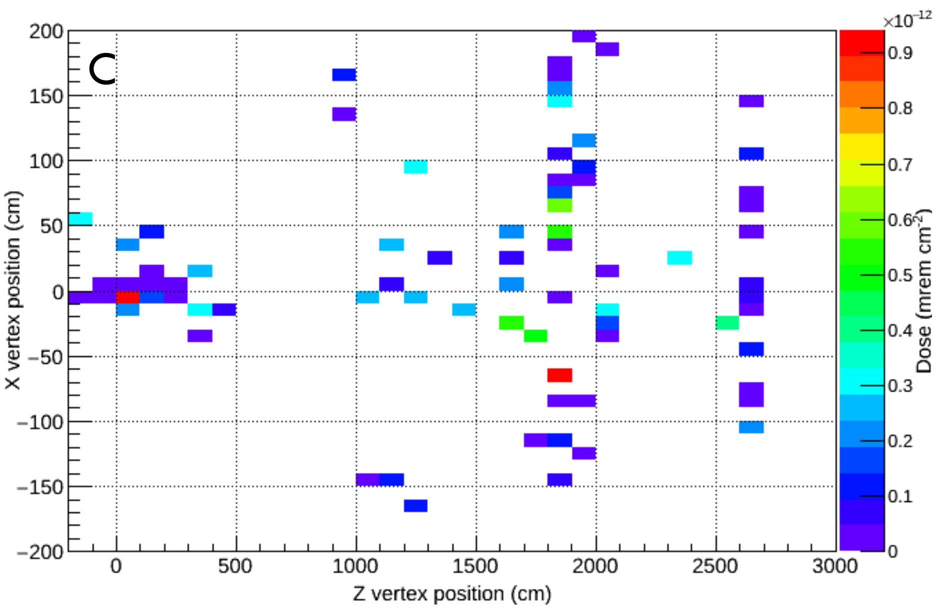
Origins of n entering Upstream detector



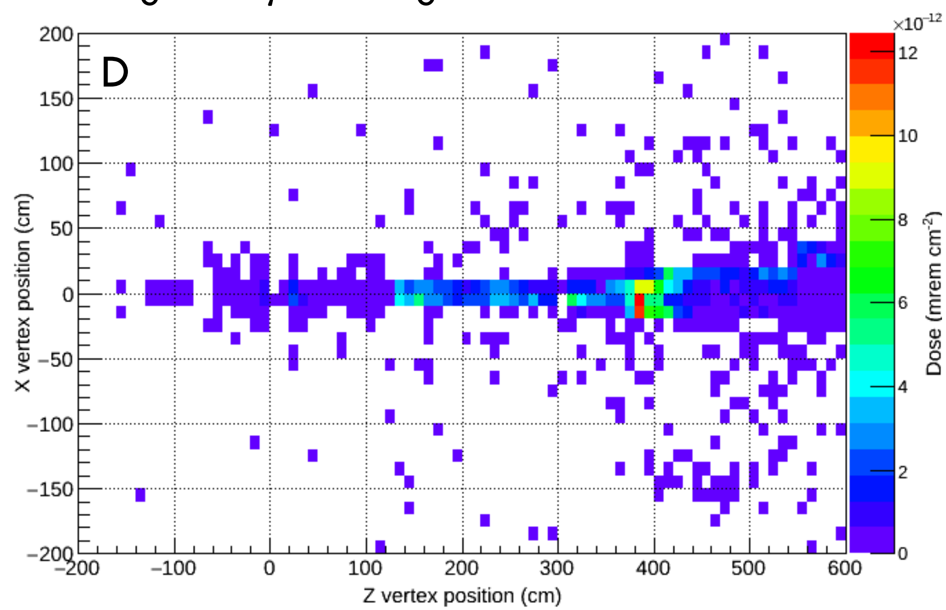
Origins of γ entering Upstream detector



Origins of n entering Left HRS electronics area



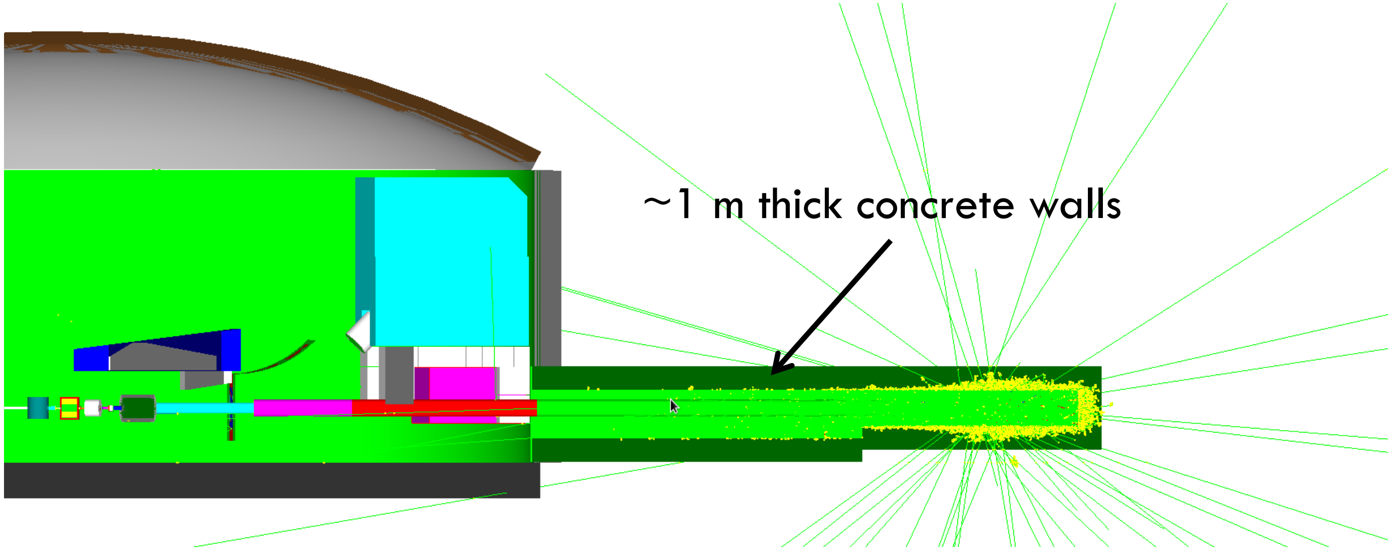
Origins of γ entering Left HRS electronics area



APEX Radiation Evaluation Results

APEX E, Current GeV, μA	Target X_0, t % r.l, mg/cm^2	Dose Rates: Upstream Detector (rem/h)	Dose Rates: Left HRS electronics area detector (rem/h)
1.1 GeV, 100 μA	Carbon 0.7 % r.l. 298.9 mg/cm^2	e: under study γ: 0.12 n: 0.20	e: under study γ: 0.53 n: 0.11
2.2 GeV, 100 μA	Tungsten 4.0 % r.l. 270.4 mg/cm^2	e: under study γ: 0.34 n: 0.82	e: under study γ: 1.88 n: 0.41
3.3 GeV, 100 μA	Tungsten 8.0 % r.l. 540.8 mg/cm^2	e: under study γ: 0.76 n: 1.77	e: under study γ: 4.11 n: 0.97
4.4 GeV, 100 μA	Tungsten 8.0 % r.l. 540.8 mg/cm^2	e: under study γ: 0.65 n: 1.57	e: under study γ: 2.93 n: 0.72

Neutron Dose rate contribution from Beam dump

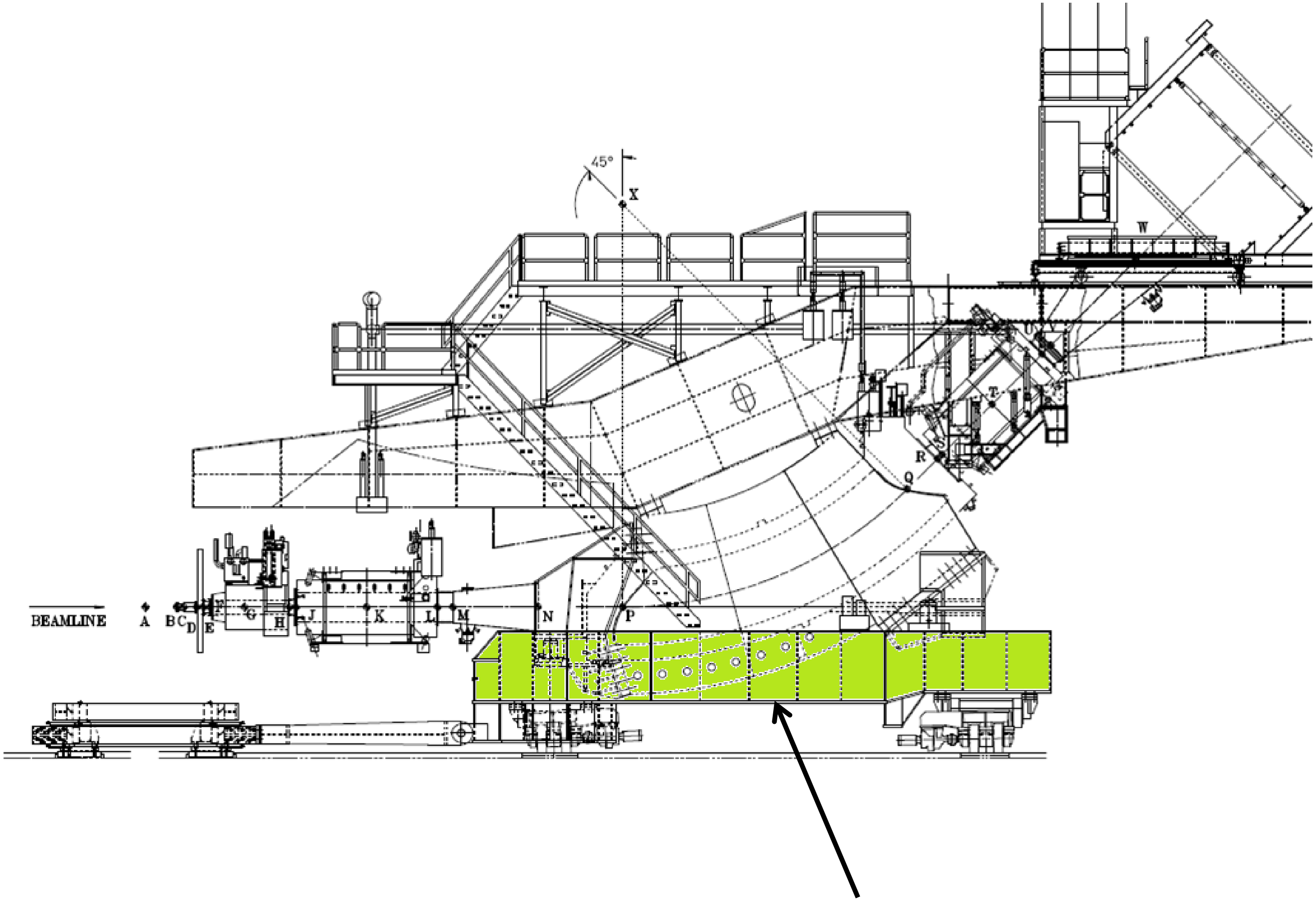


APEX E, Current GeV, μA	Target X_0, t % r.l, mg/cm^2	Dose Rates: Upstream Detector (rem/h)	Dose Rates: Left HRS electronics area detector (rem/h)
2.2 GeV, 100 μA	Tungsten 4.0 % r.l. 270.4 mg/cm^2	n: 0.84	n: 0.415

Only ~ 3% contribution from beam dump

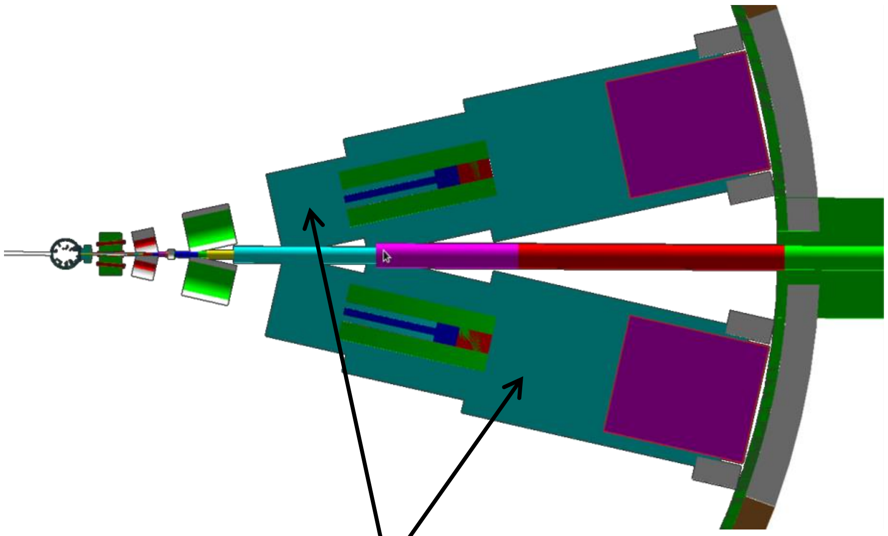
Only ~ 1% contribution from beam dump

Affect of HRS Cradle



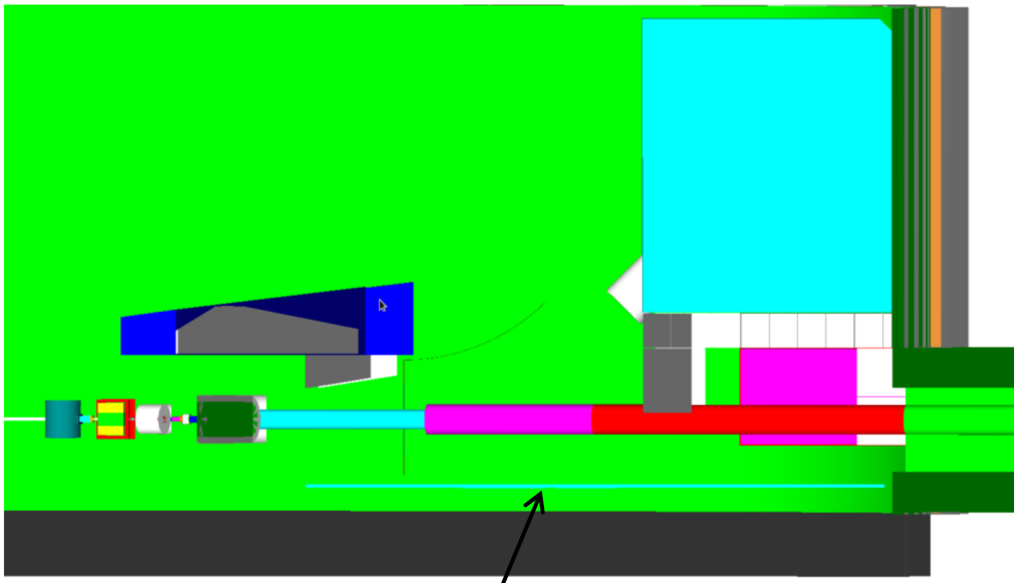
Cradle was simplified using 4" thick steel plate

Top View



4” thick Steel plate

Side View



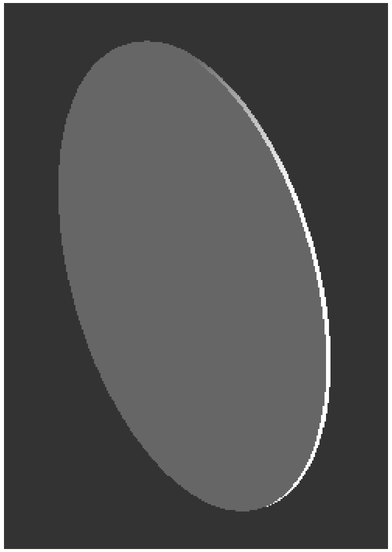
4” thick Steel plate

APEX E, Current GeV, μA	Target X_0, t % r.l, mg/cm^2	Dose Rates: Upstream Detector (rem/h)	Dose Rates: Left HRS electronics area detector (rem/h)
2.2 GeV, 100 μA (Without steel plate)	Tungsten 4.0 % r.l. 270.4 mg/cm^2	γ: 0.389 n: 0.878	γ: 2.570 n: 0.593
2.2 GeV, 100 μA (With steel plate)	”	γ: 0.390 n: 0.846	γ: 2.535 n: 0.620

Validation of the Monte Carlo code

- Simulation code need to be validated.
- Used the GEANT4 model to simulate PREX and APEX-test run.
- Compared results with experimental data from PREX and APEX-test run in 2010.

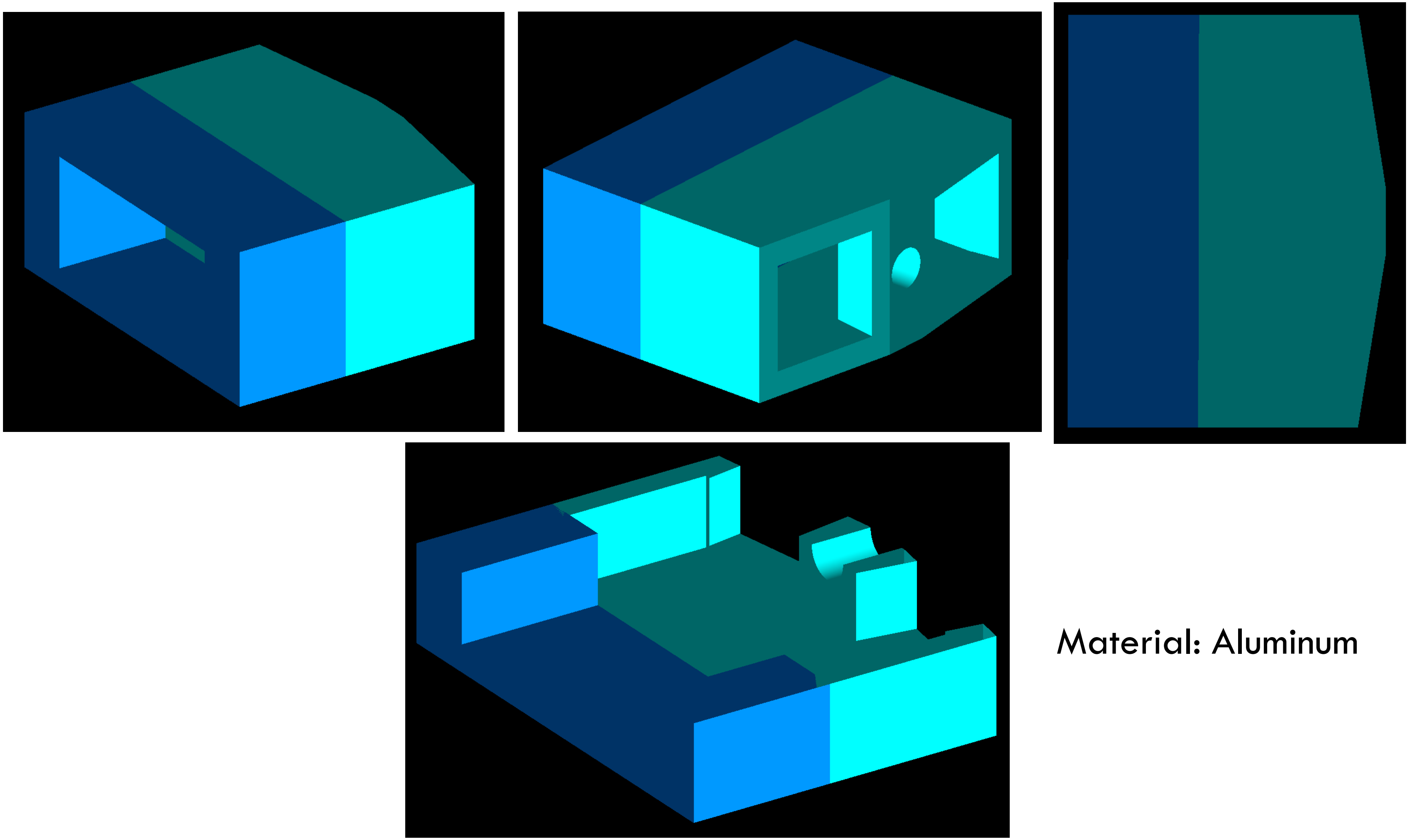
PREX



$\mathbf{567\,mg/cm^2}$

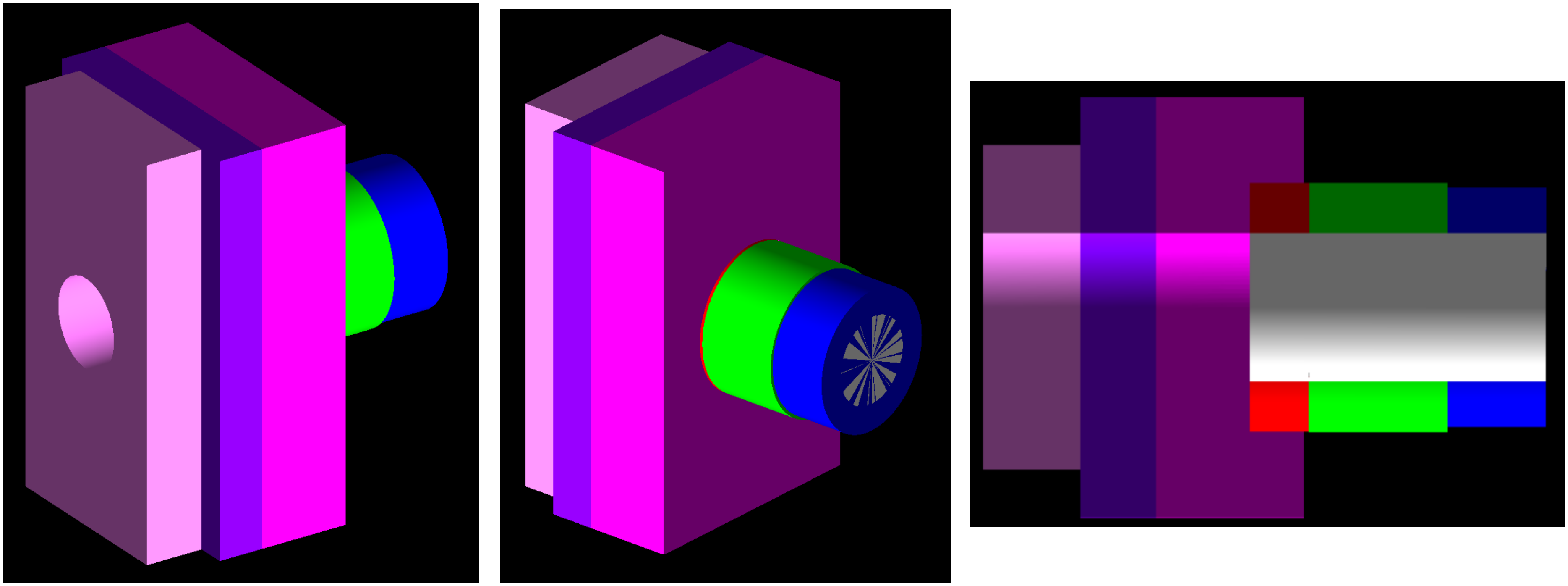
- $Target$: 0.5 mm $thick$ $Lead$ $target$ (10% rad $length$ of Pb)
- $PREX$ $Extension$ Box
- $PREX$ $Collimator$
- $APEX$ $Full$ Run $Septum$ $Magnet$
- $Beam$: 1.06 GeV
- HRS: $positioned$ at 12.5^o

PREX Extension Box



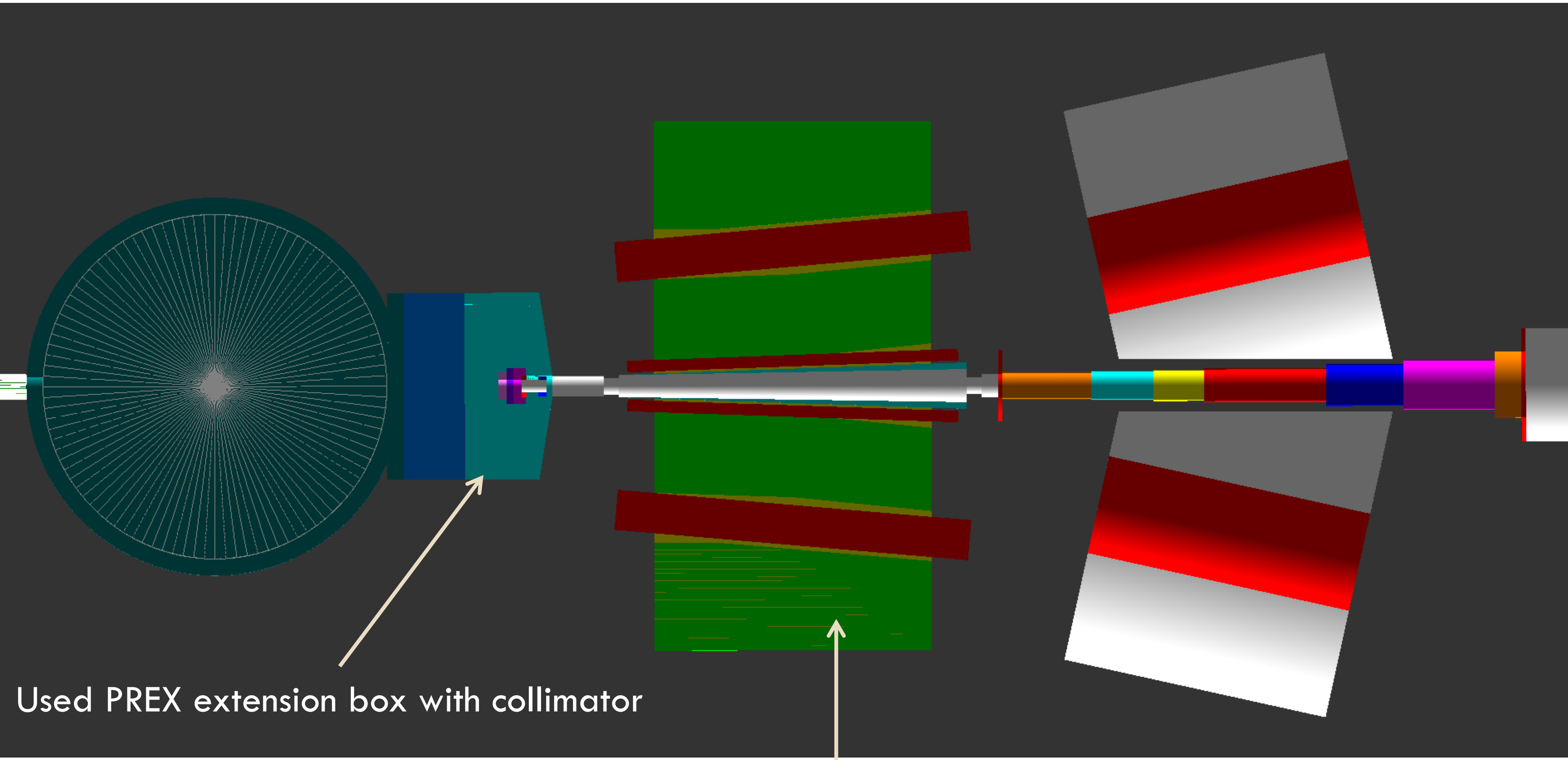
Material: Aluminum

PREX Collimator



Material: Tungsten

PREX Beam Line

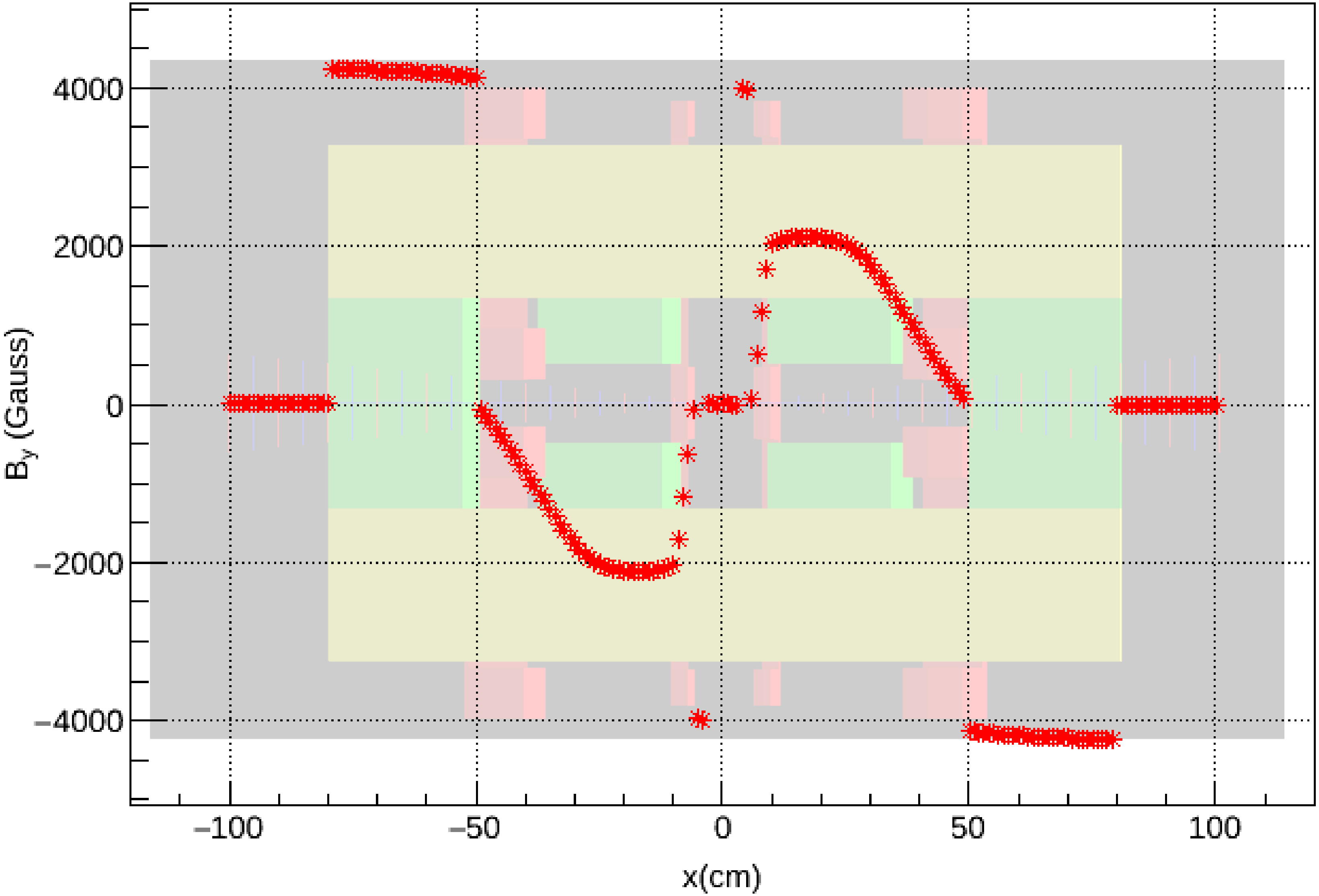


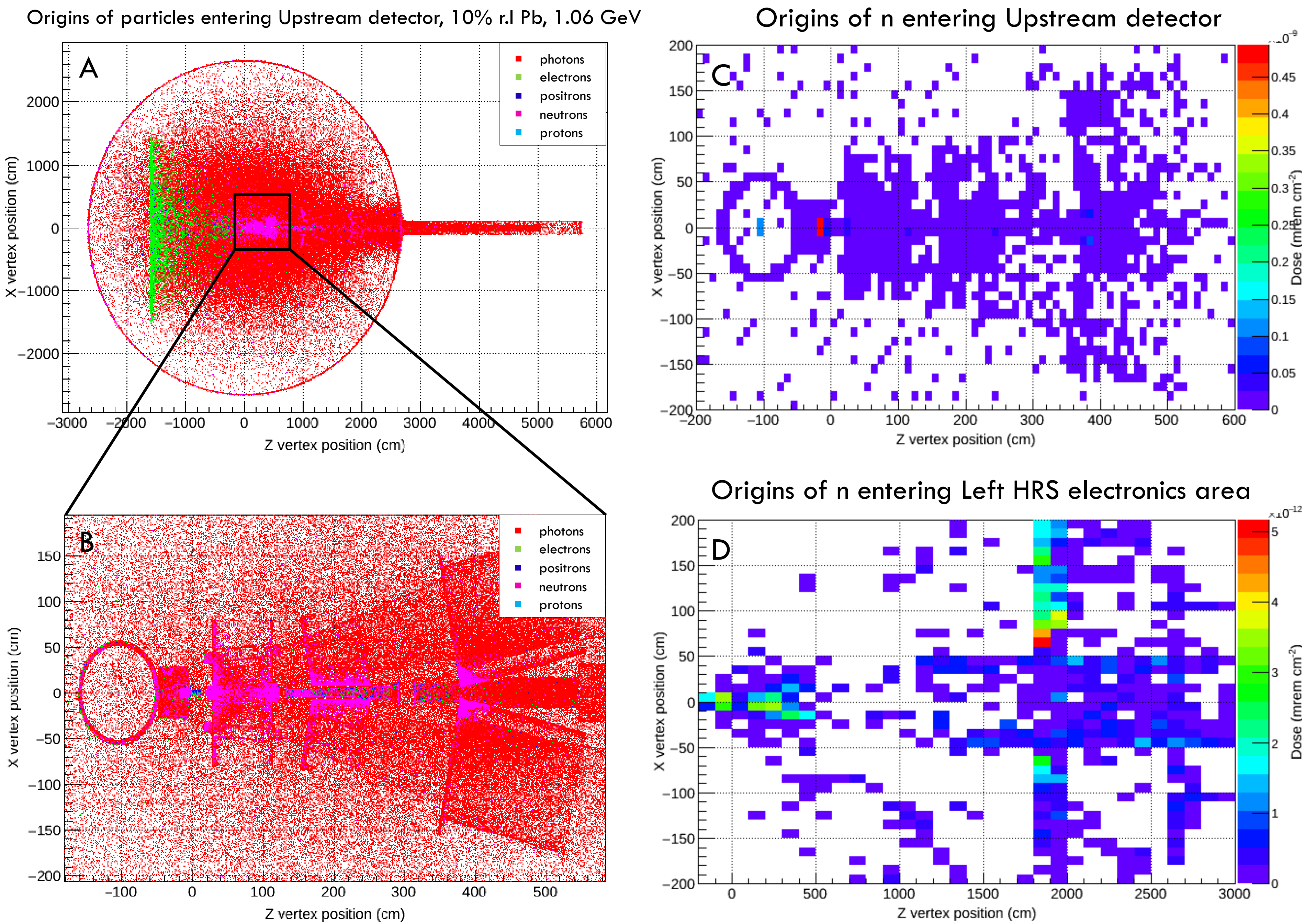
APEX full run septum magnet

PREX

Septum Magnetic Field for PREX

B_y $vs.$ x $(y = 0, z = 0)$ *looking from the beam dump*

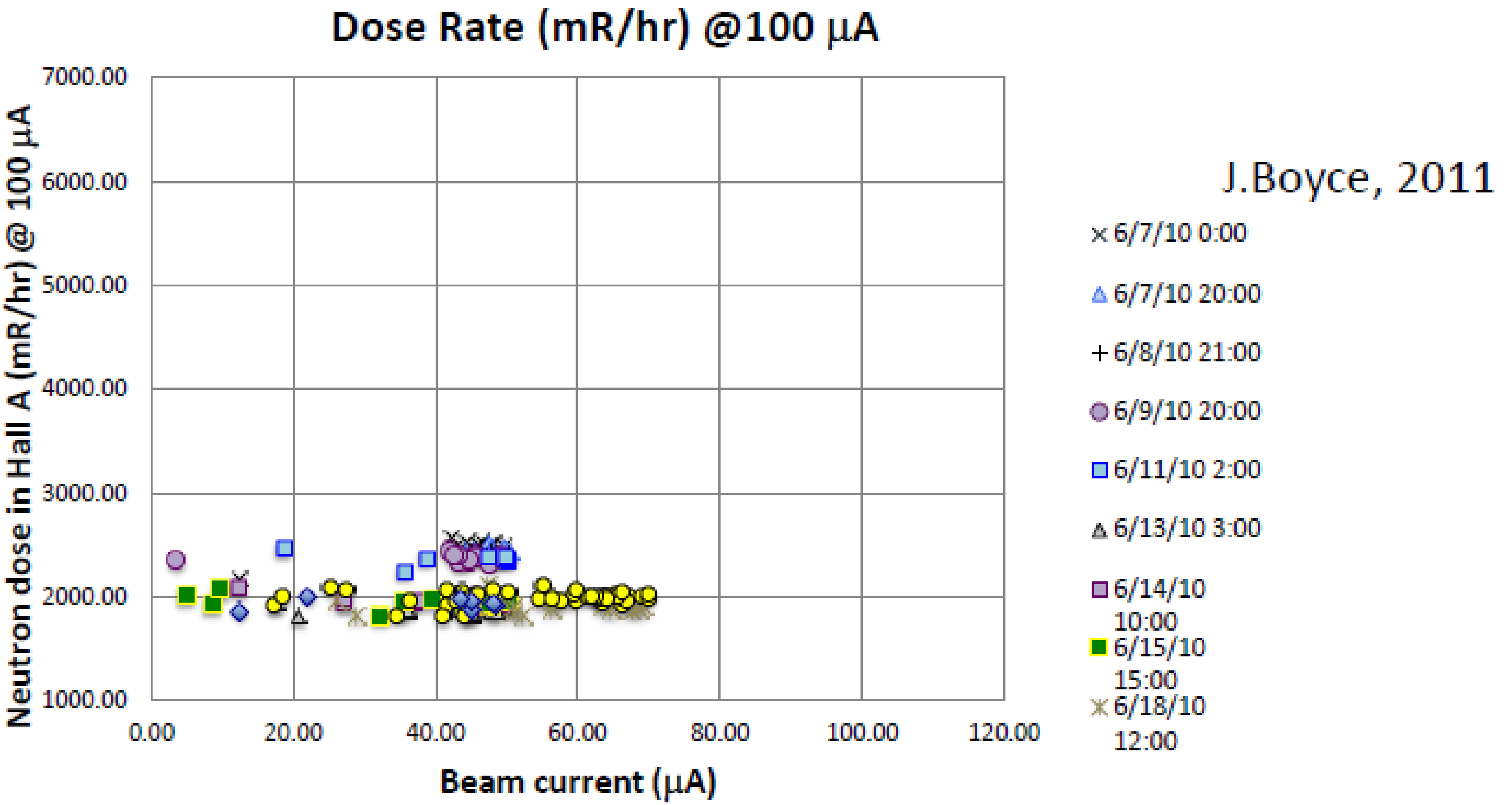



Origins of particles entering Upstream detector, 10% r.l Pb, 1.06 GeV
A
photons
electrons
positrons
neutrons
protons
X vertex position (cm)
Z vertex position (cm)
B
photons
electrons
positrons
neutrons
protons
X vertex position (cm)
Z vertex position (cm)
Origins of n entering Upstream detector
C
X vertex position (cm)
Z vertex position (cm)
Dose (mrem cm^-2)
×10^-9
Origins of n entering Left HRS electronics area
D
X vertex position (cm)
Z vertex position (cm)
Dose (mrem cm^-2)
×10^-12

PREX Radiation Evaluation Results

PREX E, Current GeV, μA	Target X_0, t % r.l, mg/cm^2	Dose Rates: Upstream Detector (rem/h)	Dose Rates: Left HRS electronics area detector (rem/h)
1.06 GeV, 100 μA	Lead 10 % r.l. 567 mg/cm^2	e: _ γ: _ n: 6.5	e: _ γ: _ n: 7.0

PREX – June 2010: E_{e^-} = 1.06 GeV

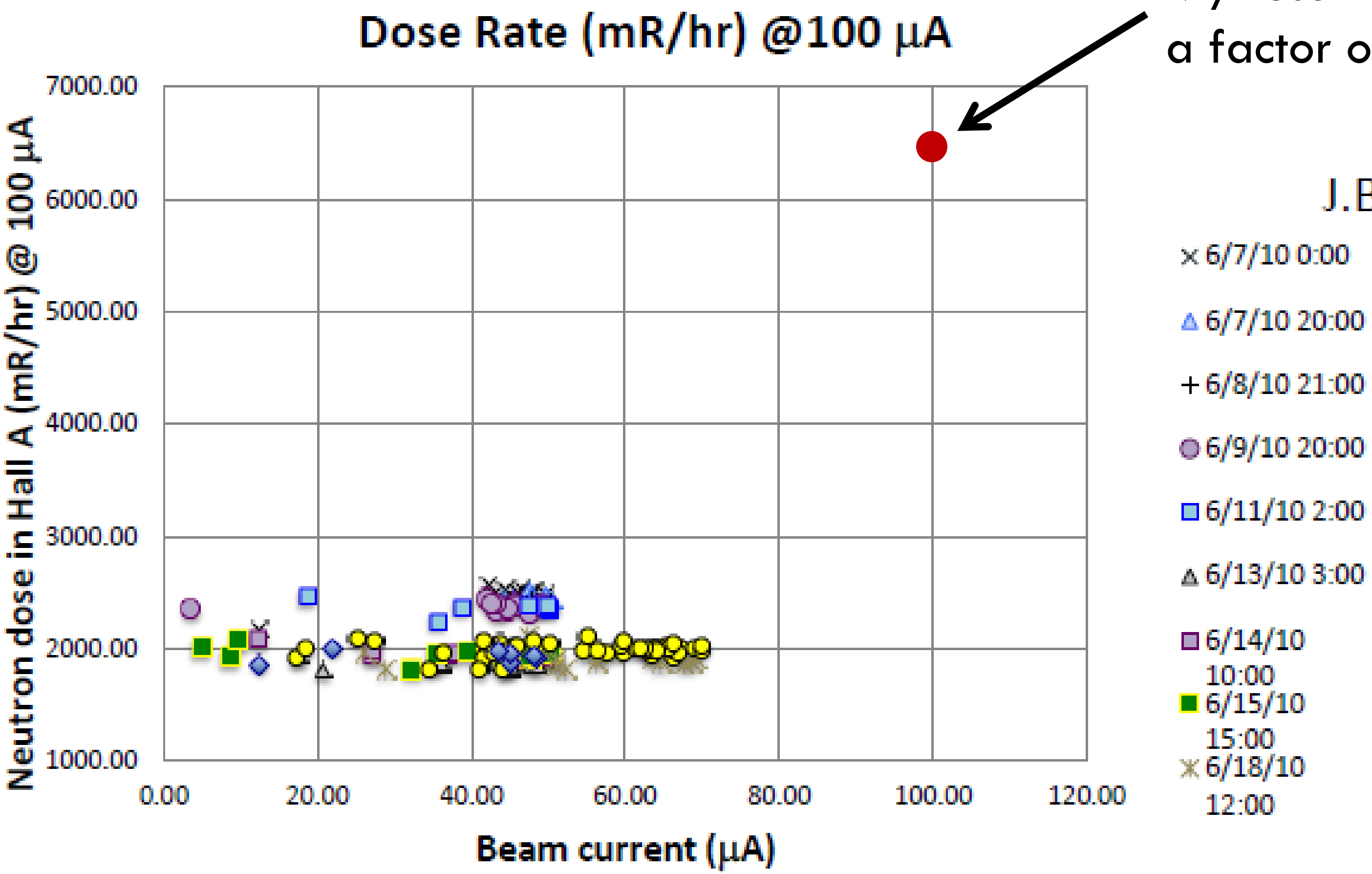


Target thickness = 637 mg/cm² (Pb)

Average Dose Rate = 2080 mR/hr at 100 μA

PREX

PREX – June 2010: E_{e-} = 1.06 GeV



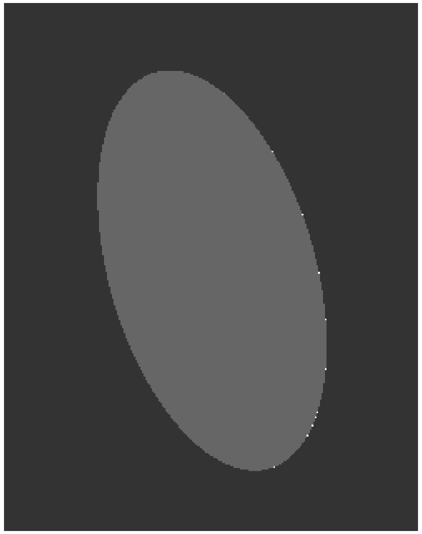
My result with roughly a factor of 3 higher.

J.Boyce, 2011

Target thickness = 637 mg/cm^2 (Pb)

Average Dose Rate = 2080 mR/hr at 100 µA

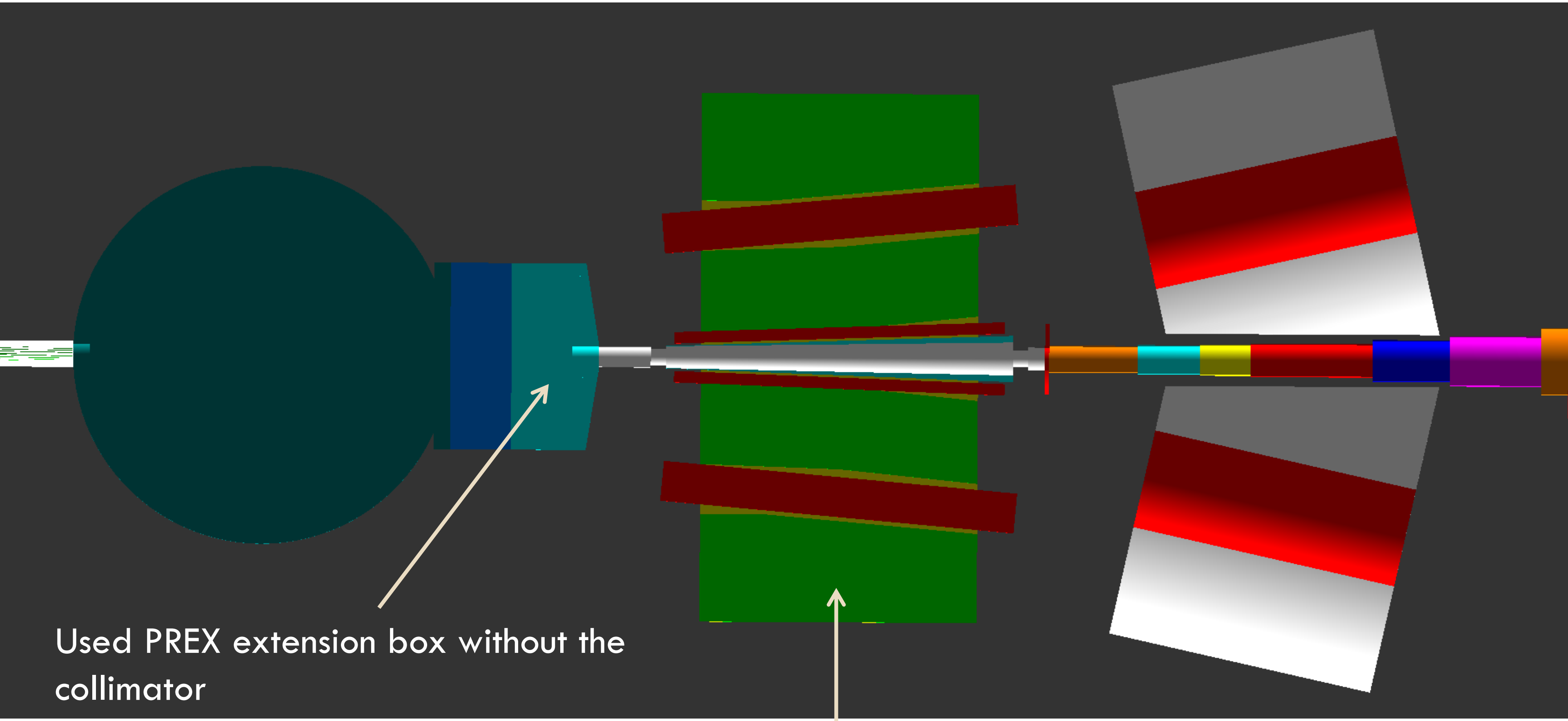
APEX Test Run



$\mathbf{22\,mg/cm^2}$

- $Target$: $\sim 13\ \mu m\ thick\ Tantalum\ (Ta)$
- $PREX\ Extension\ Box$
- $APEX\ Full\ Run\ Septum\ Magnet$
- $Beam$: $2.26\ GeV$
- HRS: $positioned\ at\ 12.5^o$

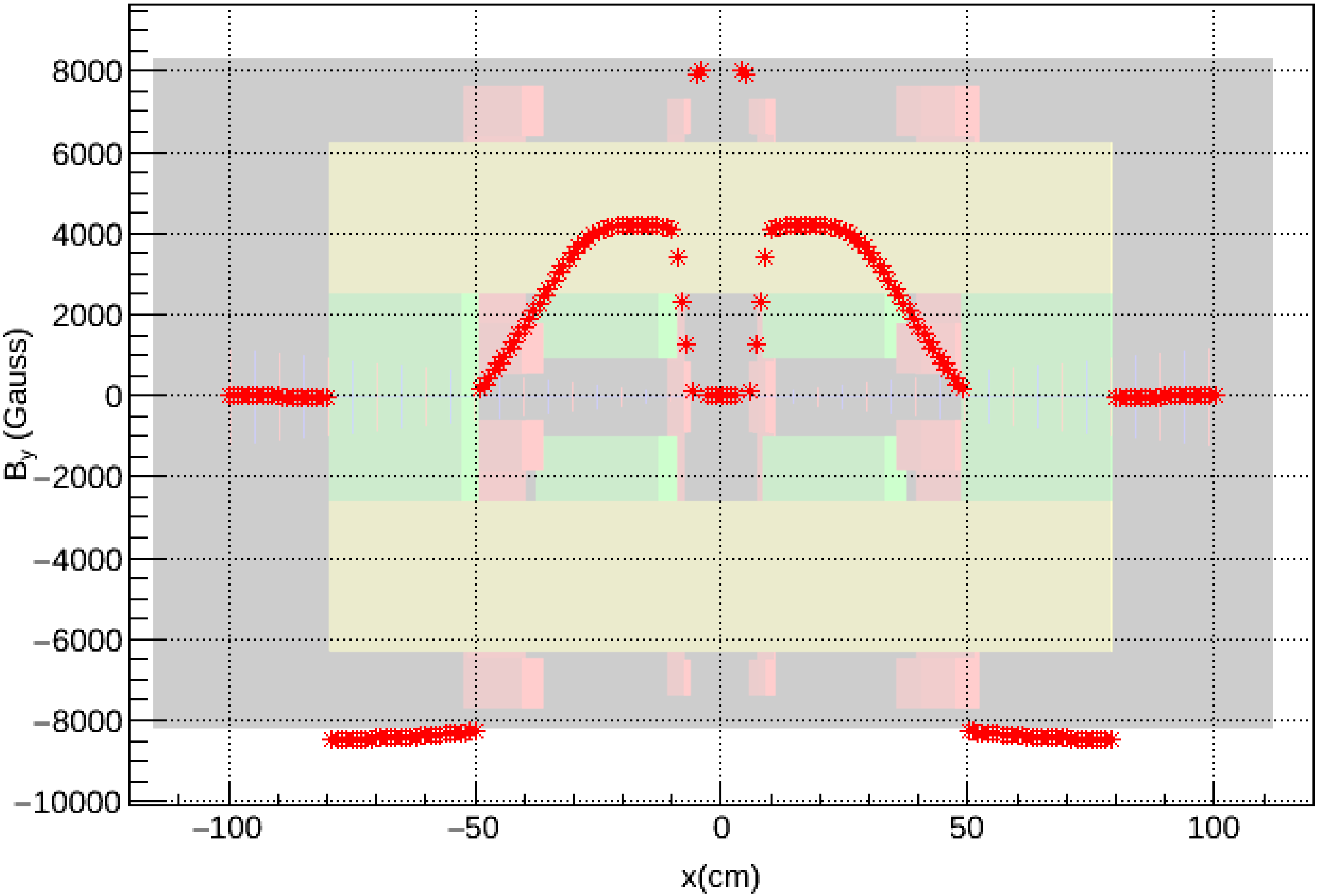
APEX Test Run Beam Line



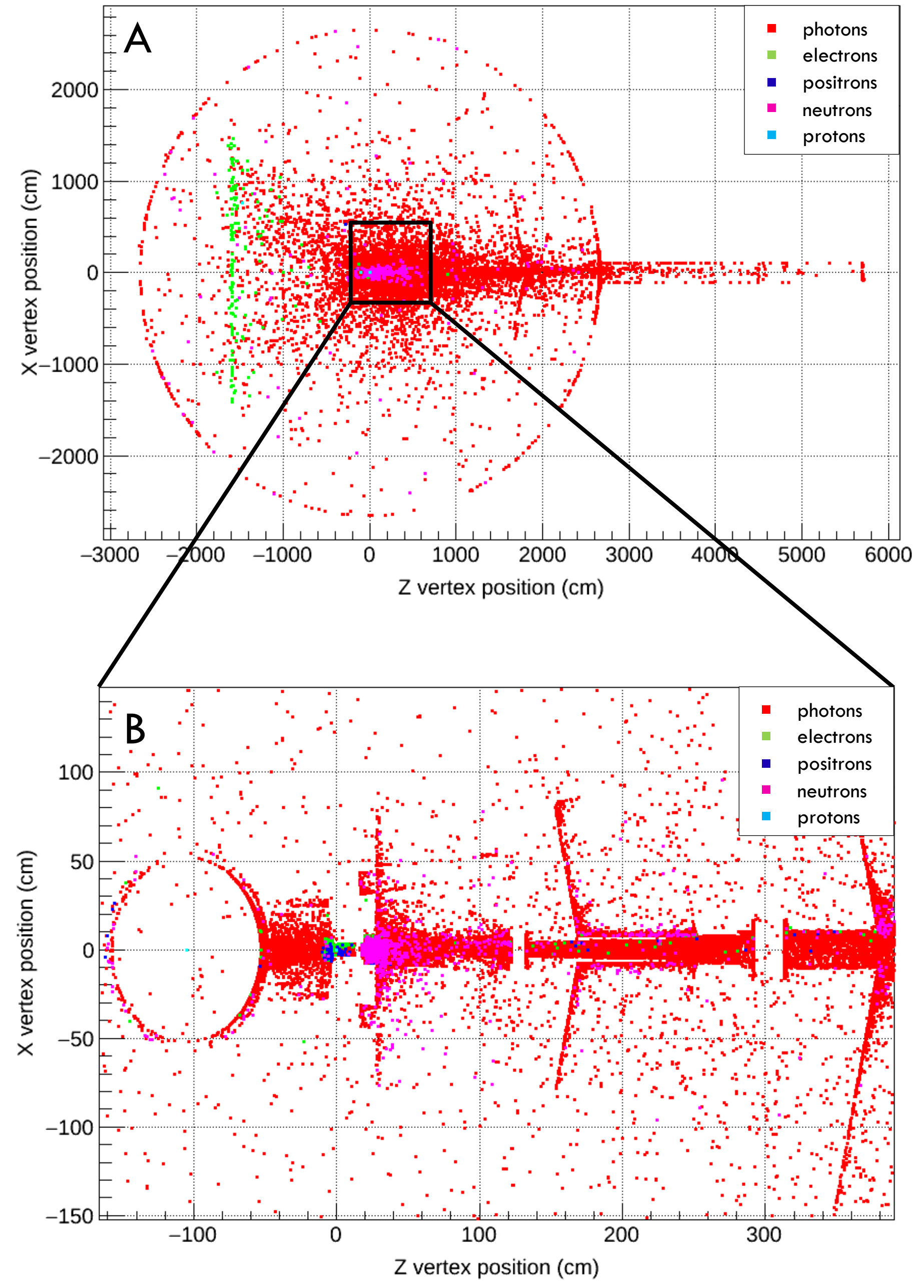
APEX full run septum magnet

Septum Magnetic Field for APEX

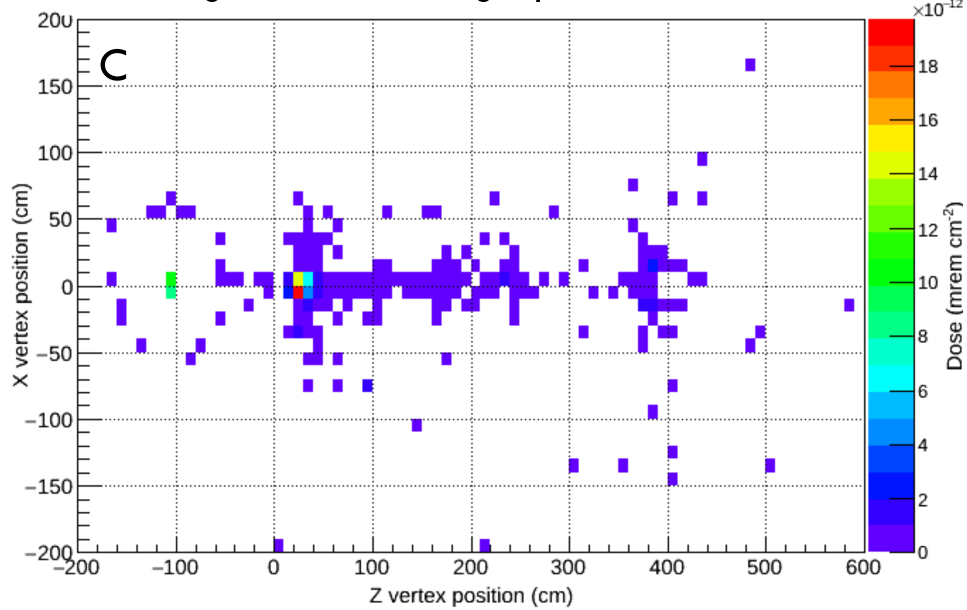
$$B_y\ vs.\ x\ (y = 0, z = 0)$$



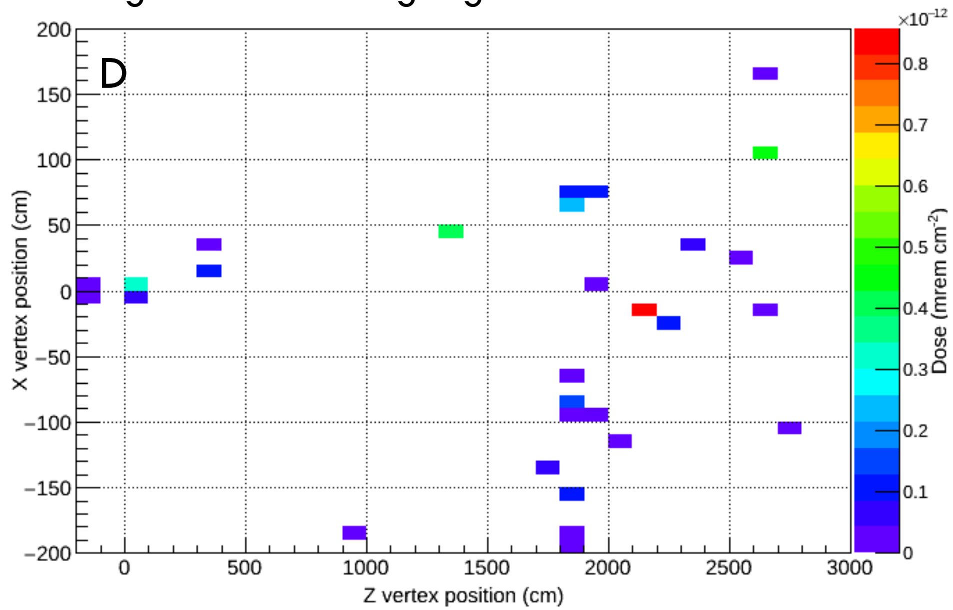
Origins of particles entering Upstream detector, 0.3% r.l Ta, 2.26 GeV



Origins of n entering Upstream detector



Origins of n entering Right HRS electronics area

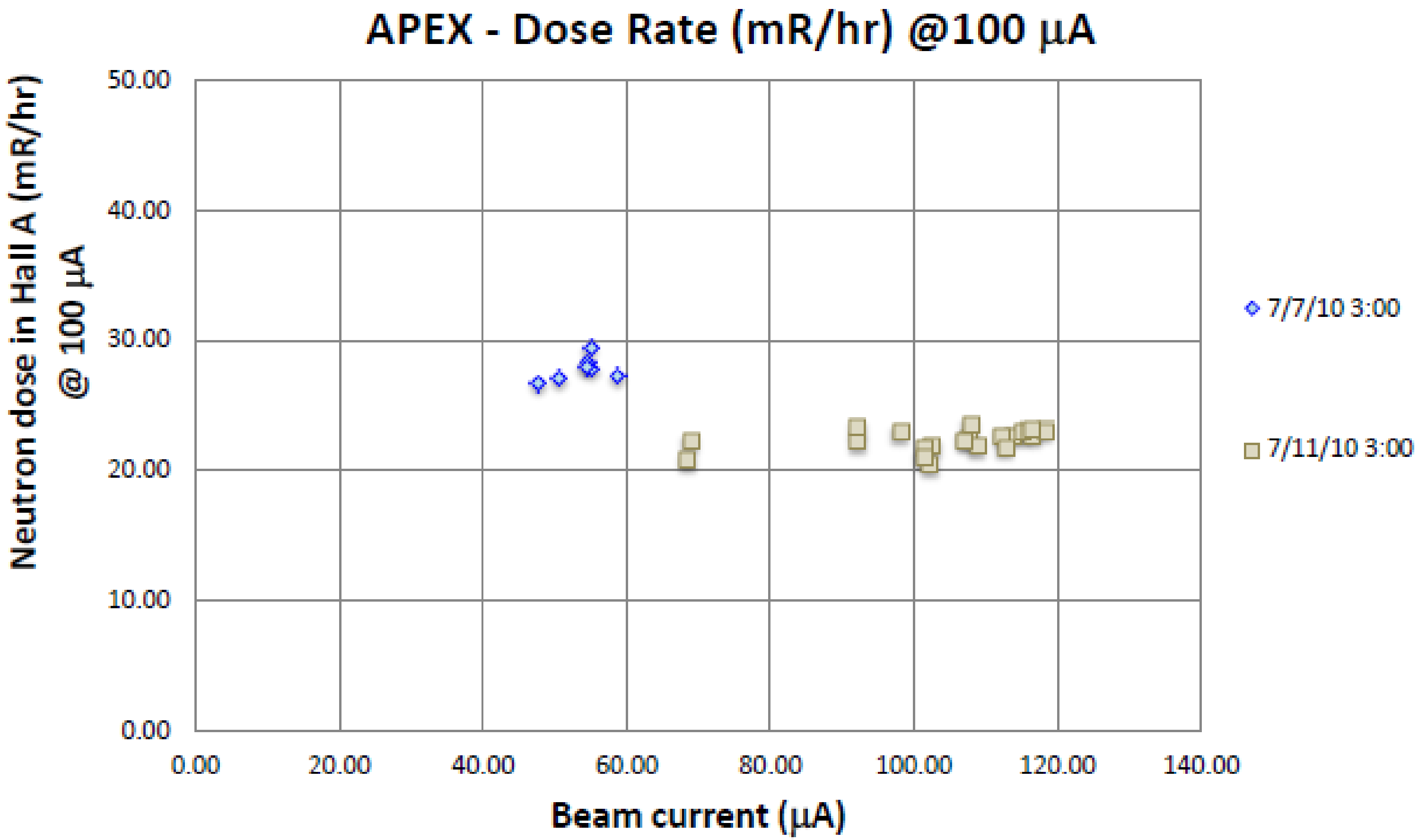


APEX Test Run Radiation Evaluation Results

PREX E, Current GeV, μA	Target X_0, t % r.l, mg/cm^2	Dose Rates: Upstream Detector (rem/h)	Dose Rates: Right HRS electronics area detector (rem/h)
2.26 GeV, 100 μA	Tantalum 0.3 % r.l. 22 mg/cm^2	e: _ γ: _ n: 0.0475	e: _ γ: _ n: 0.027

APEX (test) – July 2010: E_{e^-} = 2.26 GeV

J.Boyce, 2011

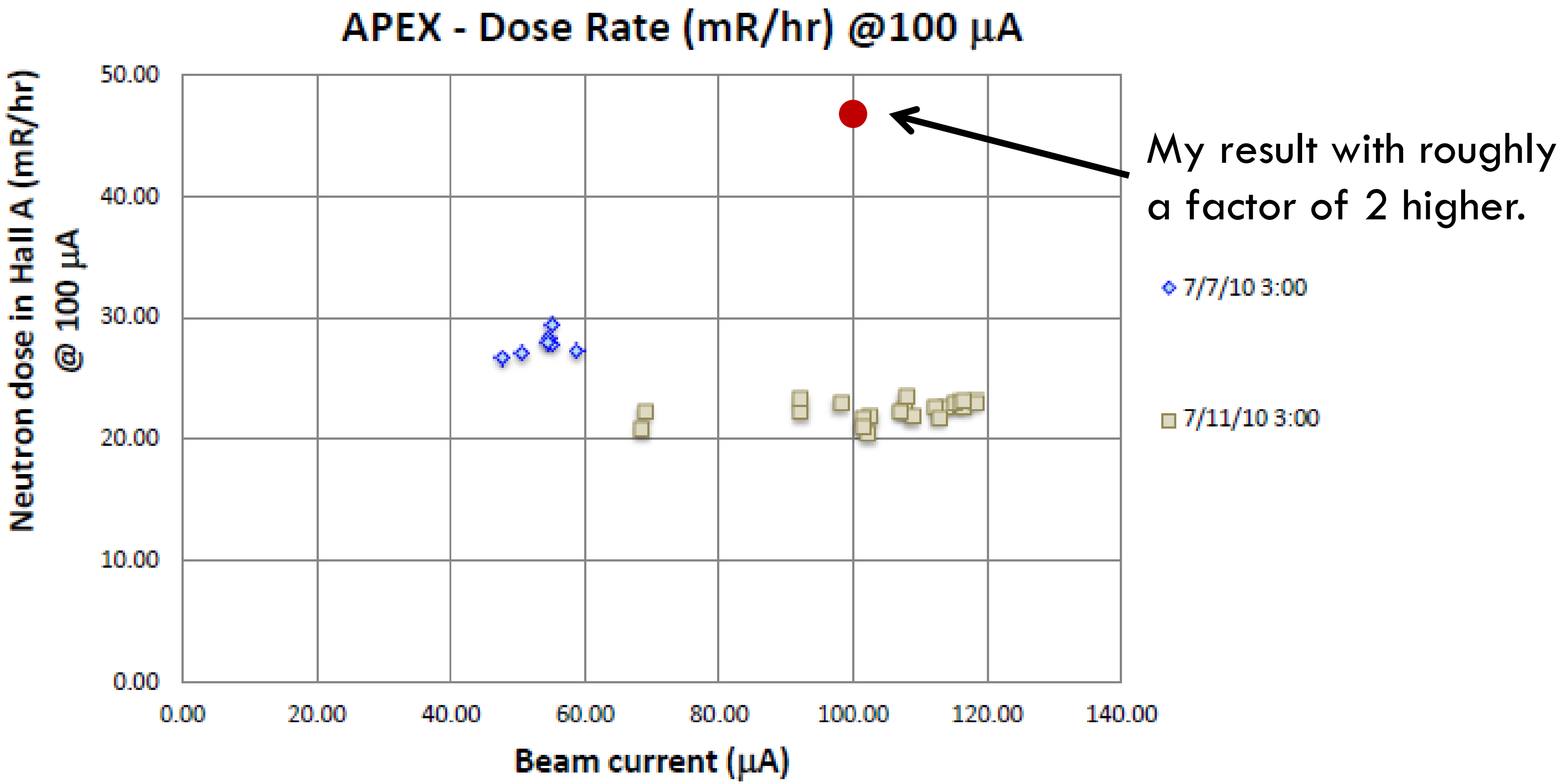


Target thickness = 22 mg/cm² (Ta)

Average Dose Rate = 24 mR/hr at 100 µA

APEX (test) – July 2010: E_{e^-} = 2.26 GeV

J.Boyce, 2011

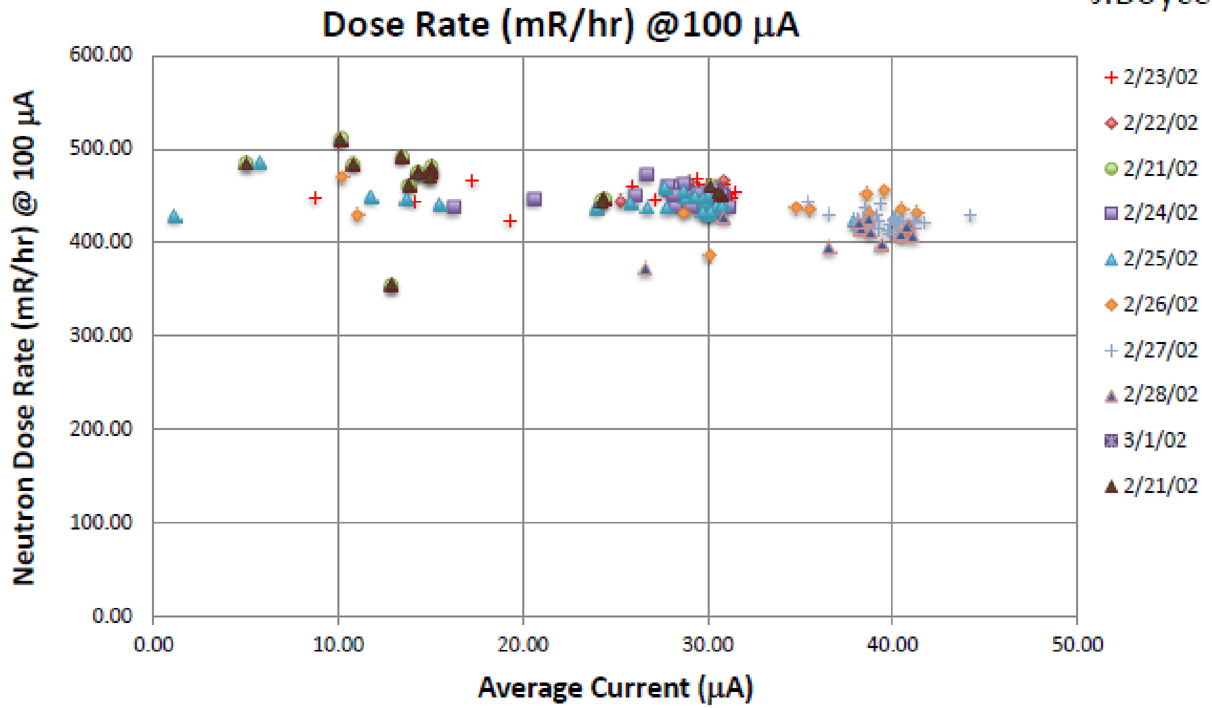


Target thickness = 22 mg/cm² (Ta)

Average Dose Rate = 24 mR/hr at 100 µA

RCS - Feb. 2002: E_{e^-} = 3.48 GeV

J.Boyce, 2011



Target thickness = 637 mg/cm² (Cu) + 1040 mg/cm² (H)

Average Dose Rate = 440 mR/hr at 100 µA

- During Real Compton Scattering (RCS) experiment HRS electronics and Power supply operated well.
- Will use this as a benchmark for acceptable radiation in the experimental hall.

Summary:

- A GEANT4 model for JLab Hall A was built.
- Simulated for PREX, APEX test run and APEX full run.
- Dose calculations for PREX and APEX test run using the model agrees with a factor of 2-3 difference with experimental data.
- We can now predict how much dose to expect at APEX full run.
- These results will be used to improve shielding in Hall A and for APEX Readiness Review.

Acknowledgement

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Pavel Degtiarenko, Jlab

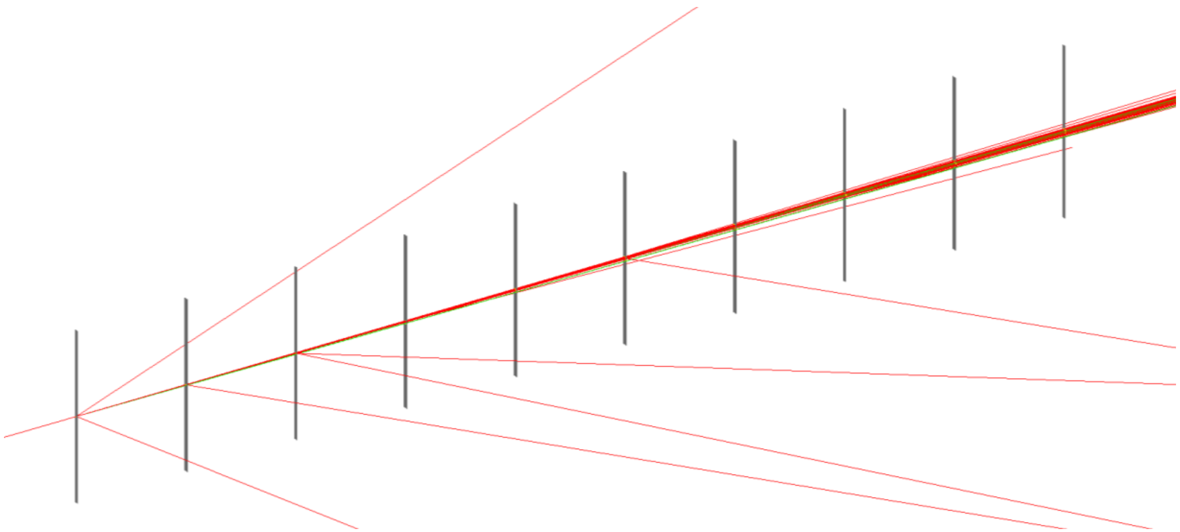
Bryan Wright, UVa

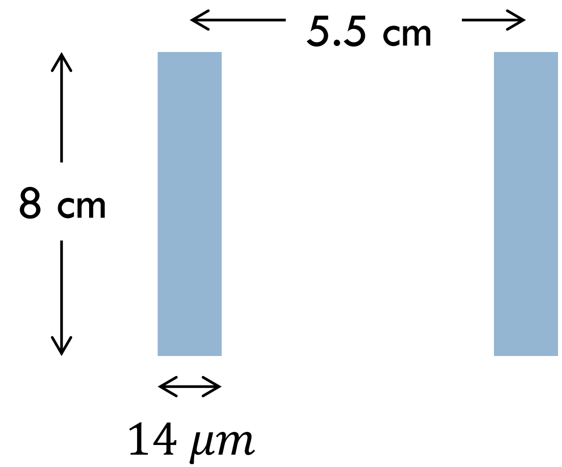
Alan Gavalya, Jlab

Joyce Miller, JLab

Backup Slides

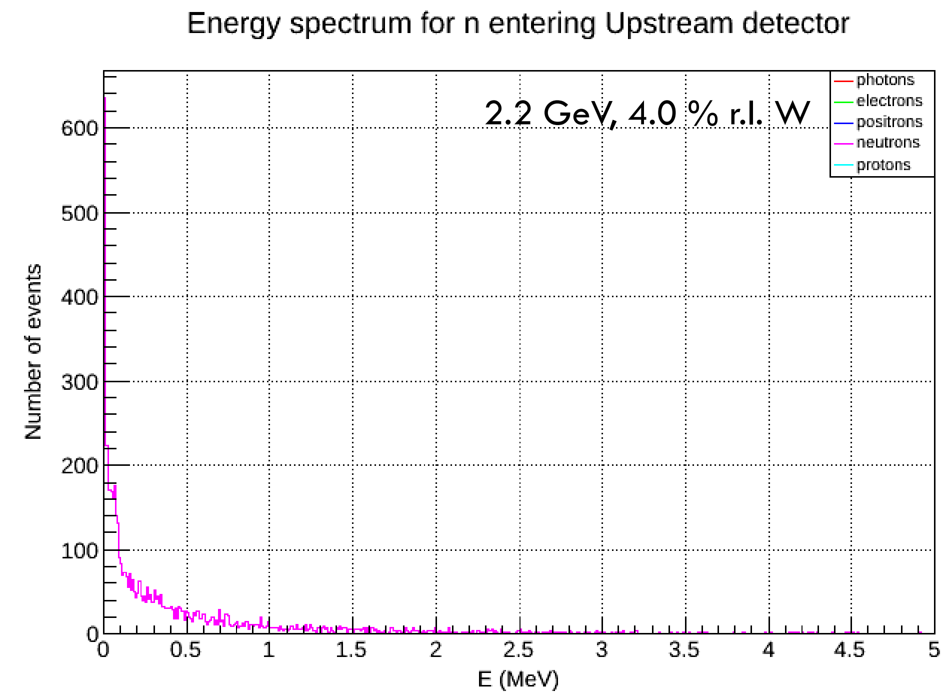
APEX Target

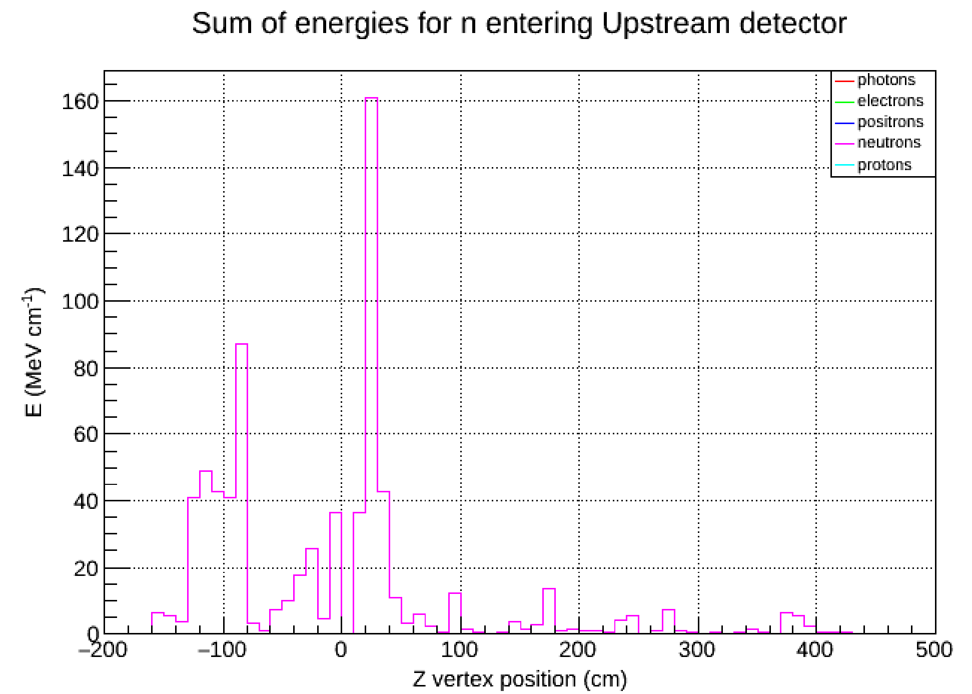


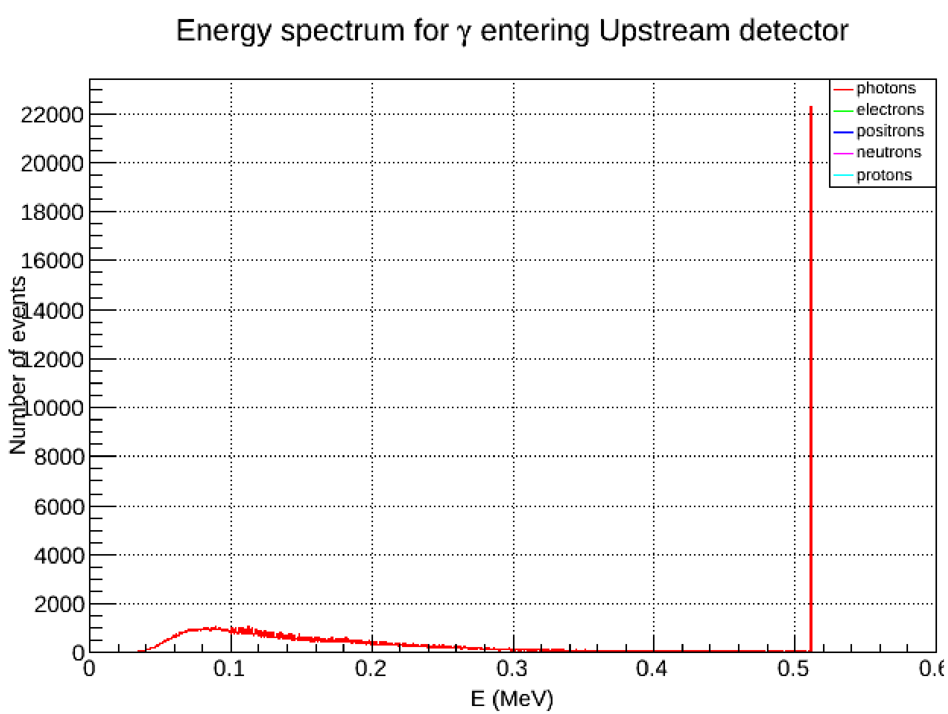


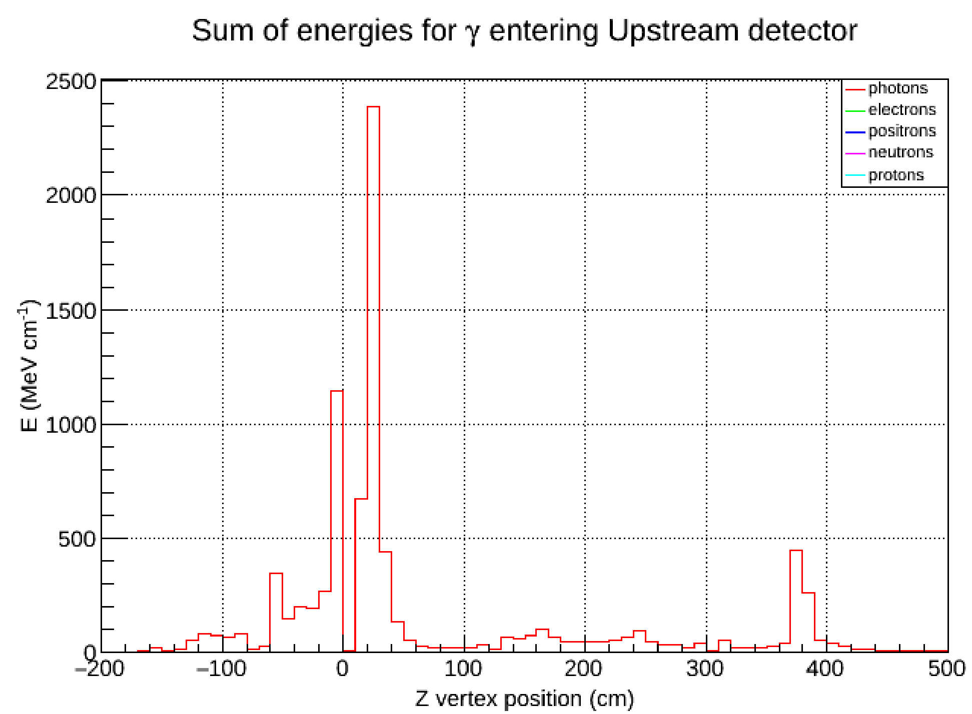
10 ribbons of Tungsten

$4\% \; X_o$

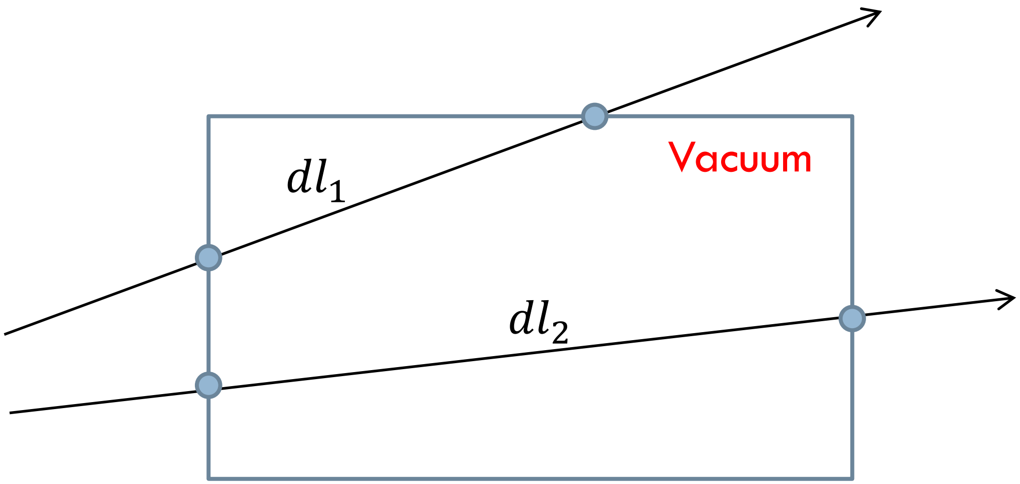

Energy spectrum for n entering Upstream detector
2.2 GeV, 4.0 % r.l. W
photons
electrons
positrons
neutrons
protons
Number of events
E (MeV)


Sum of energies for n entering Upstream detector
photons
electrons
positrons
neutrons
protons
E (MeV cm^{-1})
Z vertex position (cm)

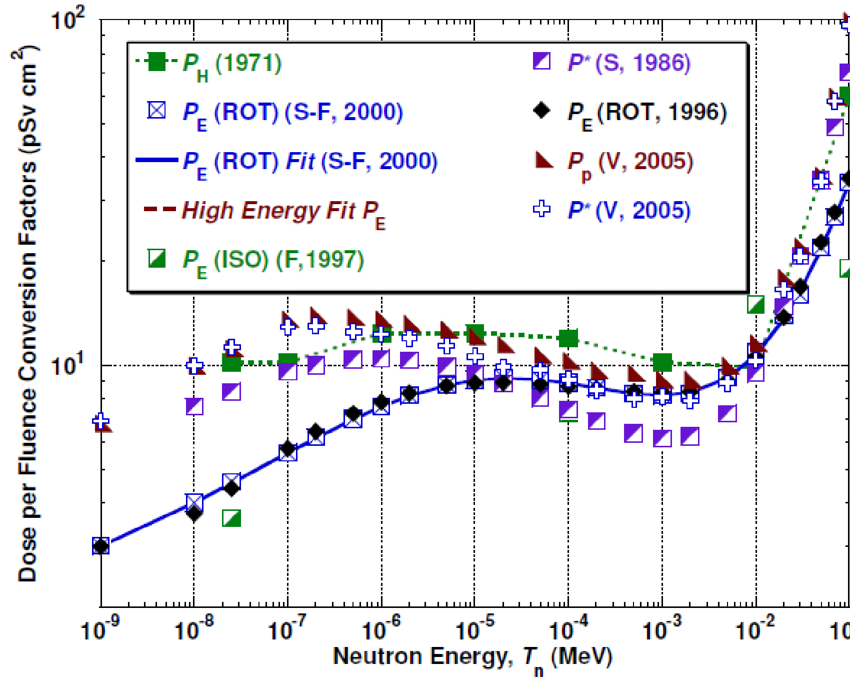

Energy spectrum for γ entering Upstream detector
photons
electrons
positrons
neutrons
protons
Number of events
E (MeV)


Sum of energies for γ entering Upstream detector
photons
electrons
positrons
neutrons
protons
E (MeV cm^{-1})
Z vertex position (cm)

Dose Calculation



FERMILAB-PUB-08-244-ESH-REV



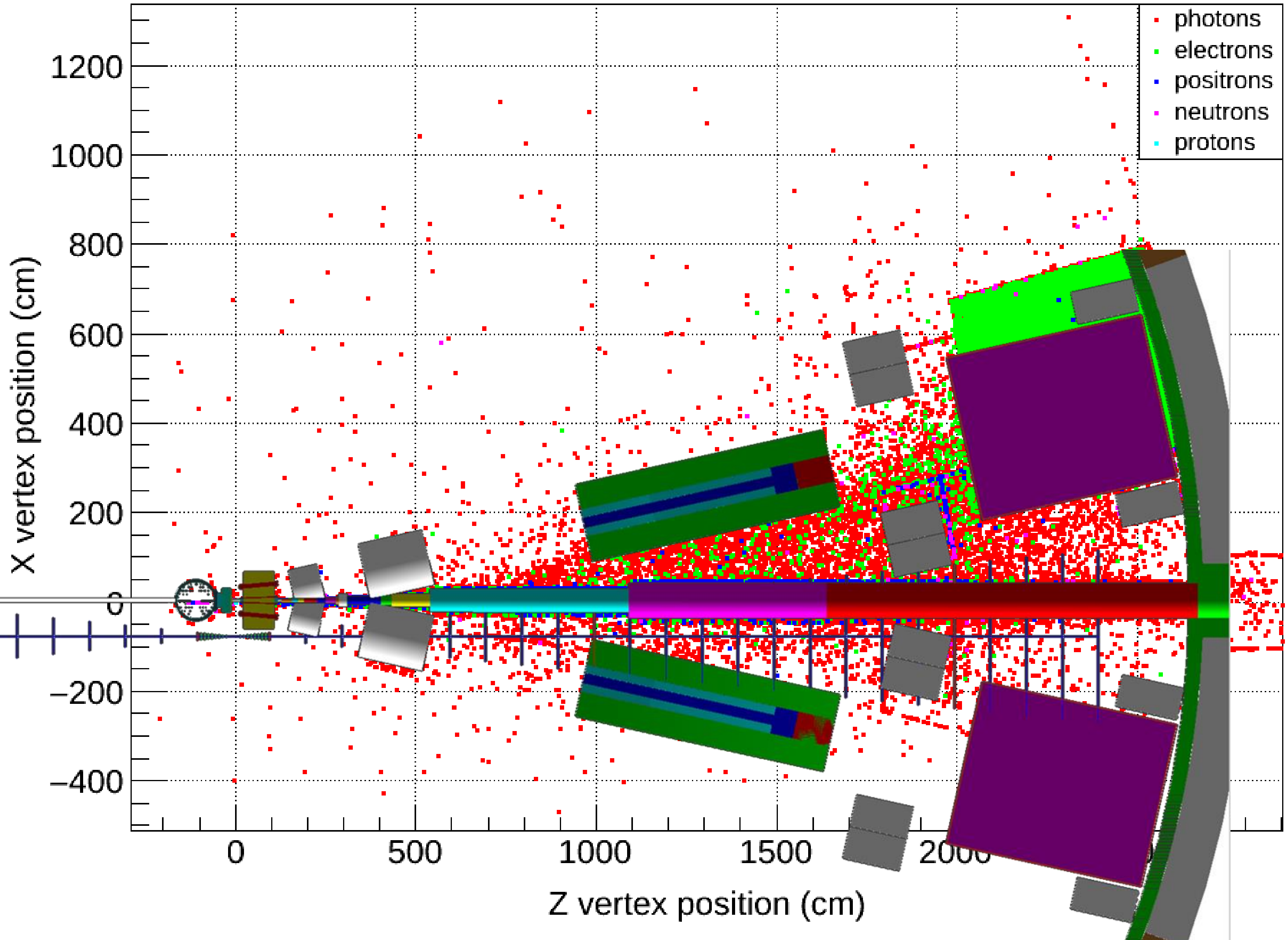
$$Fluence\ (\Phi) = \frac{\sum l}{V}$$

for mono energetic particle source

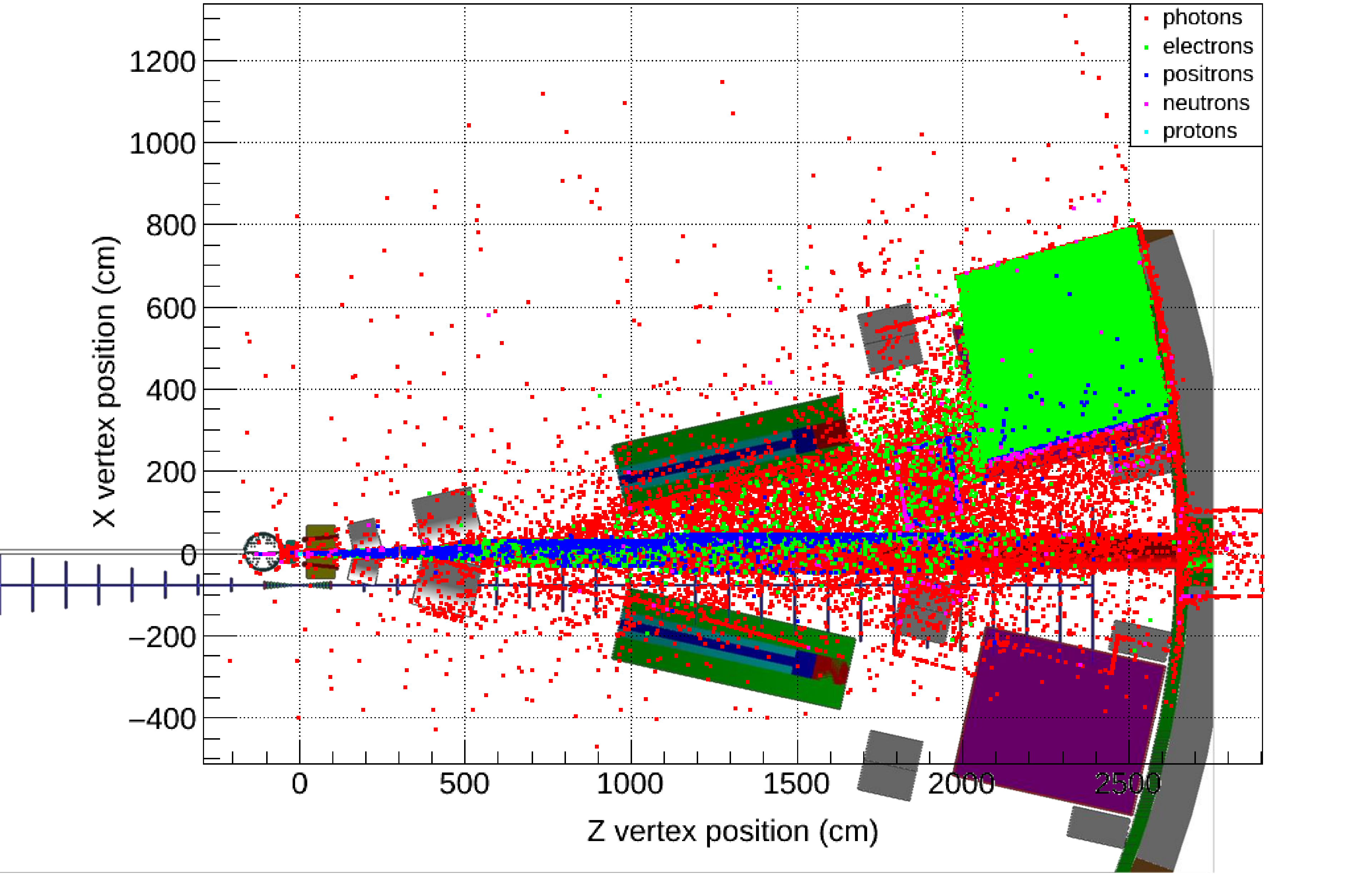
$$Dose\ (E) = f(E) \times \Phi(E)$$

Dose per fluence conversion factor

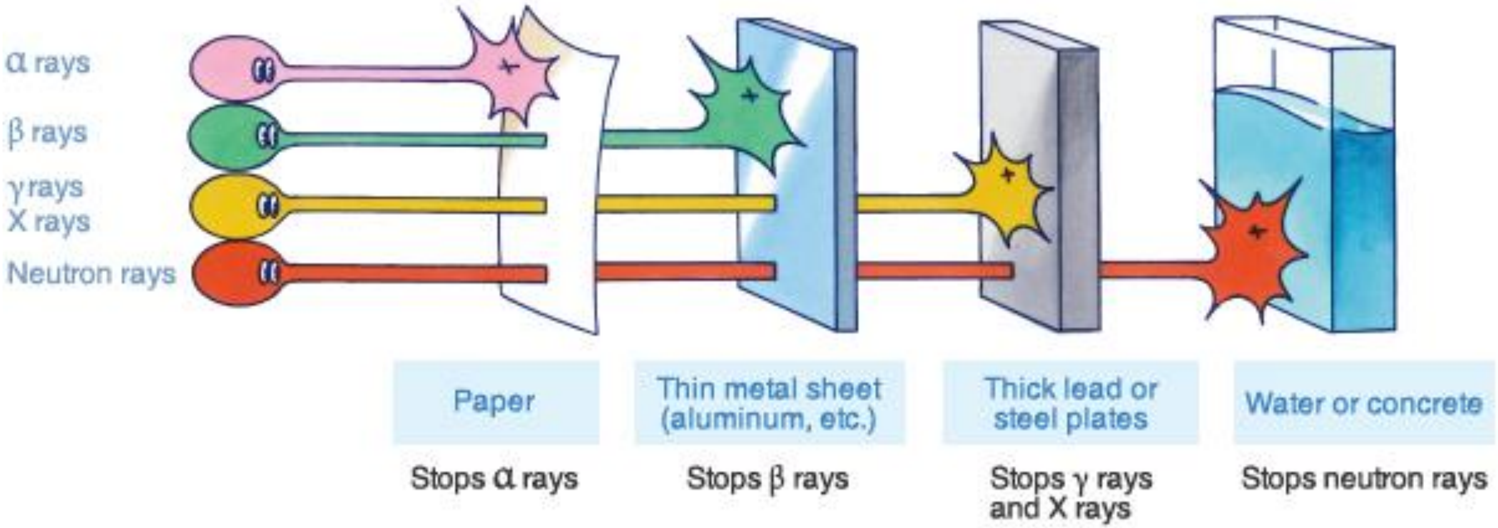
Origins of particles entering Left HRS electronics area detector



Origins of particles entering Left HRS electronics area detector



Radiation Shielding



PREX Beamline