Radiological Issues at JLab

Lessons Learned from the PREX-I
and
Preparation for PREX-II/CREX (and MOLLER)

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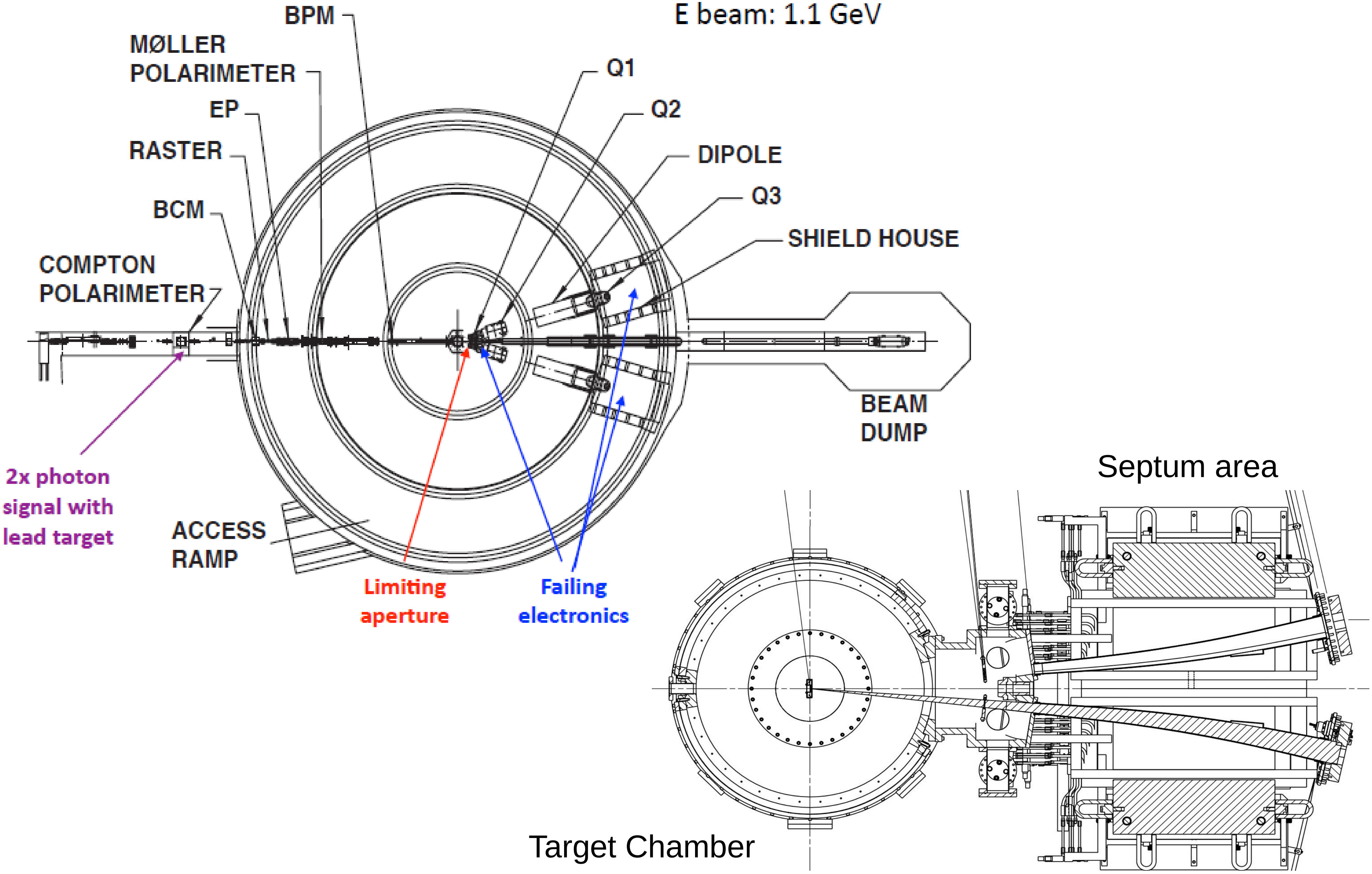
Outline

- Radiation Sources in PREX-I
- Radiation Shielding Strategy for PREX/CREX and MOLLER
- Simulation benchmarks and comparison with measurements

PREX-I Radiation Issues

Pb Target: 550 micron, 10% X_0
E beam: 1.1 GeV

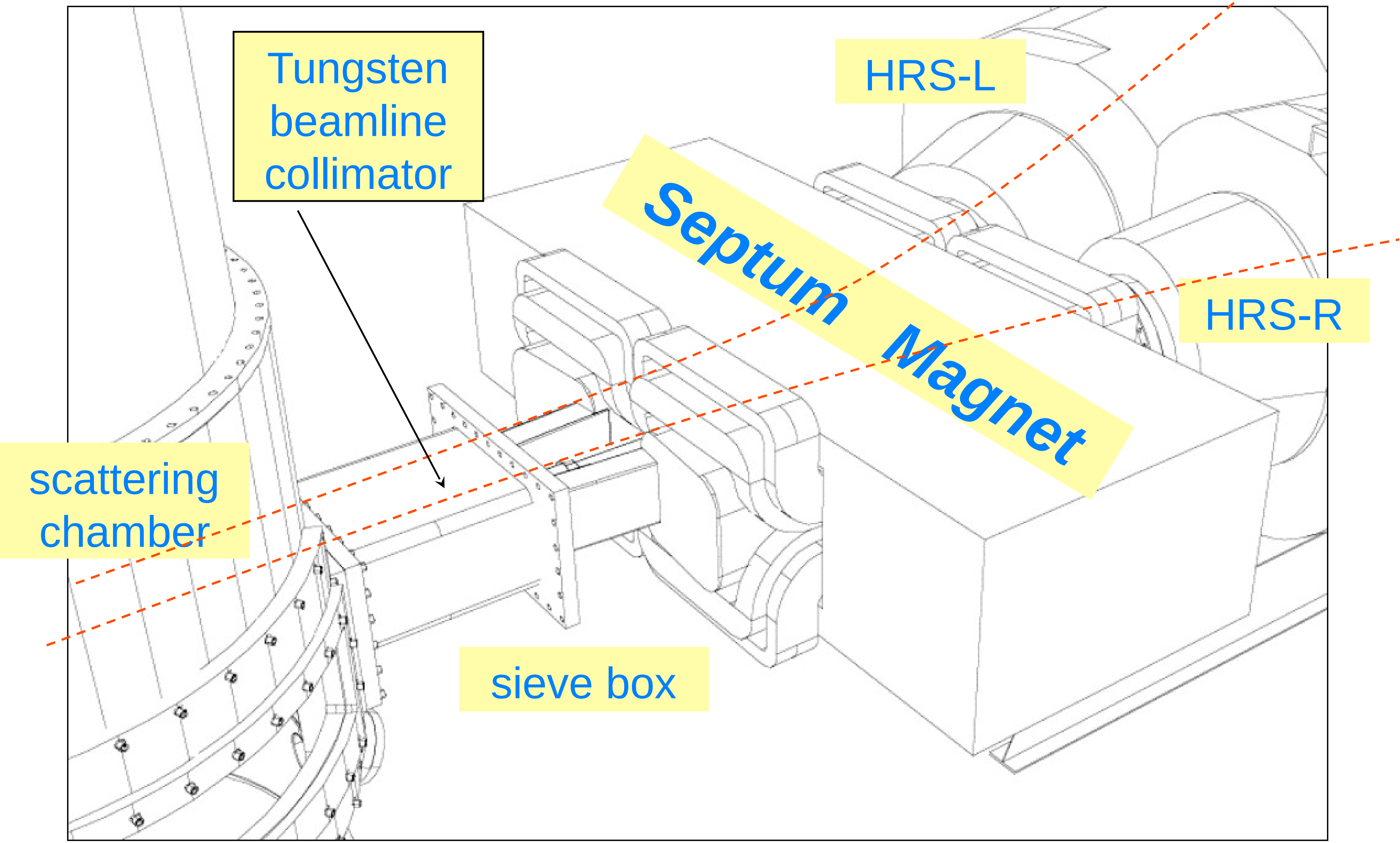


2x photon signal with lead target

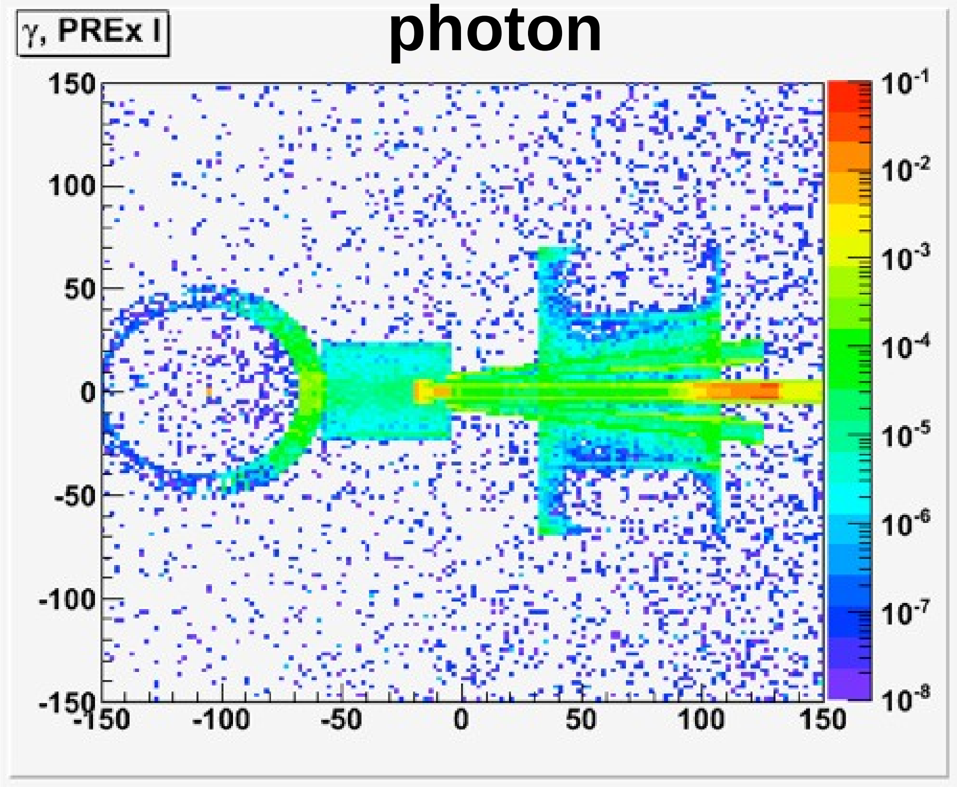
Limiting aperture

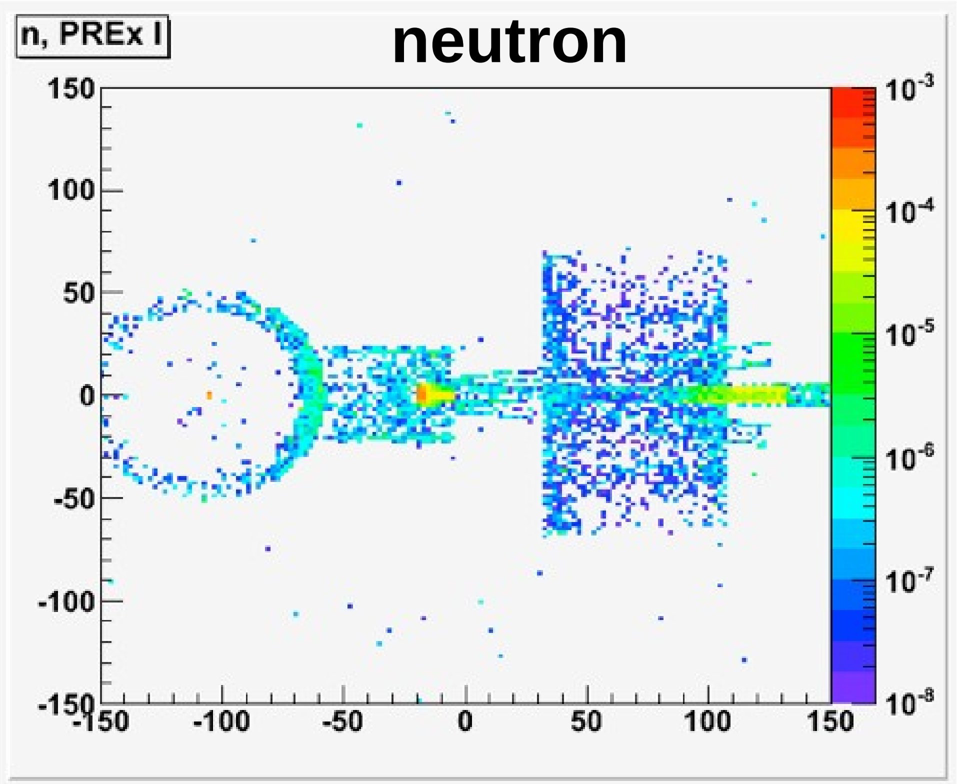
Failing electronics

Target Area Close-View



Sources of Neutron Radiation

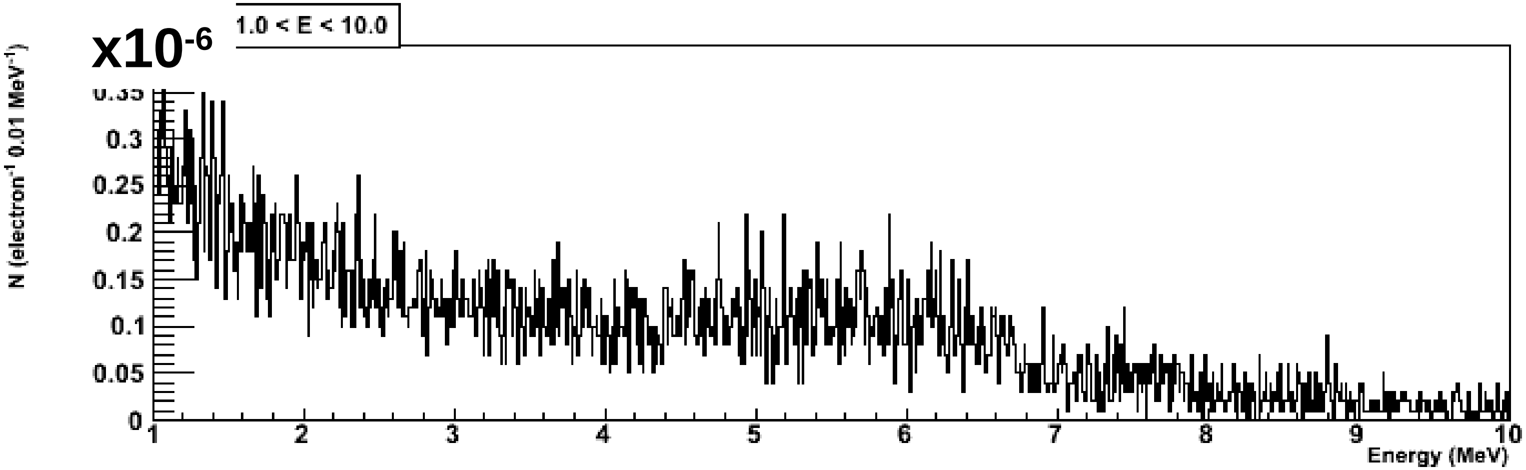




- Neutrons from the target are not the problem
  - 10% target rad. Length and elastic electrons from high Z target were a problem
- Neutron production via photo-production
  - GDR excitations in collimator and beam pipes
  - Results : soft neutron spectrum < 10 MeV

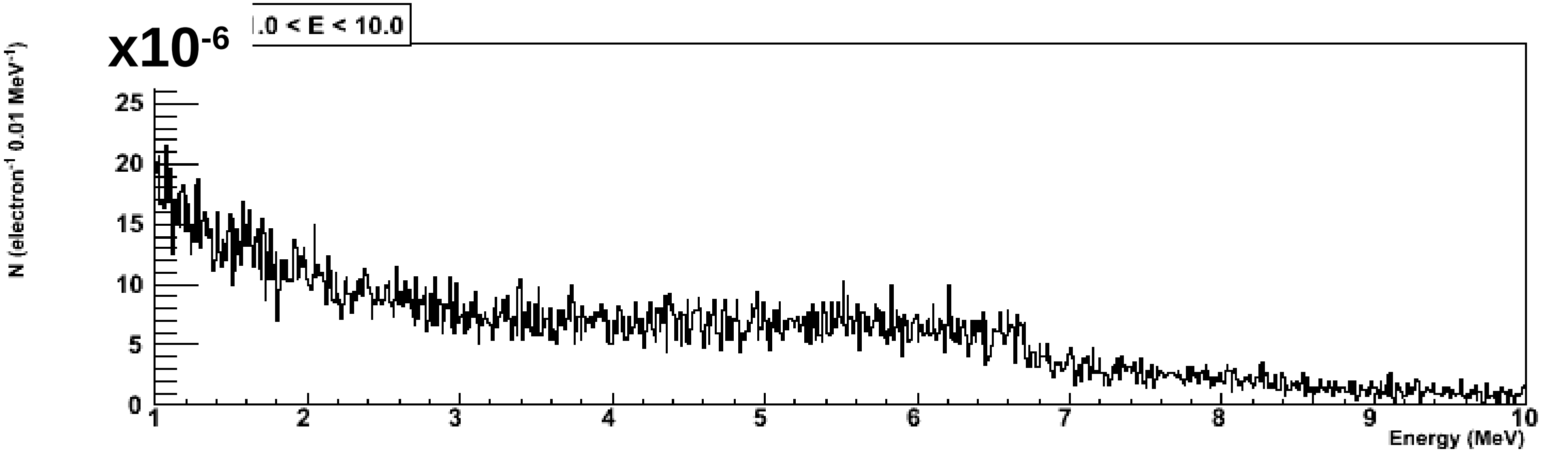
Sources of Neutron Radiation

500 um
Target

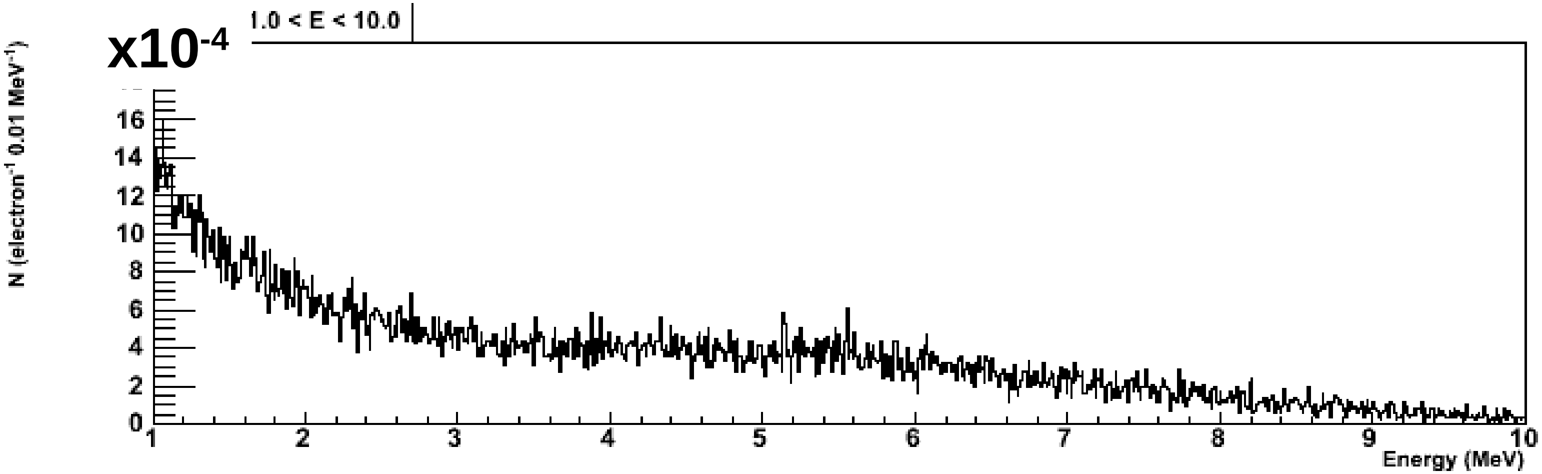


Quadratic
In
Target
thickness

5mm
target



Target
+ collimator
+ beamline



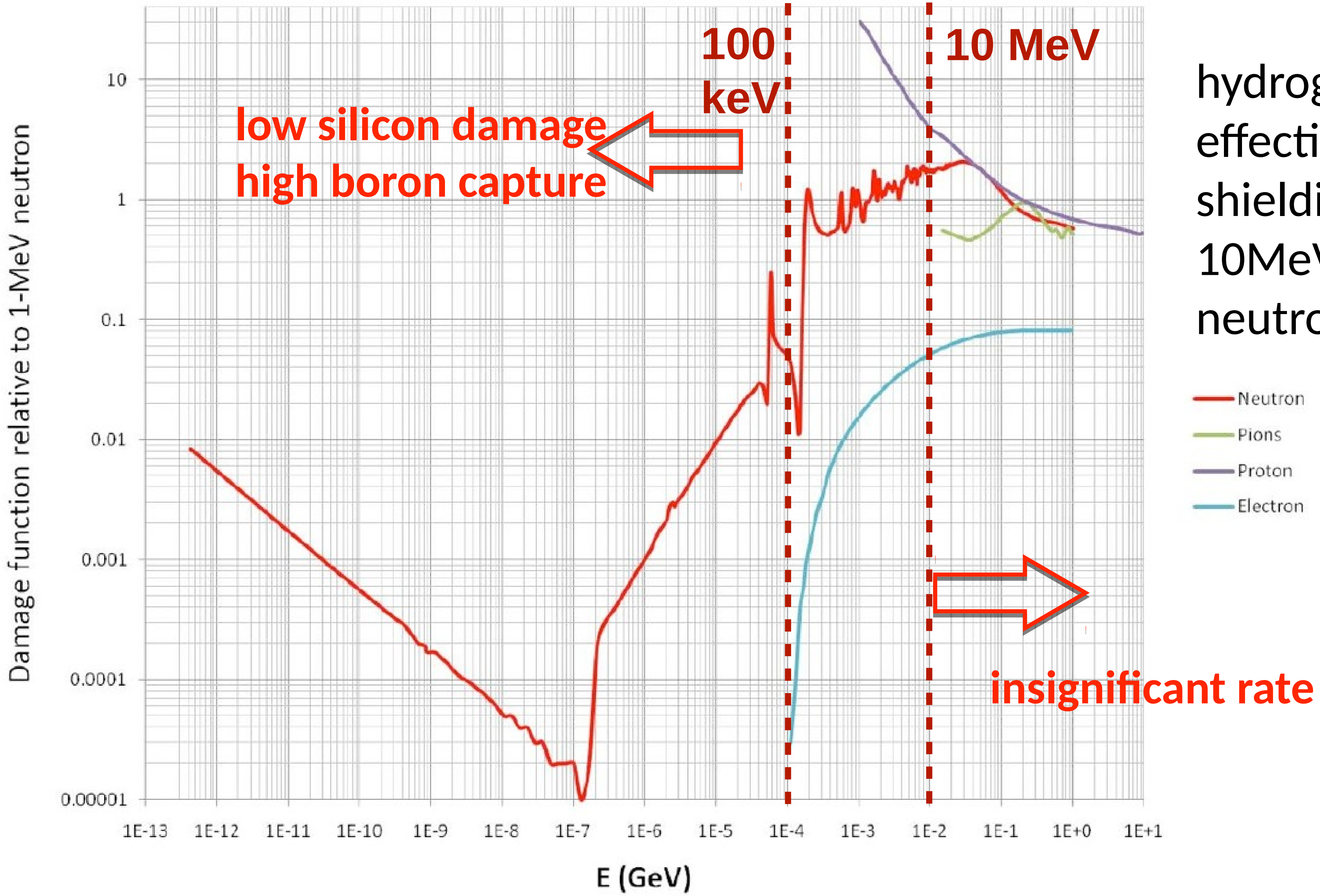
Sources of Neutron Radiation

- Limiting Aperture : scattering angle above which beam interact with the beam-pipe
  - In PREX-I this was at the downstream of the septum beam pipe : 0.84 deg
  - PREX-I collimator aperture was 1.27 deg
- Electromagnetic radiation from Pb-target as a secondary source
  - Elastic electrons
  - Bremsstrahlung photons from 10% rad. length
- Combination of fringe field leak from the septum magnet and limiting aperture at septum area resulted in significant spray in to the hall and beam-pipe

Main Strategy

- Use a single collimator to stop everything that misses the dump
  - Minimum aperture at the collimator
- More neutron production at the collimator is expected
- Shield around that collimator
  - The energy spectrum is soft enough to shield effectively
- This is the strategy implemented for PREX and proposed MOLLER experiment

Neutrons and Damage to Electronics



100 keV

10 MeV

low silicon damage
high boron capture

insignificant rate

hydrogen is effective for shielding 0.1-10MeV neutrons

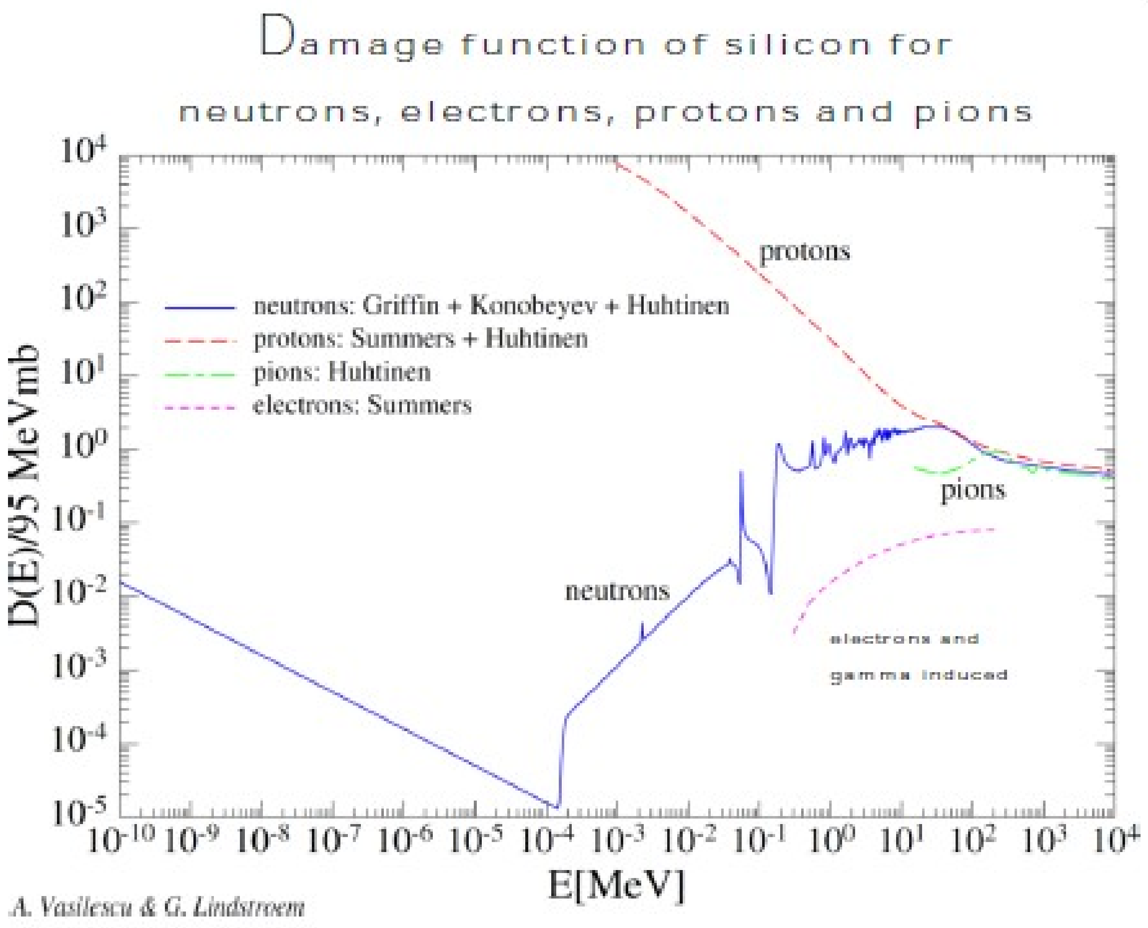
1 MeV neutron-equivalent (NIEL) metric

1 MeV Equivalent Neutron Fluence

The silicon radiation damage by “1 MeV equivalent neutron fluence”

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

which produces the same damage as an arbitrary radiation field with a spectral distribution φ(E)



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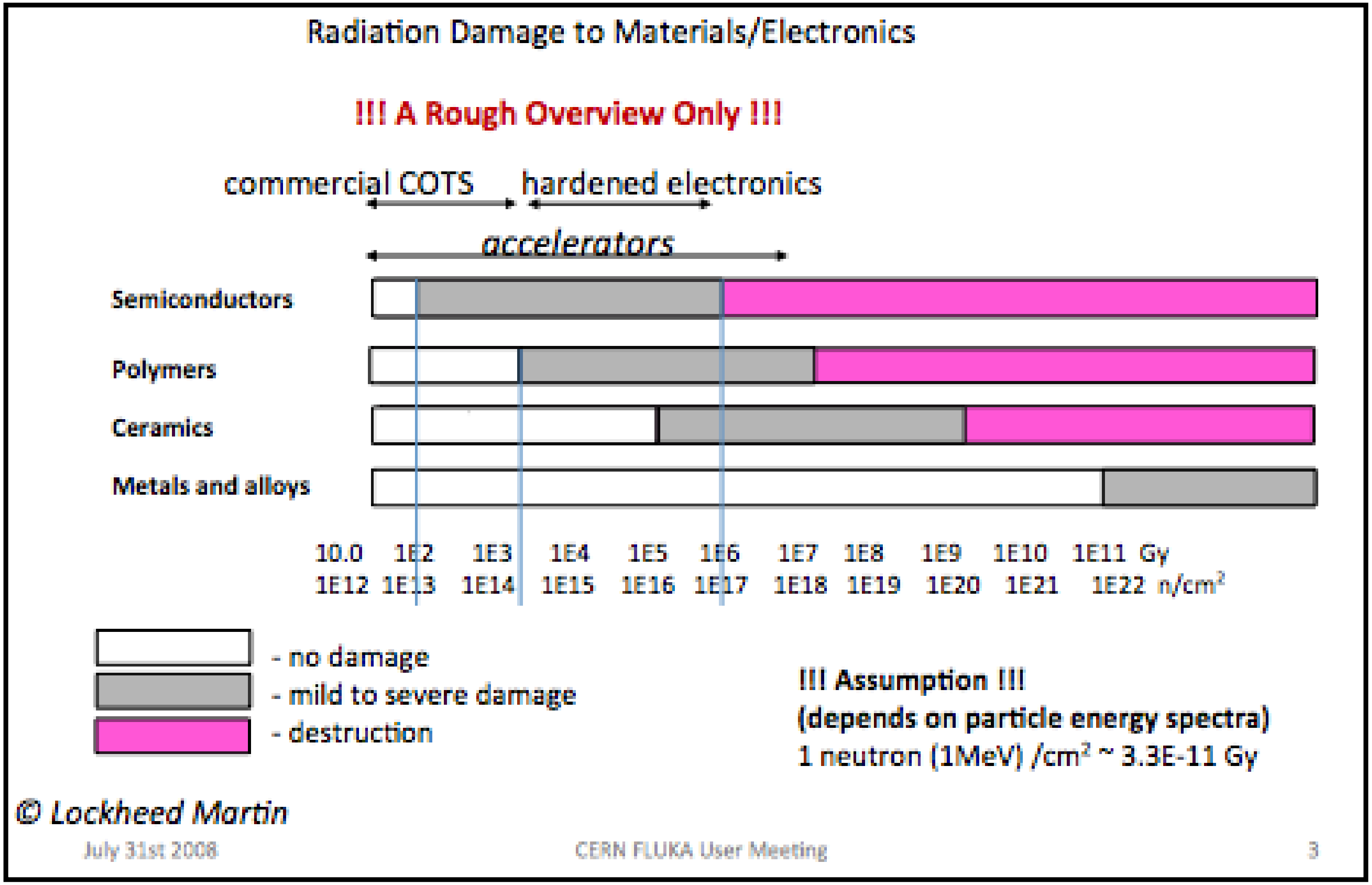
Radiation Dose Limit to Electronics



Radiation Damage to Materials/Electronics

!!! A Rough Overview Only !!!

□ - no damage
▨ - mild to severe damage
🟪 - destruction

!!! Assumption !!!
(depends on particle energy spectra)
1 neutron (1MeV) /cm² ~ 3.3E-11 Gy

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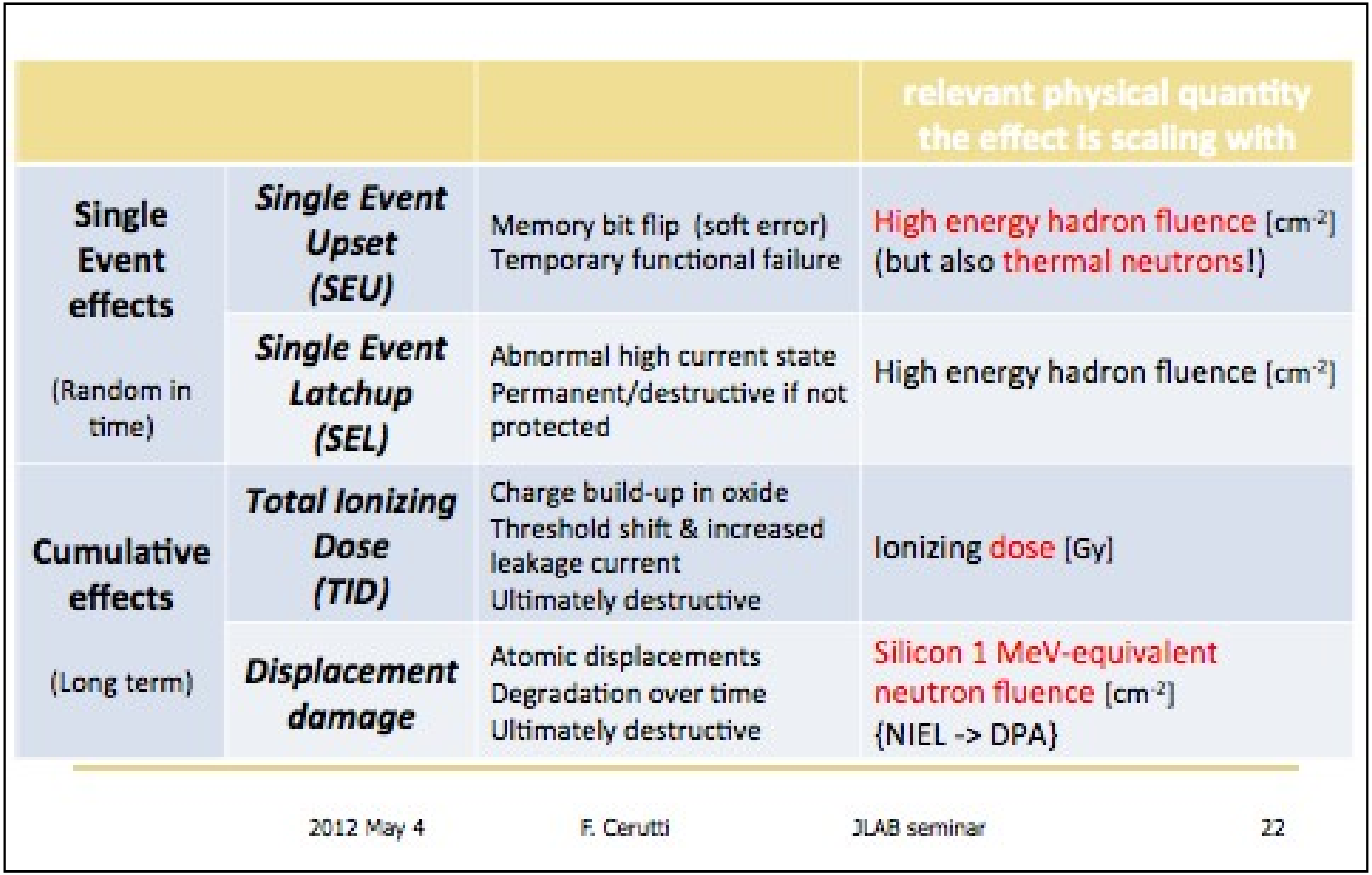
Commercial off-the-shelf (COTS) electronics are typically robust up to neutron doses of about 10^{13} n/cm^2.

Optocouplers are significantly softer, with failure at $1\text{x}10^{11}$ *1-MeV* n_{eq}/cm^2

Radiation Effects on Electronics



			relevant physical quantity the effect is scaling with
Single Event effects (Random in time)	***Single Event Upset (SEU)***	Memory bit flip (soft error) Temporary functional failure	High energy hadron fluence [cm^{-2}] (but also thermal neutrons!)
	Single Event Latchup (SEL)	Abnormal high current state Permanent/destructive if not protected	High energy hadron fluence [cm^{-2}]
Cumulative effects (Long term)	***Total Ionizing Dose (TID)***	Charge build-up in oxide Threshold shift & increased leakage current Ultimately destructive	Ionizing dose [Gy]
	Displacement damage	Atomic displacements Degradation over time Ultimately destructive	Silicon 1 MeV-equivalent neutron fluence [cm^{-2}] {NIEL -> DPA}

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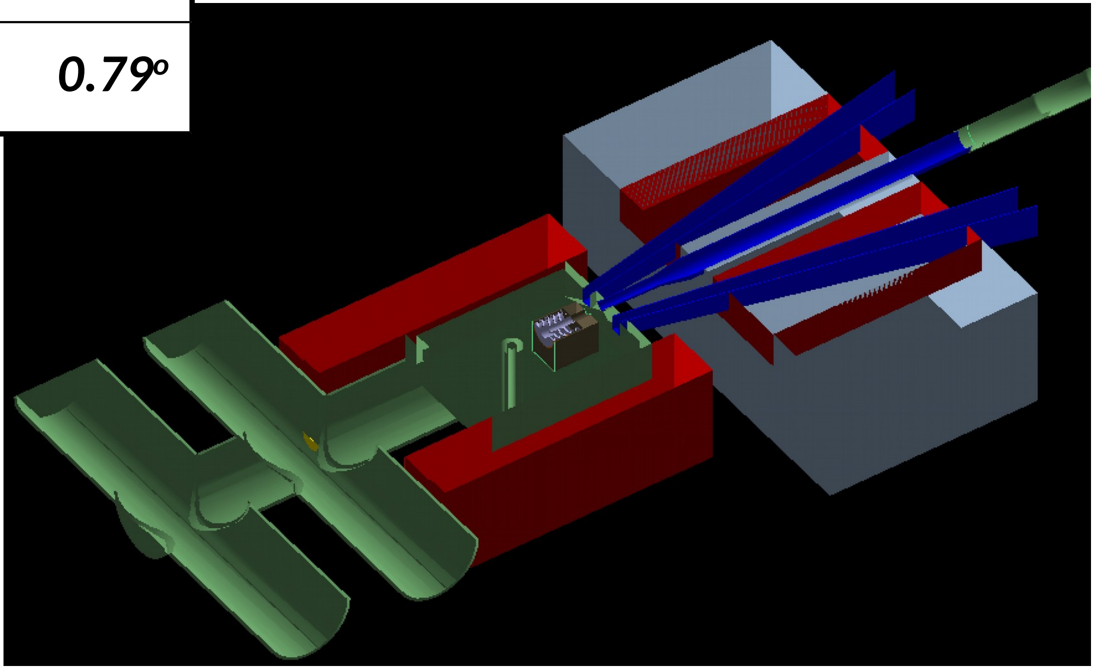
PREX Shielding Strategy

	Inner radius (cm)	*Distance from Target*	*angle*
collimator	***1.17***	***101.5***	***0.78°***
septum pipe	***4.13***	***266***	***0.86°***
gate valve	***5.08***	***337***	***0.84°***
End beam line (hall end)	***45.7***	***2757***	***0.95°***
(beam dump)	***45.7***	***3312***	***0.79°***

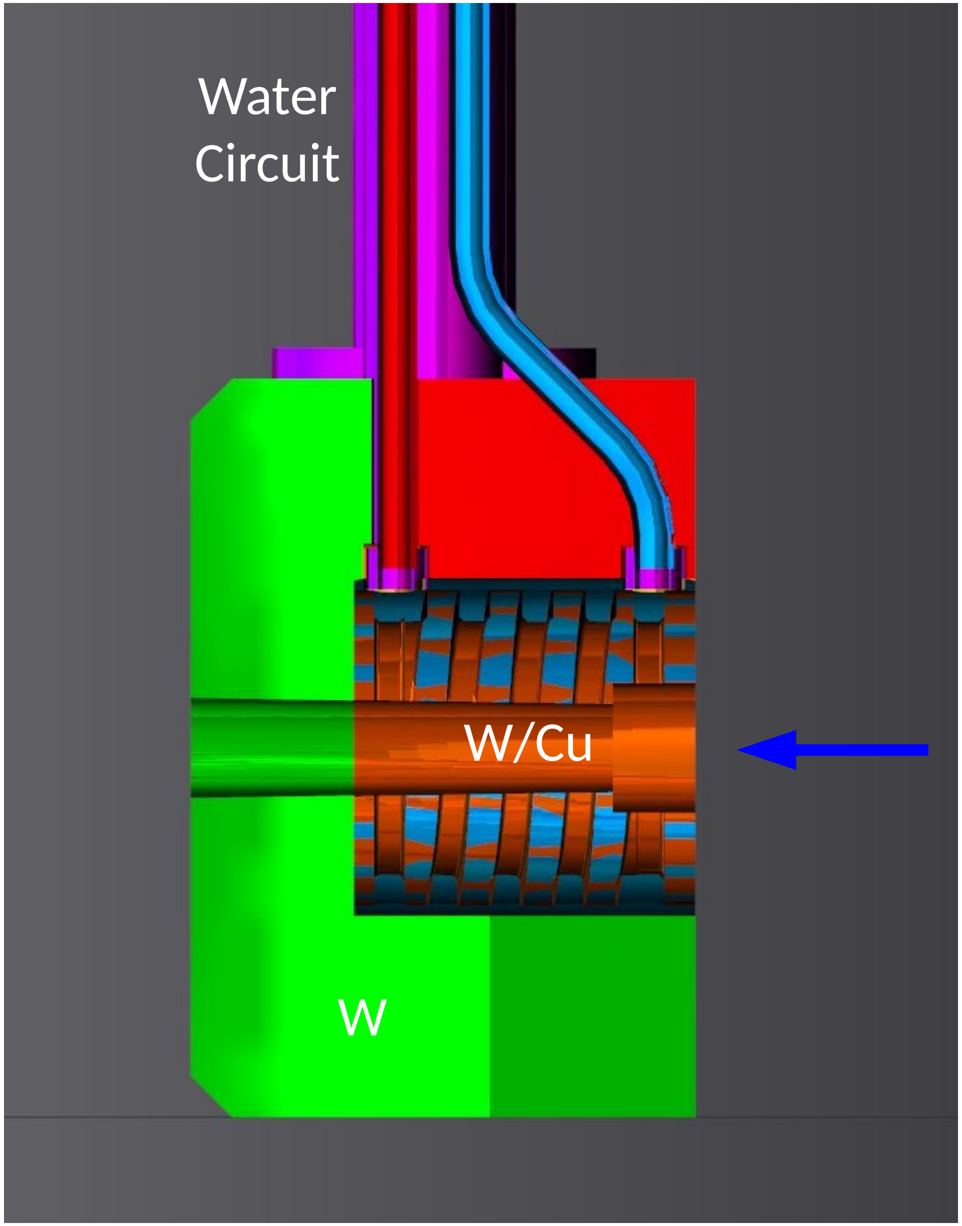
- Collimator aperture at 0.78° so whatever gets past the plug reaches the dump
- 20-30 cm thick high-density polyethylene (HDPE) shield to moderate neutrons

Maximize **solid angle** coverage of shield around collimator



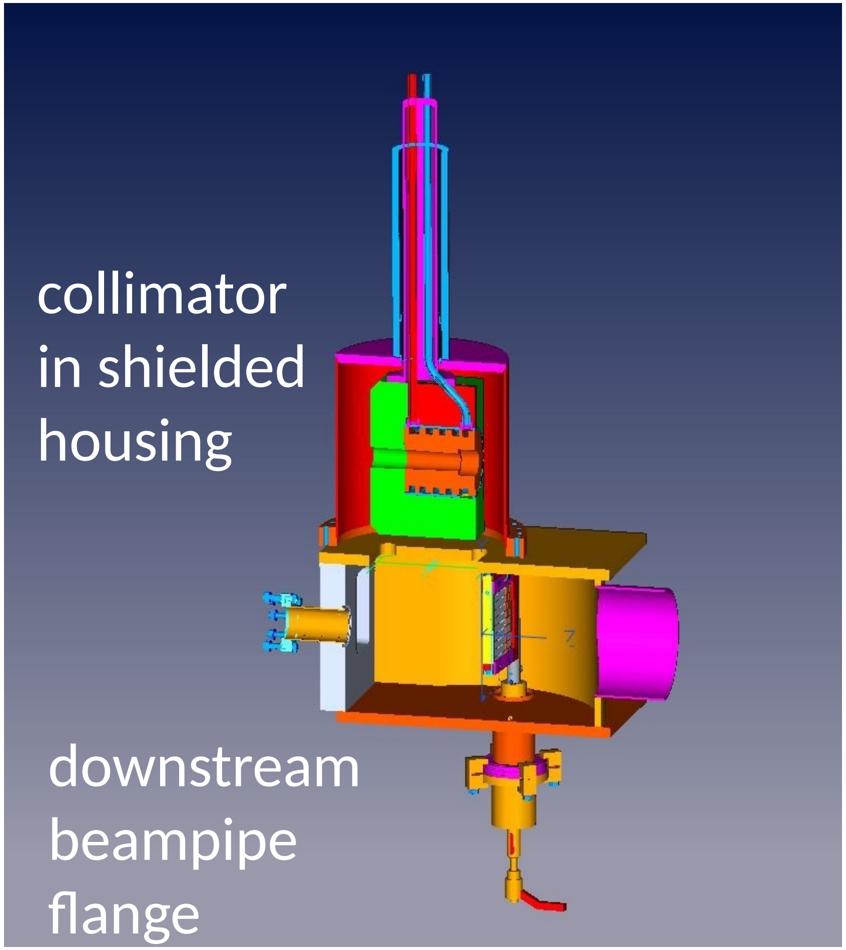
PREX-II Collimator

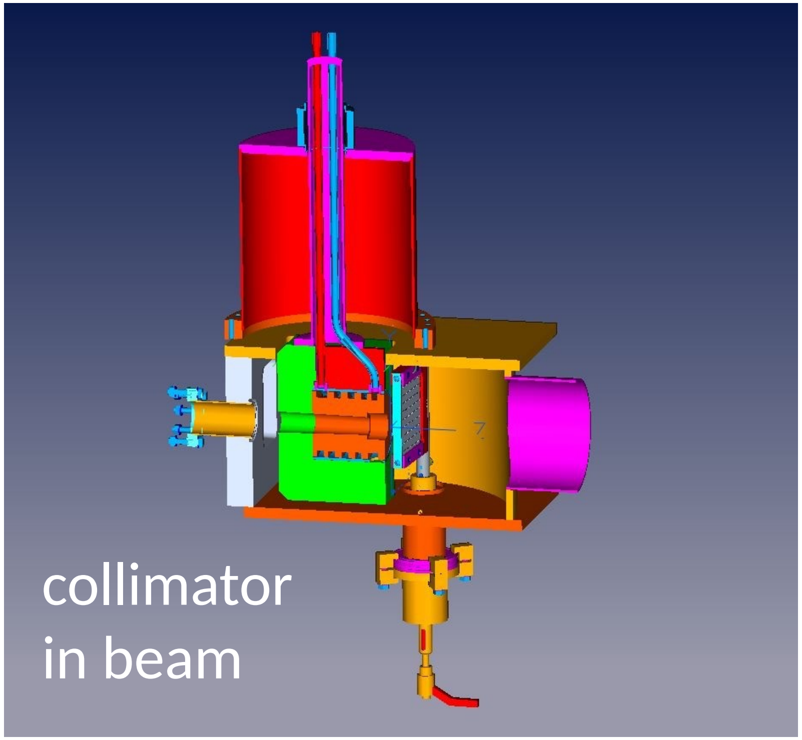
- Collimator front face 85cm from target
- Intercepts electrons >0.78°
- Power deposited: 2.1kW at 70 uA
- Inner cylinder 30% Cu-70% W alloy
  - Water-cooled with brazed cu sleeve
  - Initial estimates show cooling is sufficient
- Outer cylinder is tungsten
- Designed to slow down and self-shield neutrons
- PREX-I collimater only intercepted 1.27° and deposited 500 W



PREX-II Collimator

- Collimator will be activated by power deposited in the collimator bore
- Retract collimator into housing to shield the bore during deinstallation

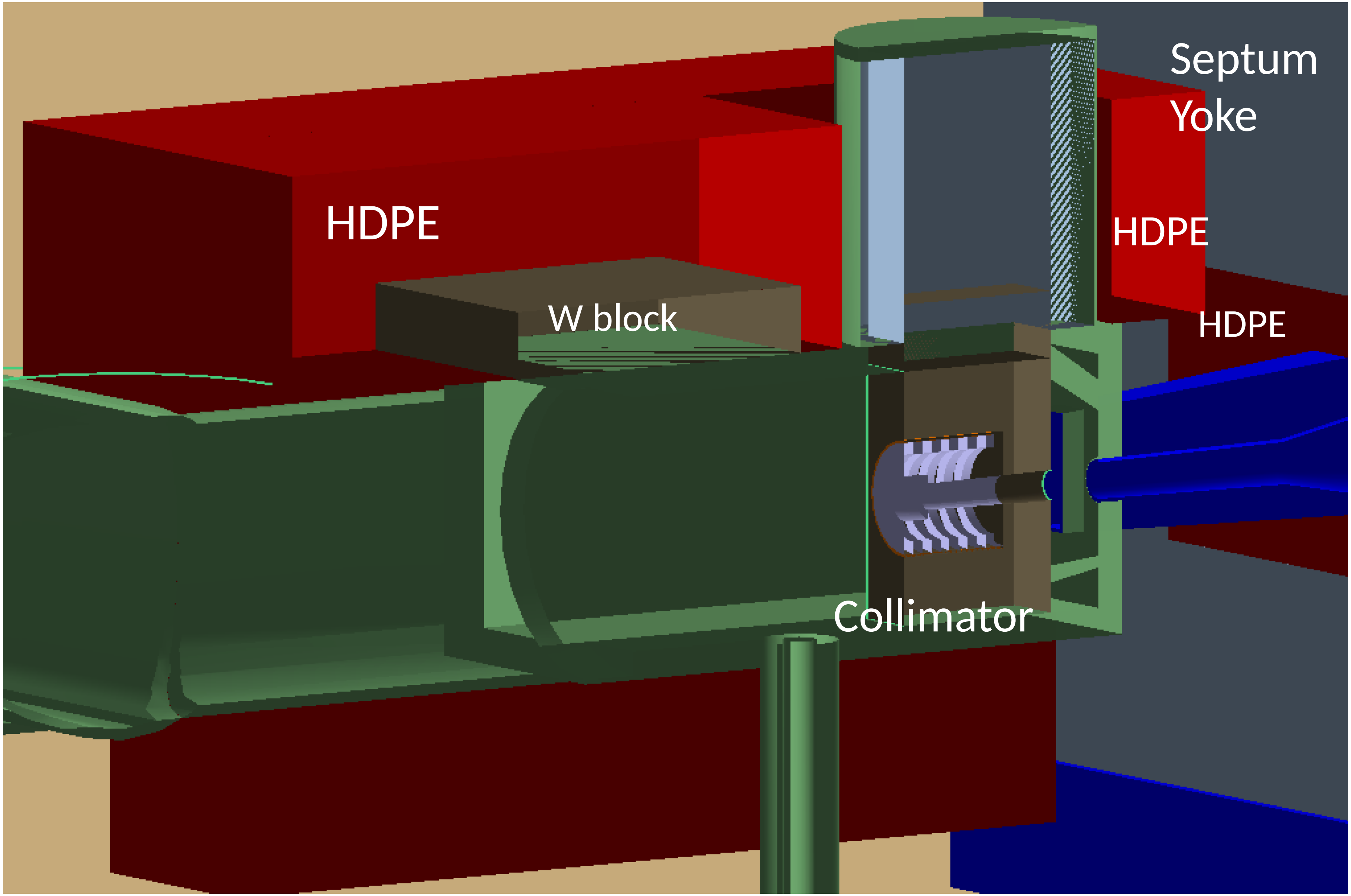




Neutron Shielding Design

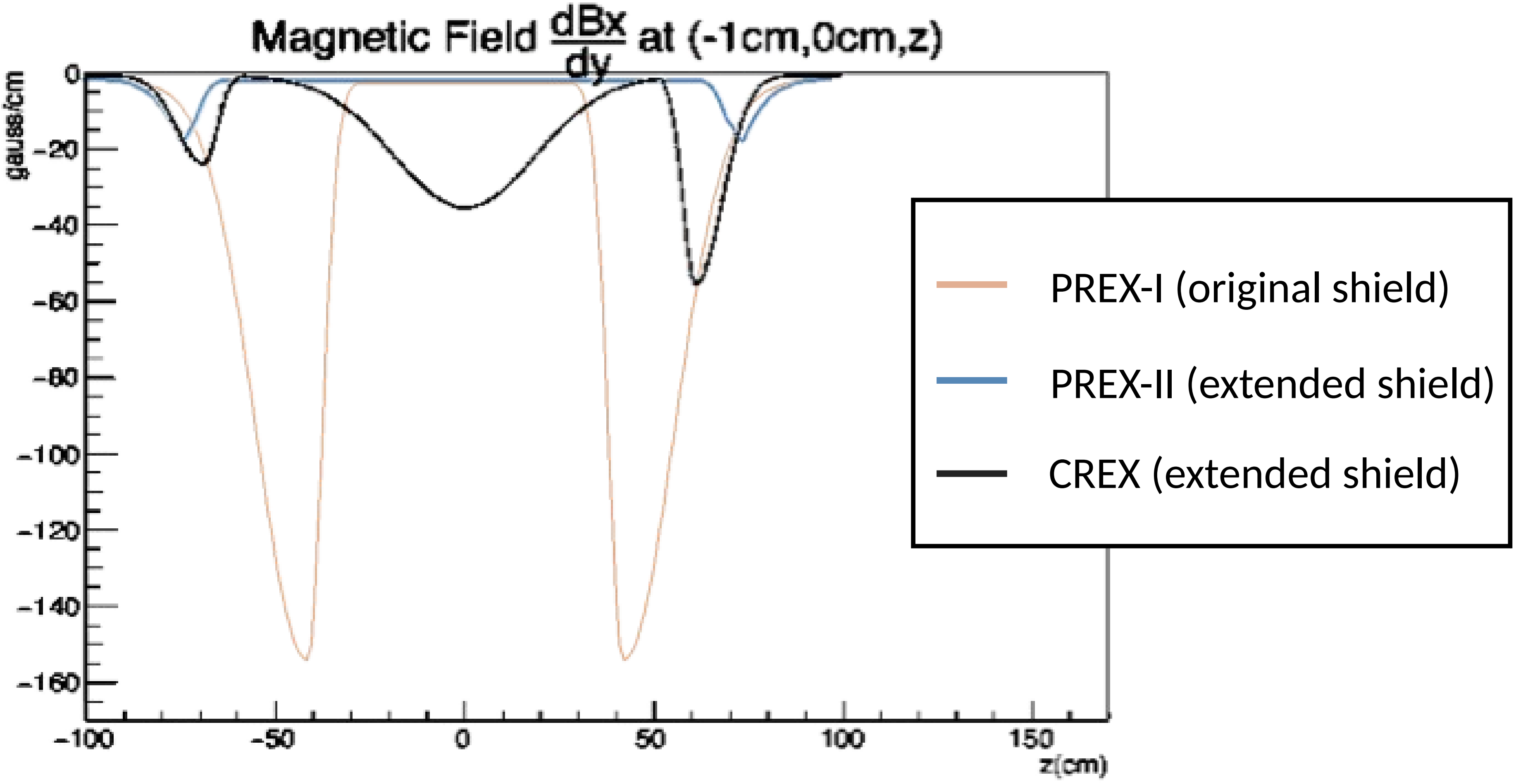
- Collimator isolated as the main source of neutron in the experiment
- Mostly soft neutrons (< 10 MeV) escape to the hall
- The collimator region is shielded using high density polyethylene (HDPE)

Neutron Shielding Design



Septum Fringe Magnetic Field

This is a simple model for fringe magnetic field inside the septum beam pipe using a Tosca model



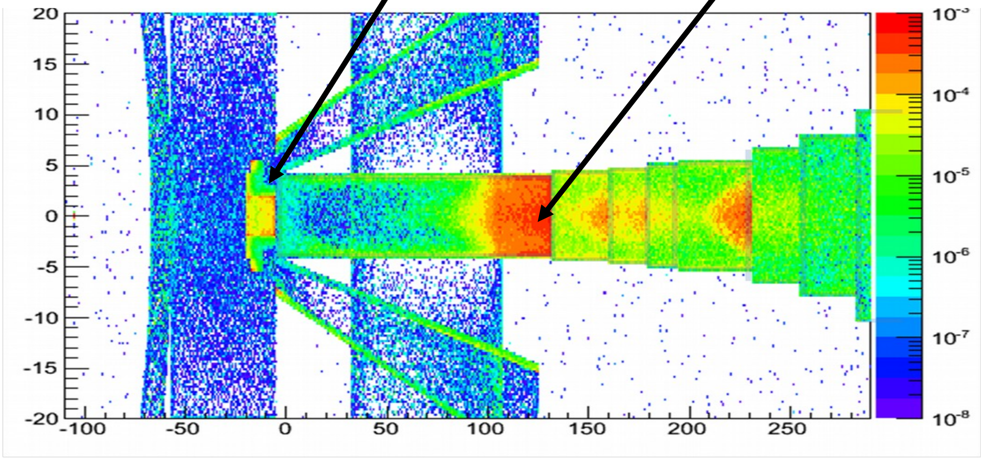
Reducing PREX-I Radiation Sources

- Large aperture collimator in PREX-I + fringe magnetic field have produced many secondary radiation sources
- Small aperture collimator + small fringe field in PREX-II design have reduced radiation sources in the hall

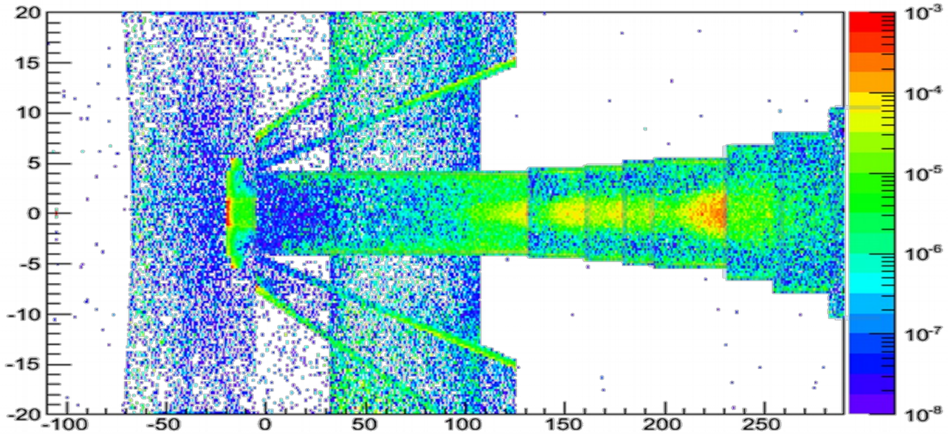
PREX I

collimator

septum
exit
beampipe



PREX II



Origin of photons

Extend magnetic shield through septum magnet

Reducing PREX-I Radiation Sources

- Large aperture collimator in PREX-I + fringe magnetic field have produce many secondary radiation sources
- Small aperture collimator + small fringe field in PREX-II design have reduced radiation sources in the hall
- PREX-II collimator absorbs more power and dissipate less power back to the hall

	PREX-I	PREX-II	CREX
EM Power in collimator (W/μA)	9.7	28.8	9.0
EM Power dissipated to the hall (W/μA)	18.0	3.0	1.5

Benchmark with Different Experiments

Simulations done with different experimental configurations to benchmark simulation results between experiments

	PREX-II	CREX	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	2.2 GeV	1 GeV	3 GeV	6 GeV
Septum	shielded fringe	shielded fringe, TOSCA model	full fringe	full fringe, scale=3	no septum, no fringe
collimator	PREX-II	PREX-II	PREX-I	PREX-I	none
target position	z=-1m	z=-1.4m	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

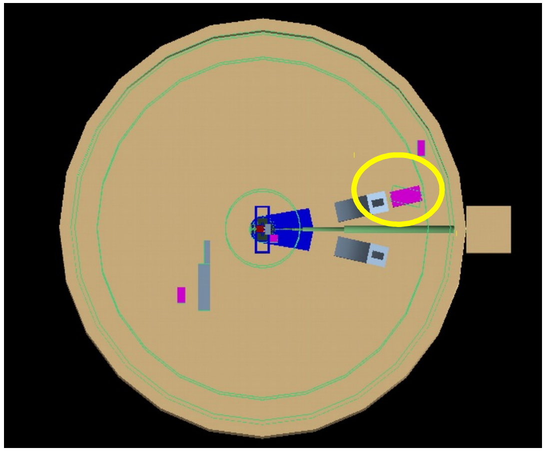
Benchmark with Different Experiments

Total power of >10 MeV electrons around the hall shows improvement with collimation and shielding

Hall Detector	***P2 / P1***	***P2 / H2***	***P2 / PVDIS***	***CREX/P1***
electrons (W) ***E>10 MeV***	***4%***	***39%***	***15%***	***5%***

Benchmark with Different Experiments

Radiation at the HRS Power Supply Platform



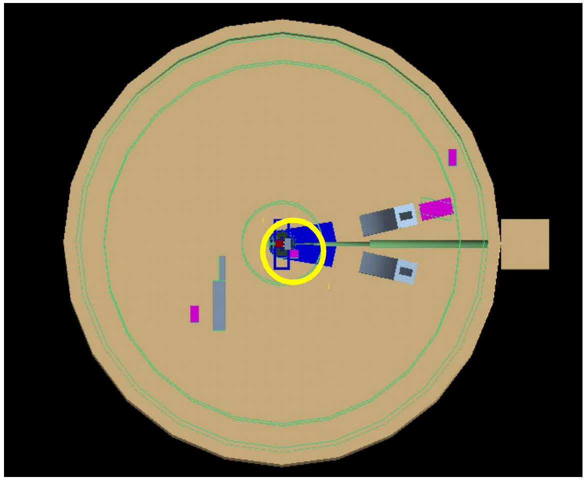
particle	E Range (MeV)	P2 / P1	P2 / H2	P2 / PVDIS	CREX/P1
neutron	0 < E < 0.1	44%	410%	270%	38%
neutron	E>0.1	**6%**	**76%**	63%	8%

Additional optimization of HDPE shielding may further improve neutron

particle	E Range (MeV)	P2 / P1	P2 / H2	P2 / PVDIS	CREX/P1
electron	0 < E < 0.1	4%	42%	21%	4%
electron	E>0.1	**6%**	**63%**	65%	5%

Benchmark with Different Experiments

Radiation at the Q1 / Above Septum



particle	E Range (MeV)	P2 / P1	P2 / H2	CREX/P1
neutron	0 < E < 0.1	133%	1100%	120%
neutron	E>0.1	20%	170%	20%

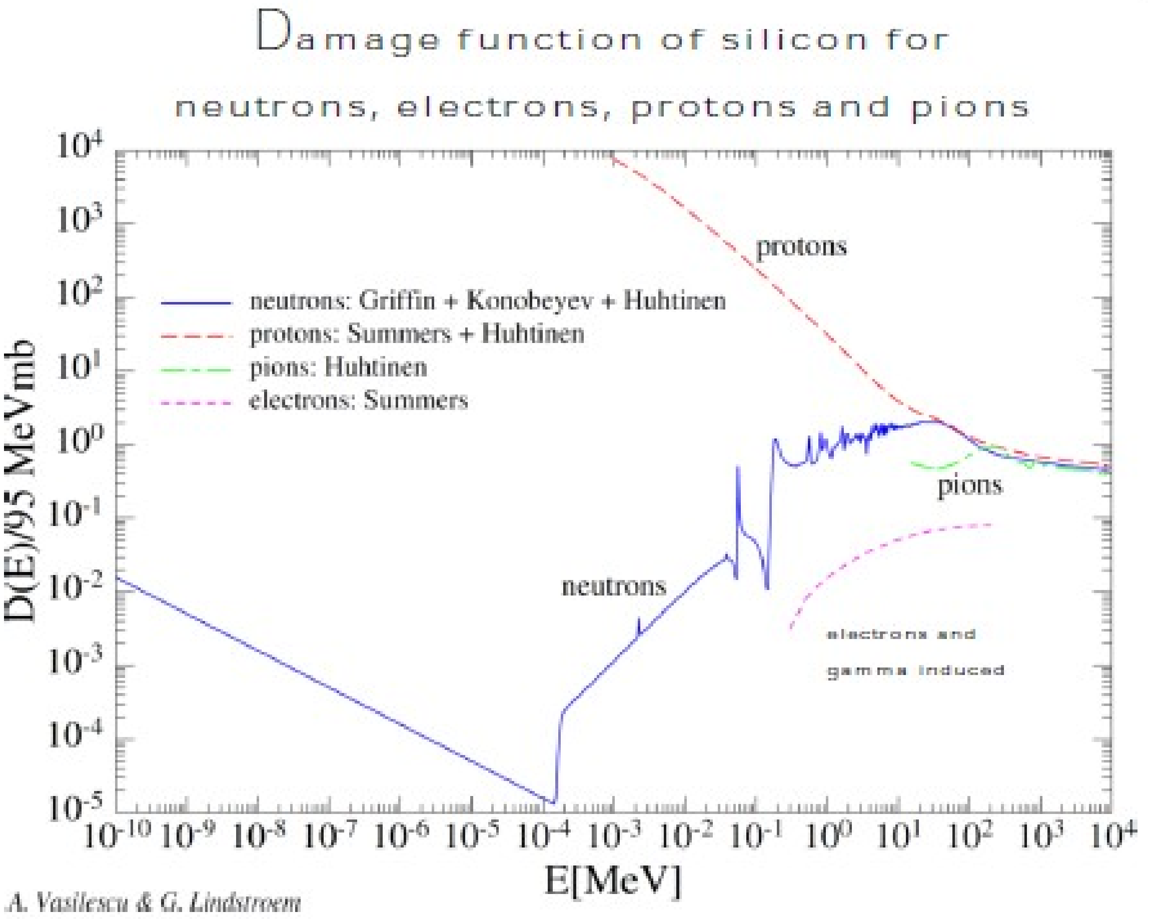
Additional optimization of HDPE shielding may further improve neutron

particle	E Range (MeV)	P2 / P1	P2 / H2	CREX/P1
electron	0 < E < 0.1	8%	100%	7%
electron	E>0.1	6%	90%	5%

Benchmark with Different Experiments

The silicon radiation damage by “1 MeV equivalent neutron fluence”

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



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which produces the same damage as an arbitrary radiation field with a spectral distribution φ(E)

Benchmark with Different Experiments

1MeV neutron Equivalent (1MeV neq /cm2) Near HRS Platform

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

HRS power supply detector	PREX-II	PREX-I	CREX	P2/P1	P2/H2	CREX/P1
neutron	7.6E+09	1.0E+11	2.4E+10	7%	70%	23%
electron	1.4E+10	1.2E+11	1.4E+10	11%	94%	12%
total	**2.1E+10**	**2.3E+11**	**3.8E+10**	9%	83%	17%

- PREX-I integrated dose estimate
  - did not reach semiconductor damage threshold.
  - exceeded optocoupler damage threshold
- PREX-II integrated dose will be down an order of magnitude from PREX-I
- CREX integrated dose will be about 1/4 of PREX-I

Benchmark with Different Experiments

1MeV neutron Equivalent (1MeV neq / cm2)
Near collimator flux will exceed optocoupler damage threshold

Q1/cryo det	PREX-II (1MeV neq / cm2)	PREX-I	CREX	P2/P1	P2/H2	CREX/P1
neutron	3.9E+11	1.1E+12	5.4E+11	35%	200%	50%
electron	1.7E+11	1.4E+12	1.9E+11	13%	140%	14%
total	5.6E+11	2.5E+12	7.4E+11	23%	180%	30%

Neutron Flux at Different Locations

HRS Side	PREX-II	CREX
neutron	1.9E+09	7.6E+09
electron	3.4E+09	4.3E+09
total	5.3E+09	1.2E+10

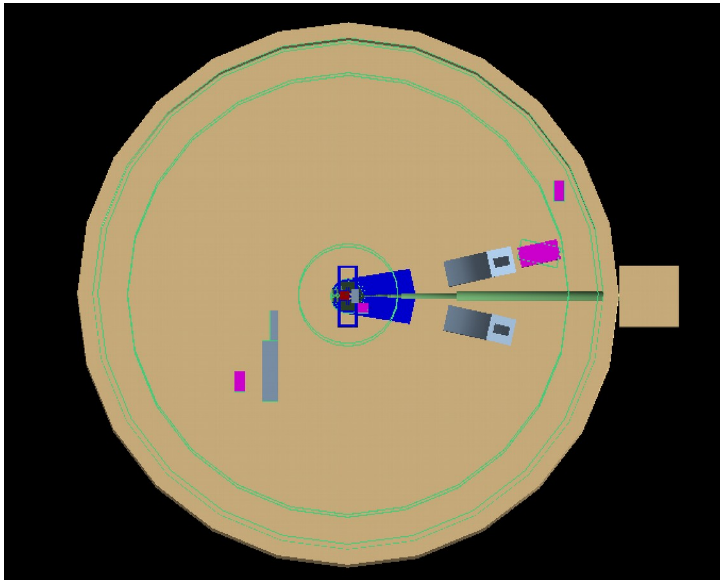
~4x less than HRS Platform

Upstream PS	PREX-II	CREX
neutron	3.2E+09	4.4E+09
electron	1.8E+06	2.6E+07
total	3.2E+09	4.4E+09

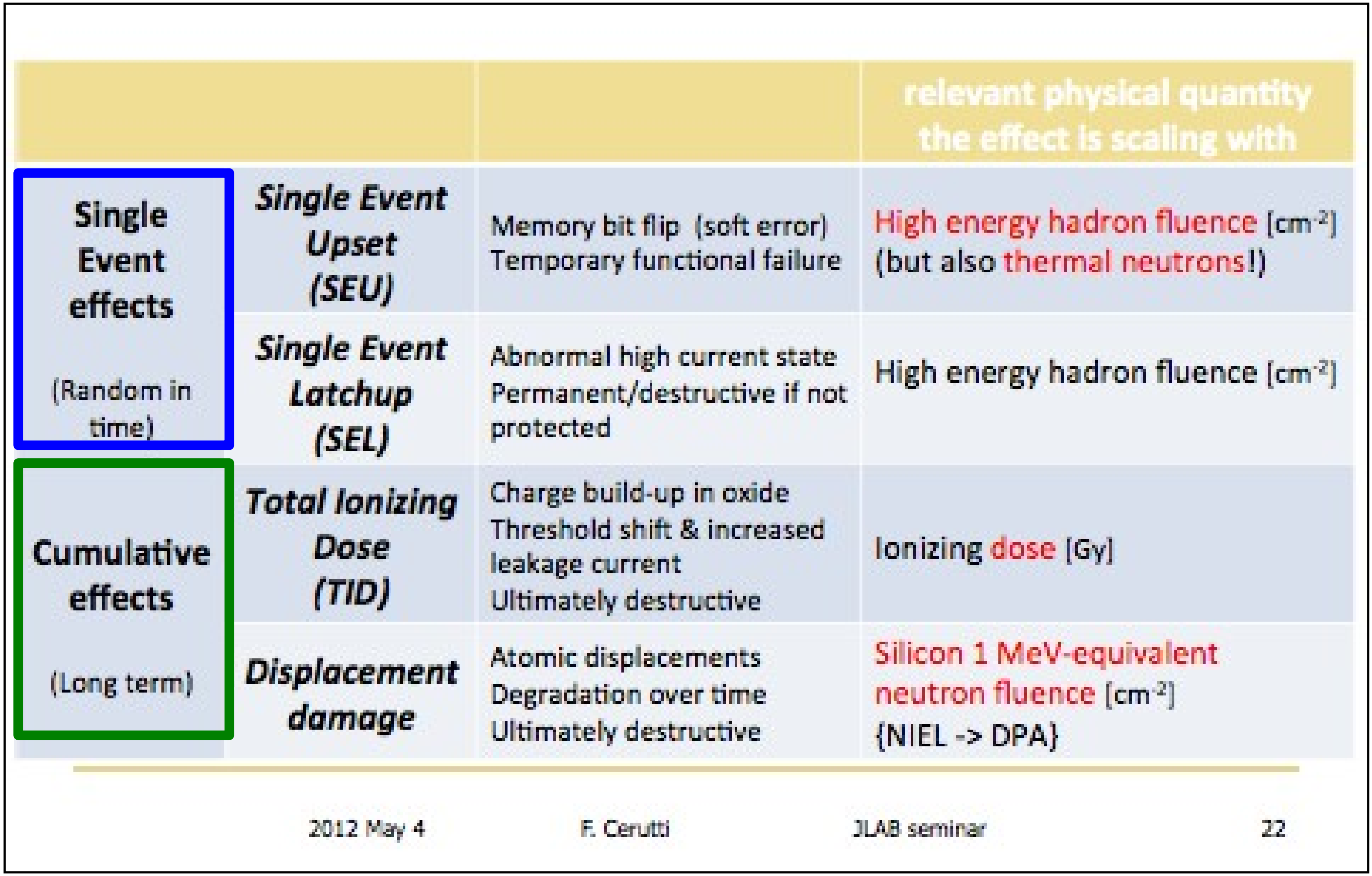
~10x less than HRS Platform

HRS Under	PREX-II	CREX
neutron	1.6E+10	1.7E+10
electron	1.4E+10	2.0E+10
total	2.9E+10	2.7E+10

similar to HRS Platform if no local shielding



Radiation Effects on Electronics



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Cumulative effects (Long term)	***Total Ionizing Dose (TID)***	Charge build-up in oxide Threshold shift & increased leakage current Ultimately destructive	Ionizing dose [Gy]
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High Energy Neutrons

- Source of SEU or SEL events (instantaneous effects)
- Reduced high energy neutrons in the hall enclosure
  - Due to new collimator with self-shielding
  - Reductions are not large as low energy neutrons

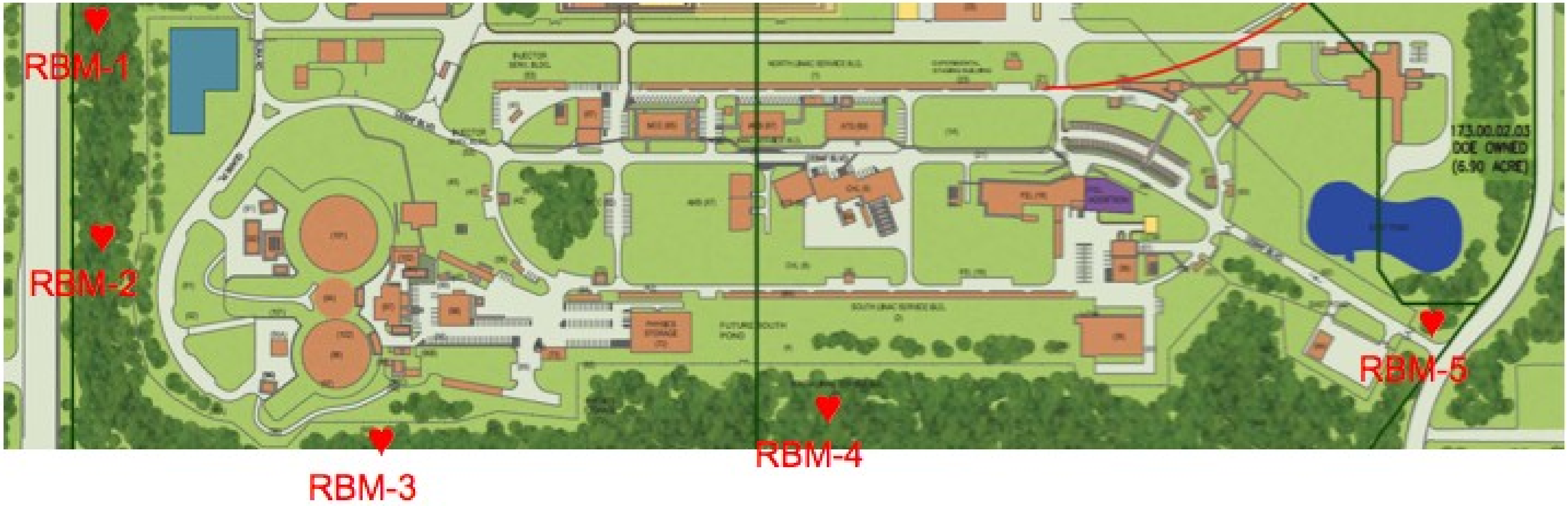
Hall Detector (n,E>10MeV) MHz/m^2	PREX-1	PREX-2	CREX
HRS Platform	8	<1	<2.3
At Q1 / Above Septum	320	51	78

High Energy Neutrons

Hall Top Detector	PREX-1	PREX-2	CREX
Integrated Flux (n>30MeV) [#/m^2]	4.5E+12	5.8E+12	1.5E+13
Integrated Energy (n>30MeV) [J/m^2]	72	87	290

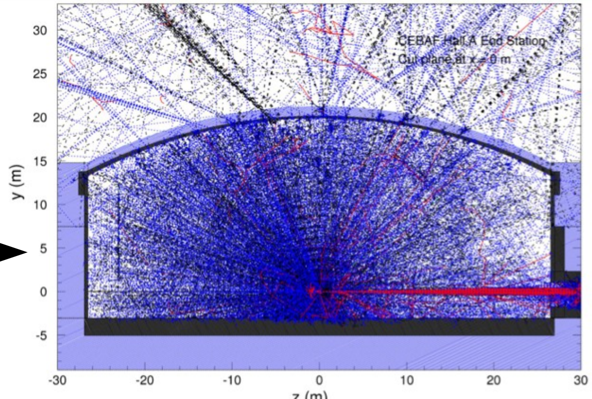
- High energy neutrons reaching the top of the hall enclosure
  - The integrated does for PREX-II is higher due assumed efficiency and longer running time compared to PREX-I
  - CREX is very high due to larger luminosity combined with high Z target
- Main influencer for site boundary

Site Boundary



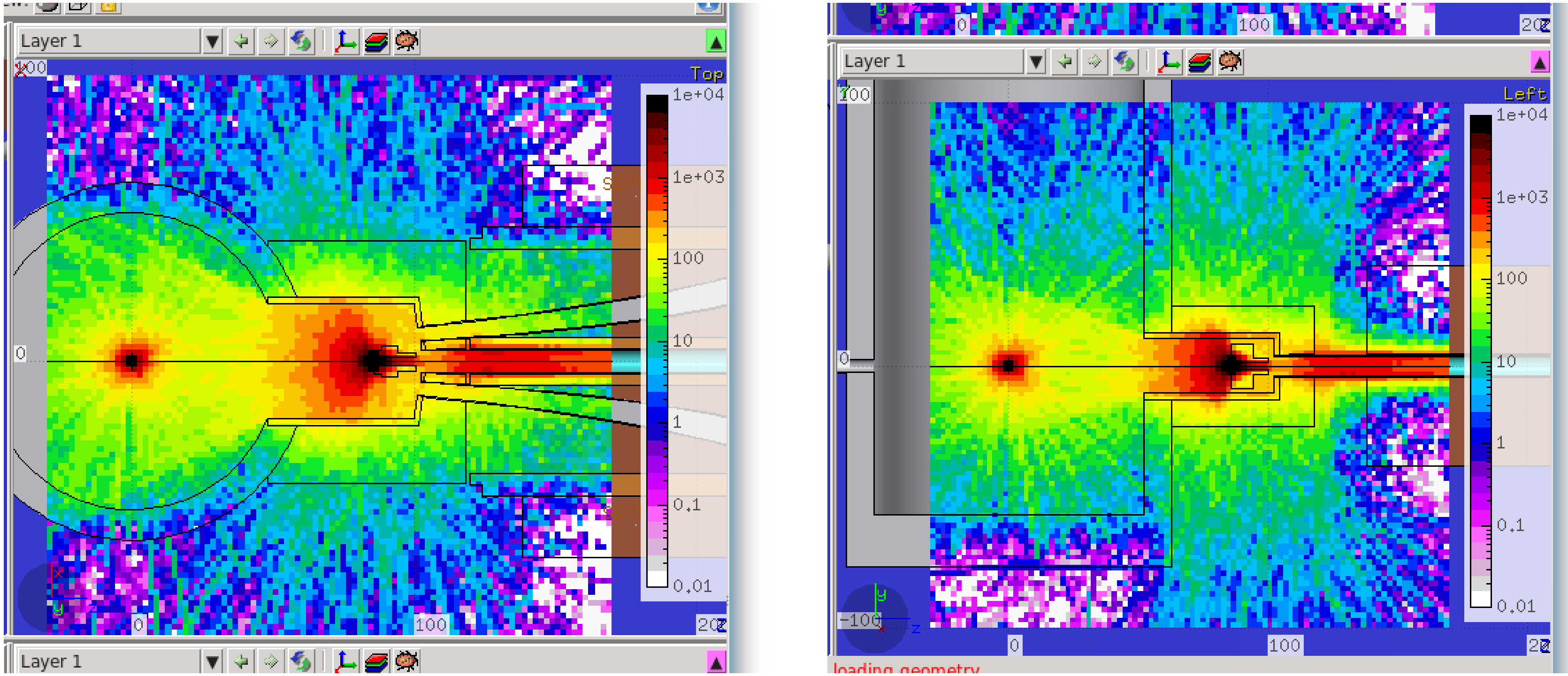
- Site-boundary mostly influenced by upward going, high-energy neutrons
  - They can penetrate the overburden and shower onto the site boundary
- Neutron rich nuclei (Pb or Ca) are a main source
- Jlab limit : 10 mrem/yr

Neutrons and EM penetration through Hall dome →



De-installation Plans

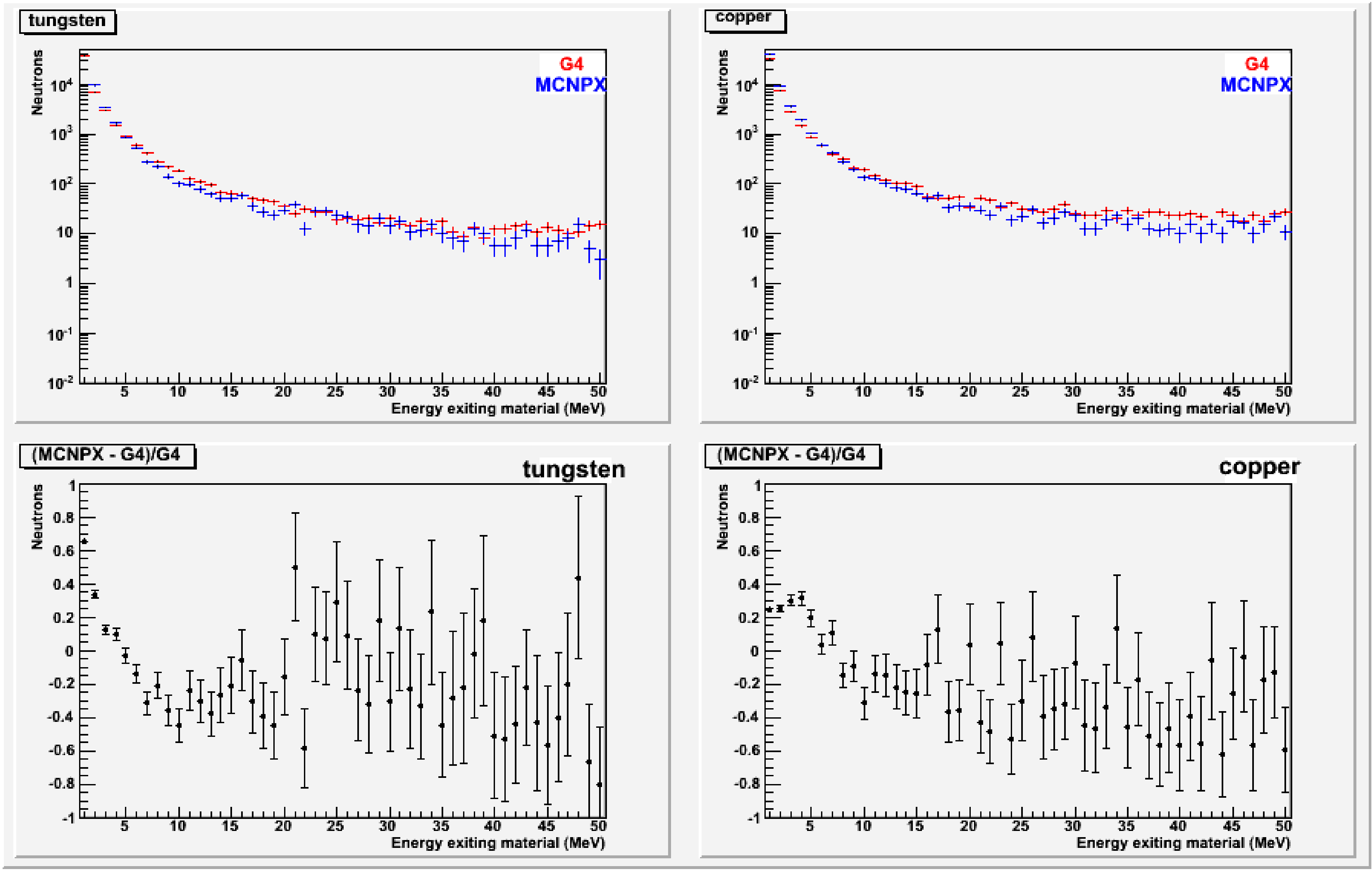
- Material activation studies via FLUKA simulation is an important aspect of de-installation plans
  - Work in progress by Lorenzo Zana aims to reduce de-installation dose and design optimal plans



Activation in mrem/h after 1 day

Simulation Benchmarks

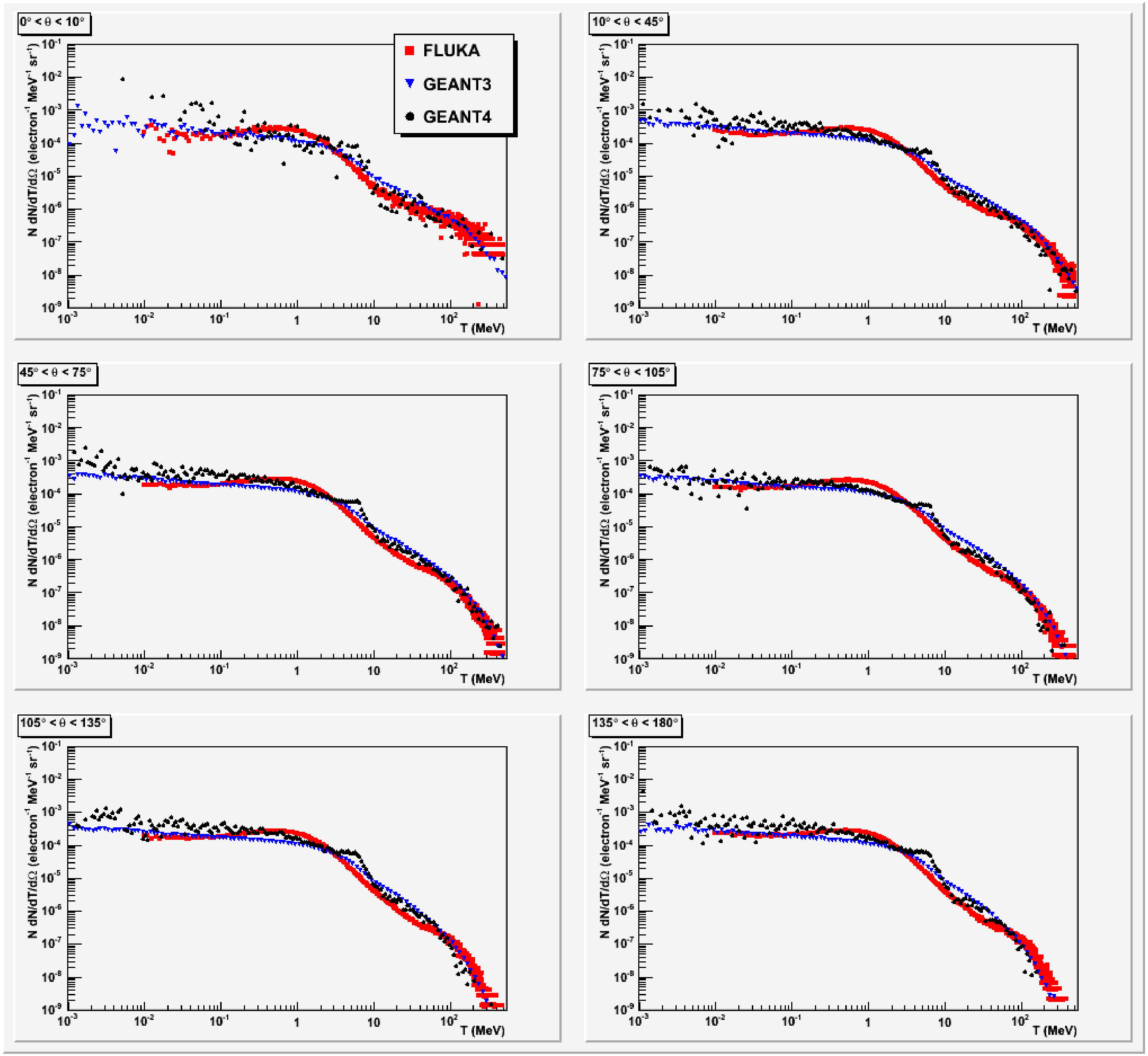
G4 and MCNPX comparison for neutron production by 1 GeV electrons



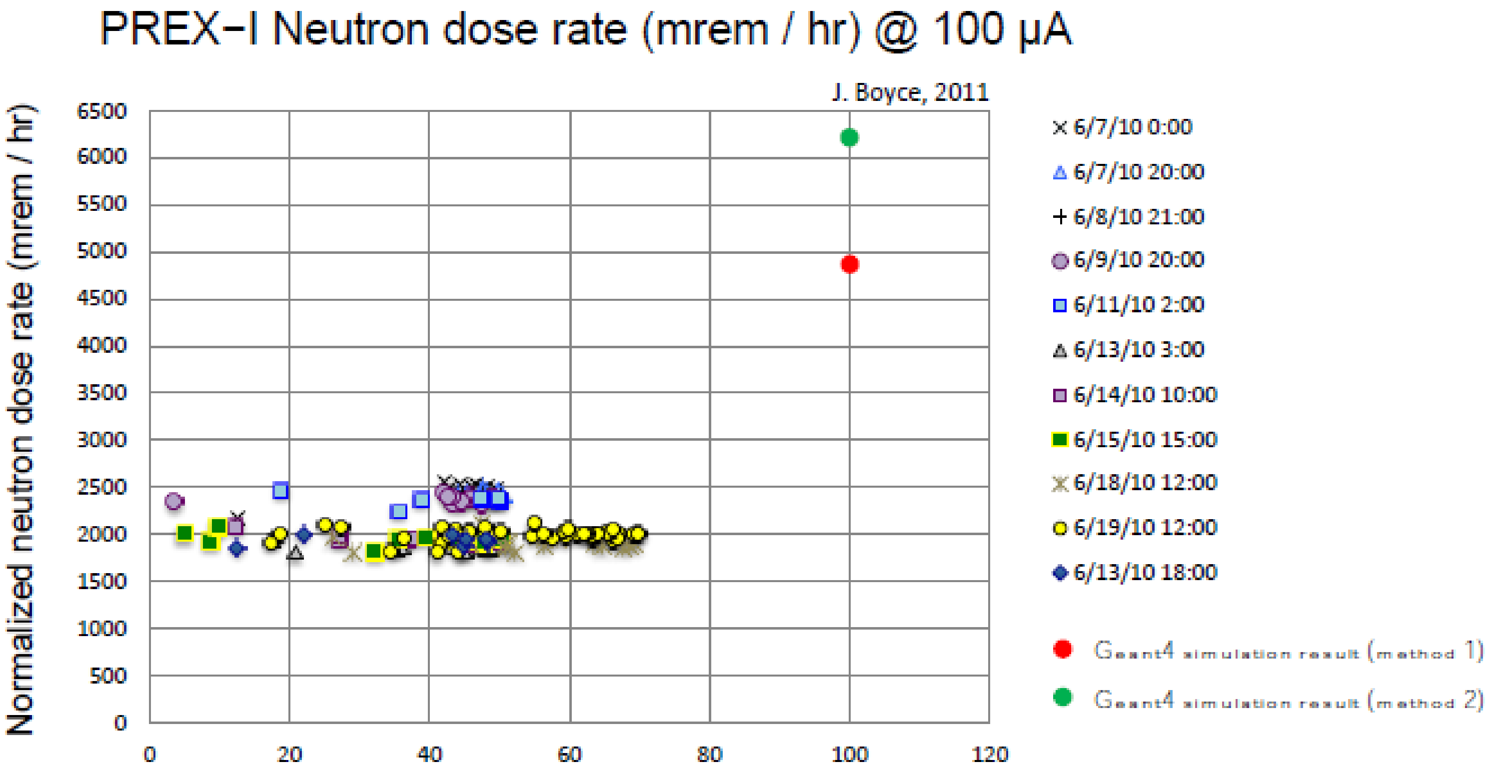
Simulation Benchmarks

G4, G3 and FLUKA comparison for neutron production by 1 GeV electrons on Pb target + collimator

Agreement within factor of 2



Simulation vs. Measurement



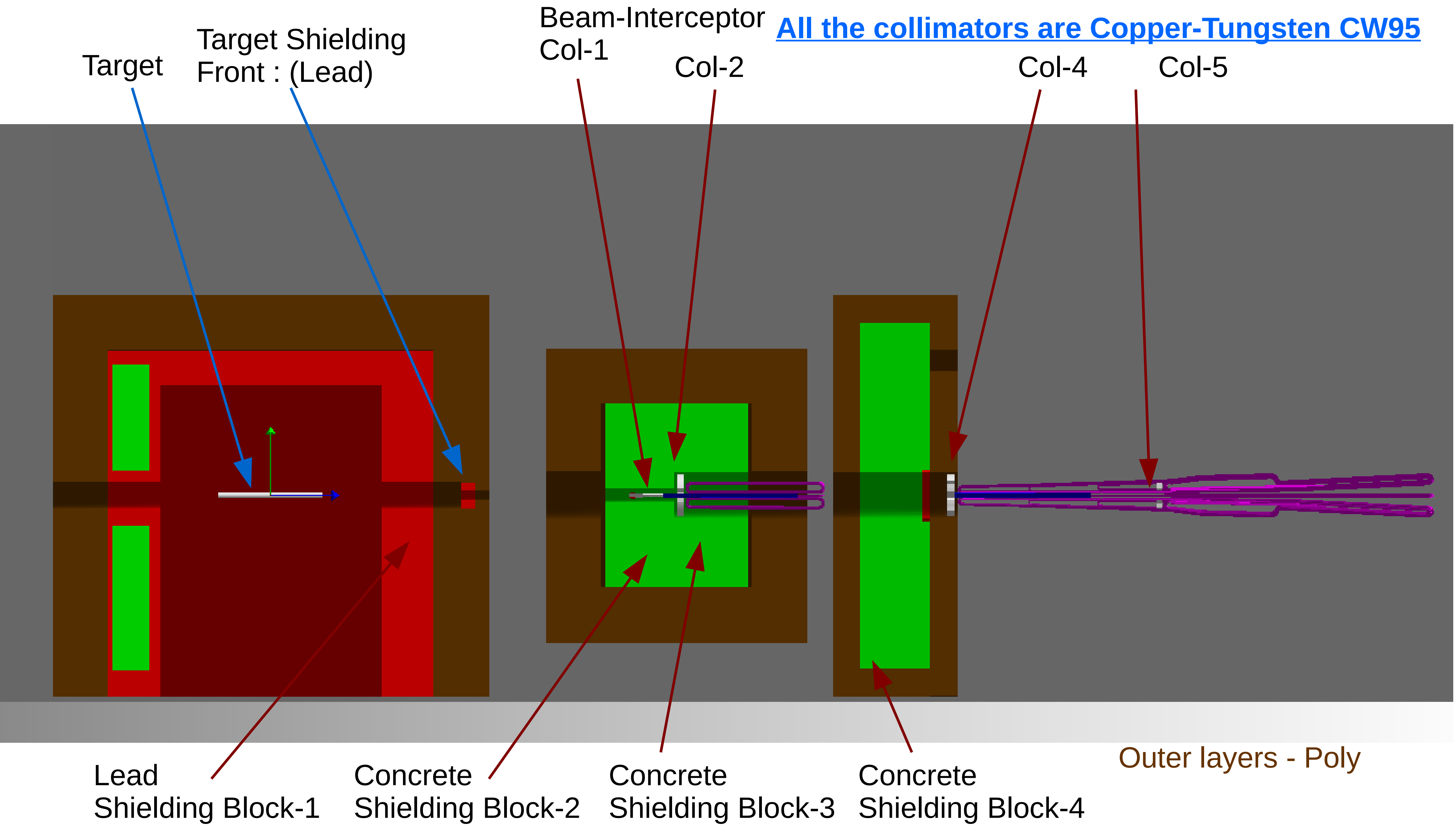
RadCon neutron dose rate measurements (units of Biological Damage (rem)) in the Hall A during PREX-I are compared with Geant4 simulation. Study by Maduka Kaluarachchi (UVA)

Consensus is we have a factor of 2 safety margin between simulation and measurements. Different simulations agree within factor of 2

Collimation and Radiation Shielding for MOLLER

- Single collimator to intercept low angle scattered beam
  - To isolate neutron production
- Target shielding required a lead wall
  - To stop EM power from the target
- Concrete and Tungsten for high energy neutrons
- Polythene for low energy neutrons (< 10 MeV)
- Goal of the shielding is to reduce the EM and neutron radiation into the hall A and reduce background at the detector region

Collimation and Radiation Shielding for MOLLER



Target

Target Shielding
Front : (Lead)

Beam-Interceptor
Col-1

Col-2

All the collimators are Copper-Tungsten CW95

Col-4

Col-5

Lead
Shielding Block-1

Concrete
Shielding Block-2

Concrete
Shielding Block-3

Concrete
Shielding Block-4

Outer layers - Poly

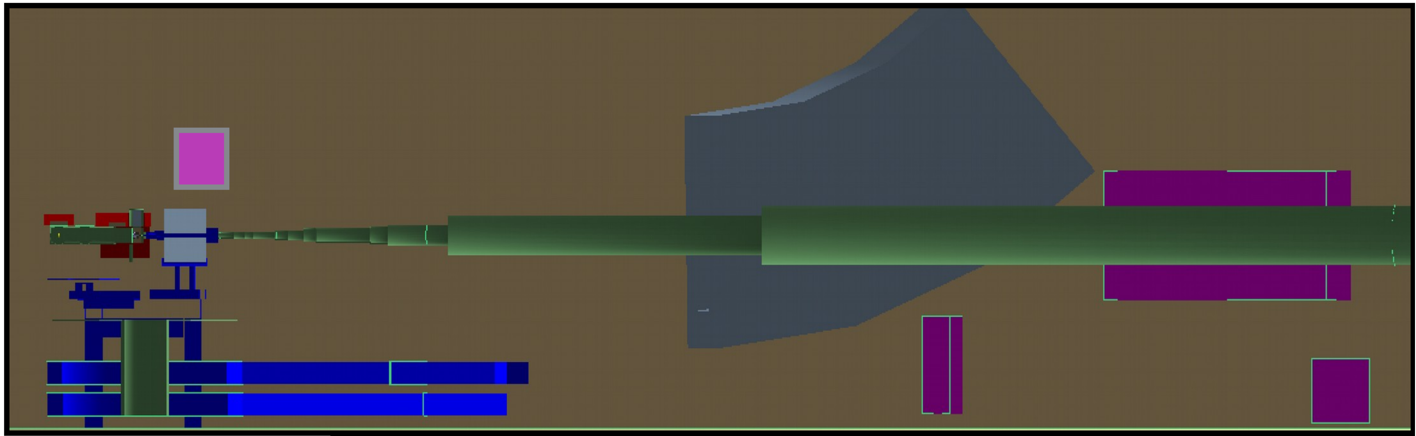
Summary

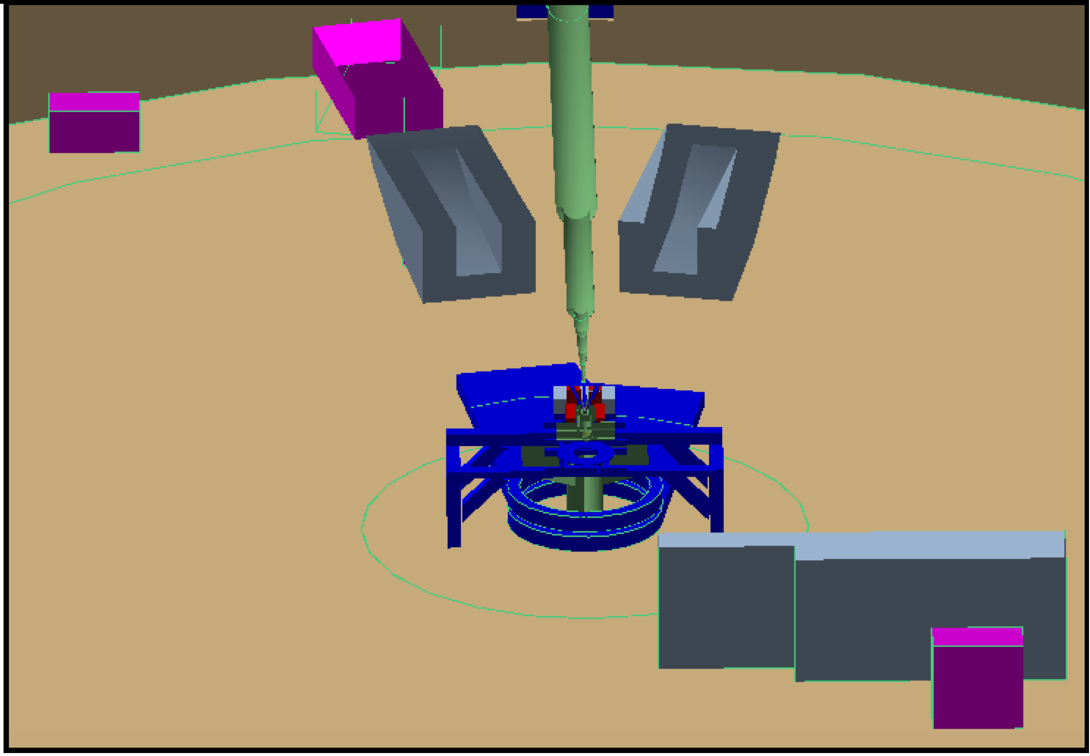
- Combination of large aperture collimator and septum fringe created many neutrons sources in the hall during PREX-I
- Isolating the main neutron source and shielding adequately is the optimum solution to minimizing the neutron radiation
  - Self-shielding collimators, concrete and HDPE
  - MOLLER design already successful at reaching the radiation goal using this strategy
- G4 simulations have shown collimation and shielding strategy reduces the expected radiation load in PREX-II to the level of previous successful experiments such as HAPPEX-2 or PVDIS in the most sensitive region of the hall

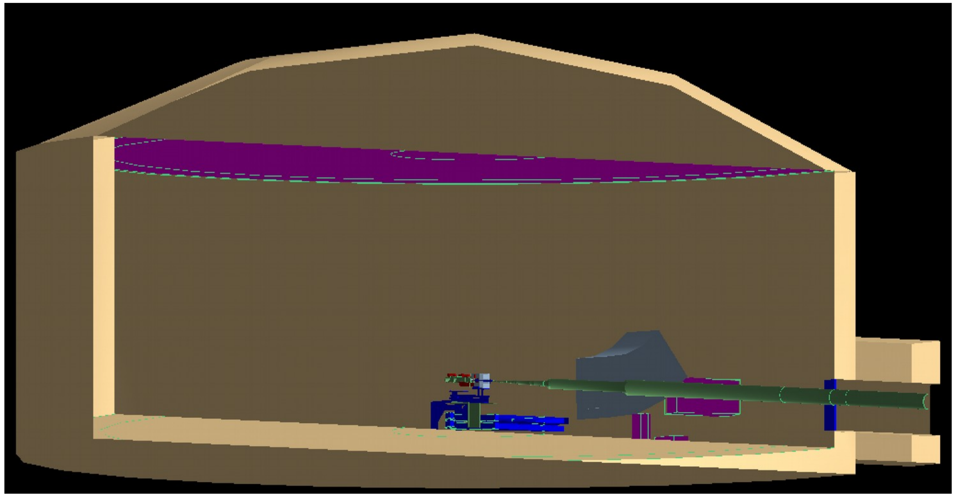
Supplementary

Simulation Geometry

- Target
- Detailed collimator
- Detailed beam-line (but not support or flanges)
- septum yoke
- HRS dipole
- detailed pivot support structure
- HDPE shielding
- concrete walls, floor, dump tunnel and vault

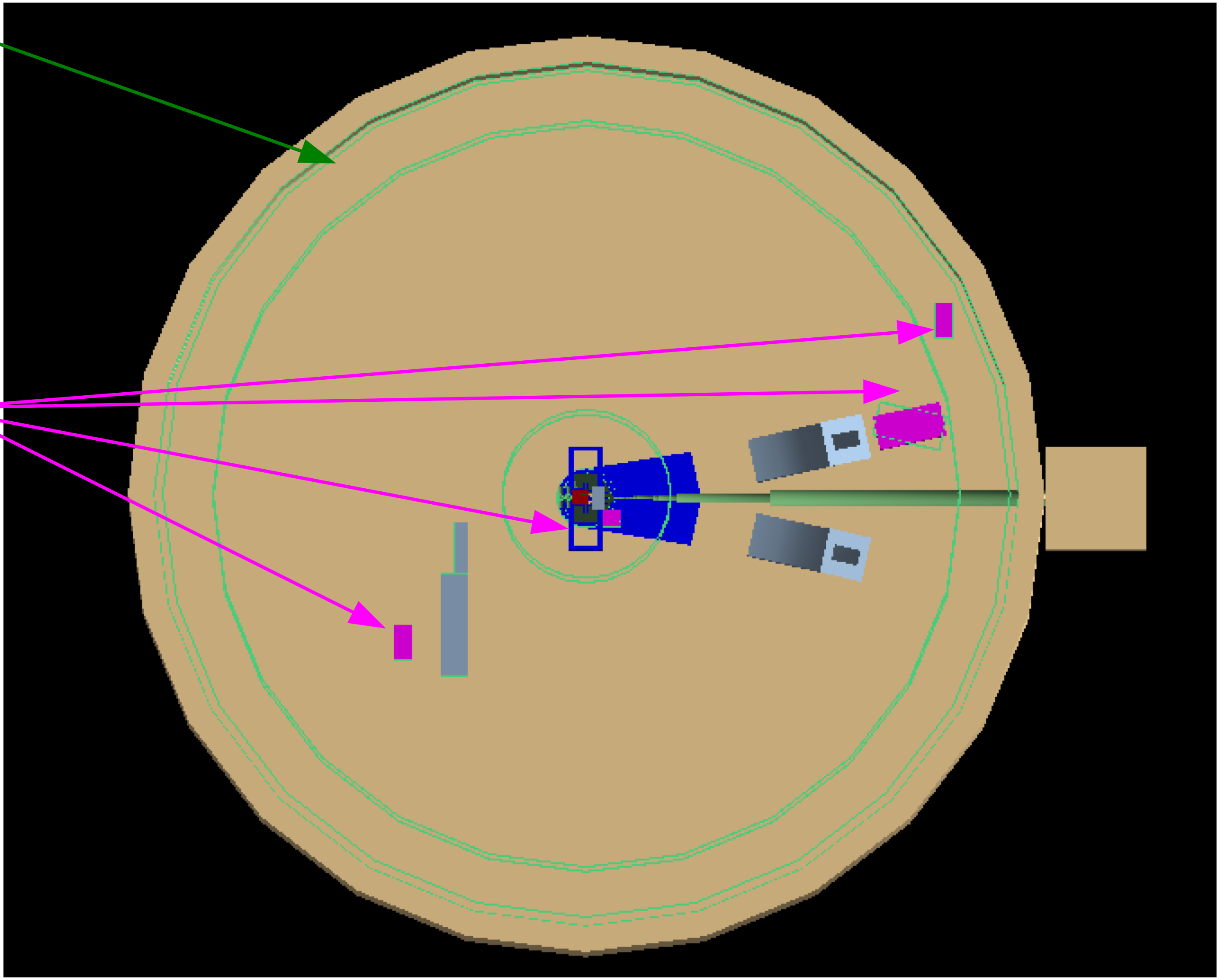






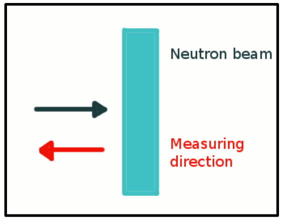
Simulation Geometry

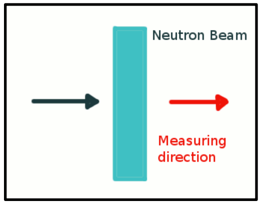
Cylindrical detector at the edge of the hall enclosure measures radiation for he hall



Test volumes to measure flux and dose

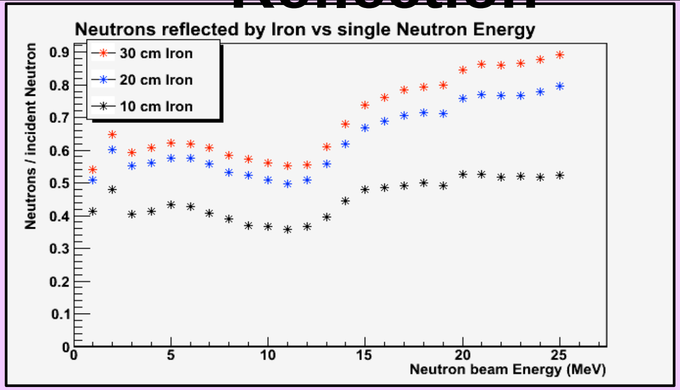
Neutrons Characteristics





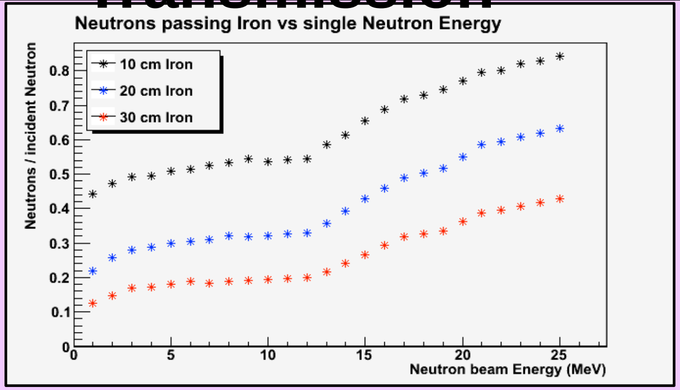
Reflection

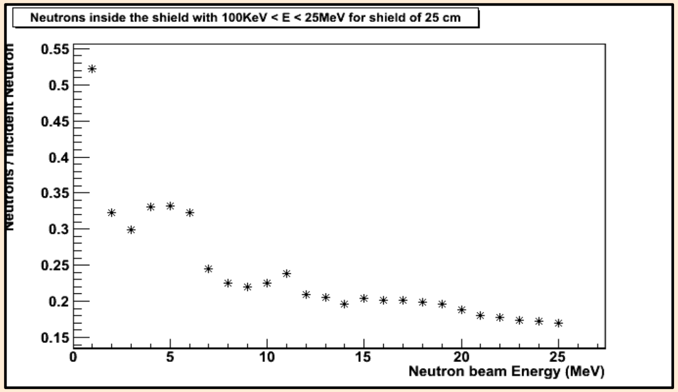
Transmission



Iron

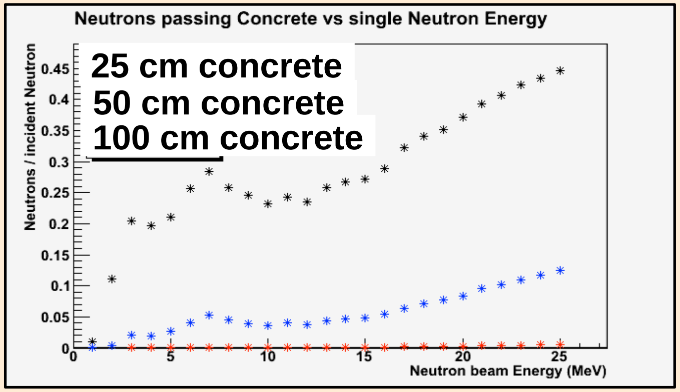
high reflection, not efficient at stopping

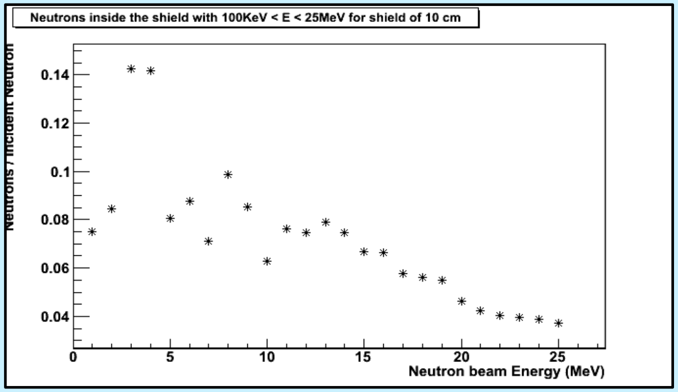




Concrete

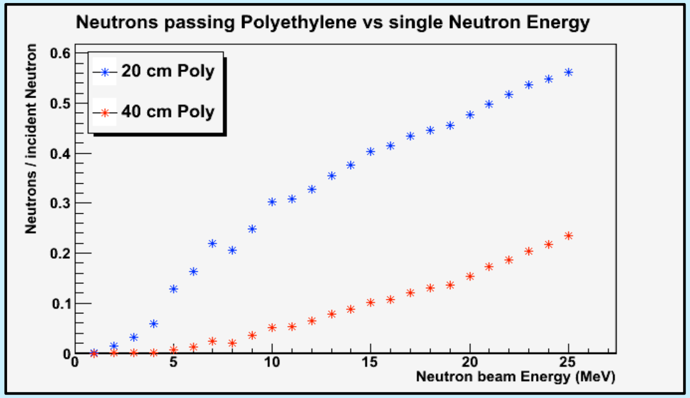
30% reflection, 0.5m to block



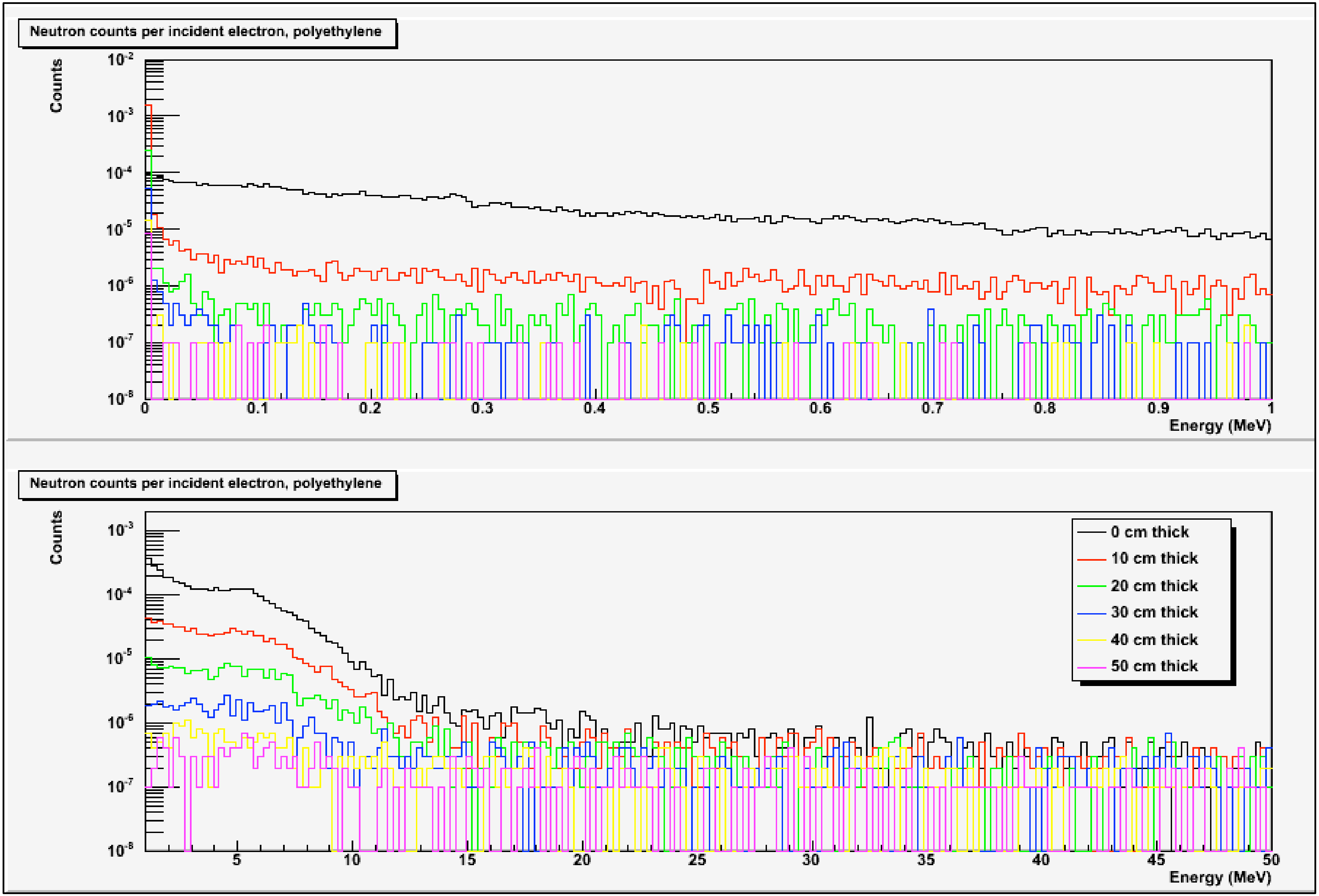


HD Polyethylene

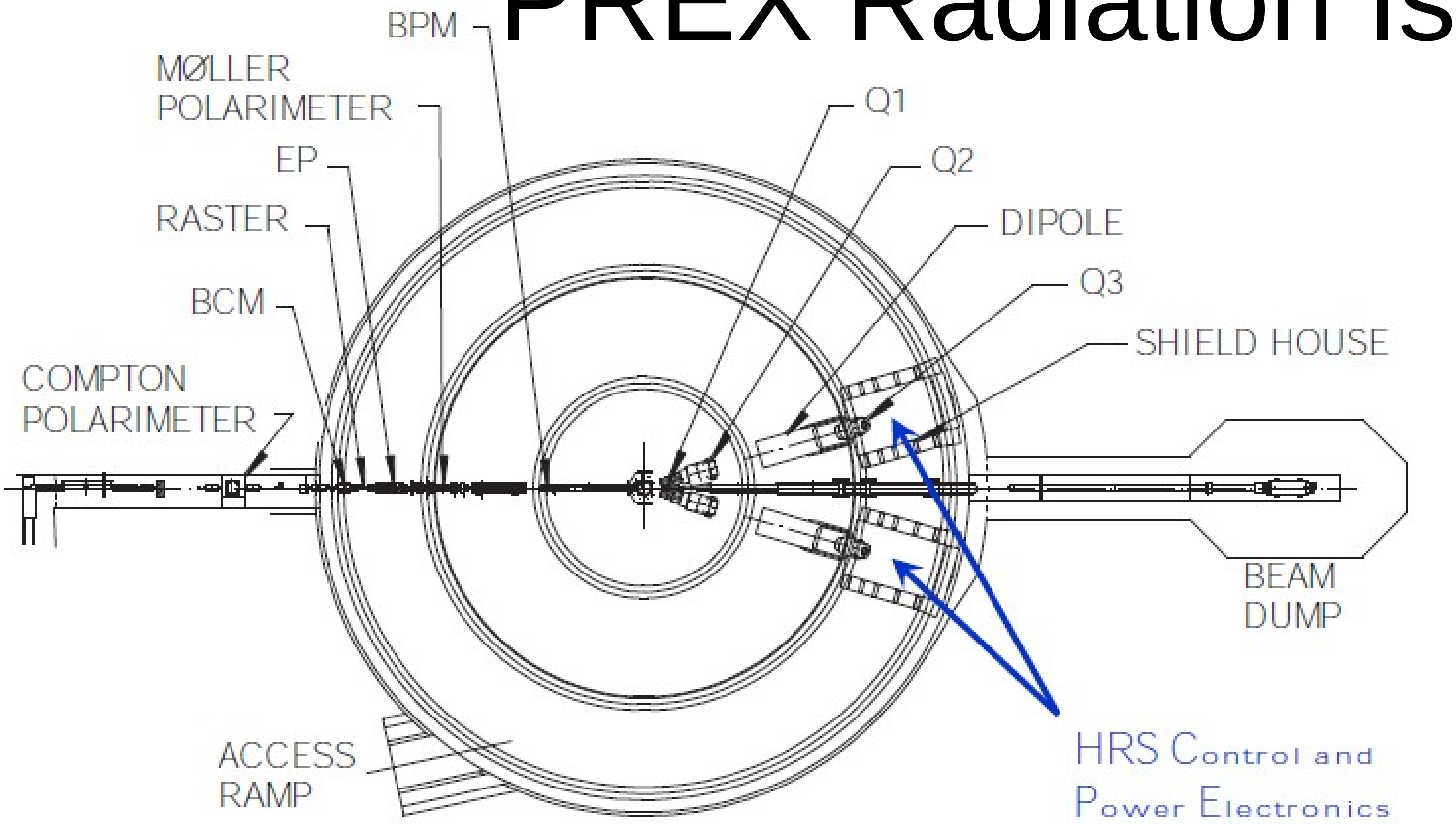
low reflection, 30cm blocks well



Neutron Stopping Power of HDPE

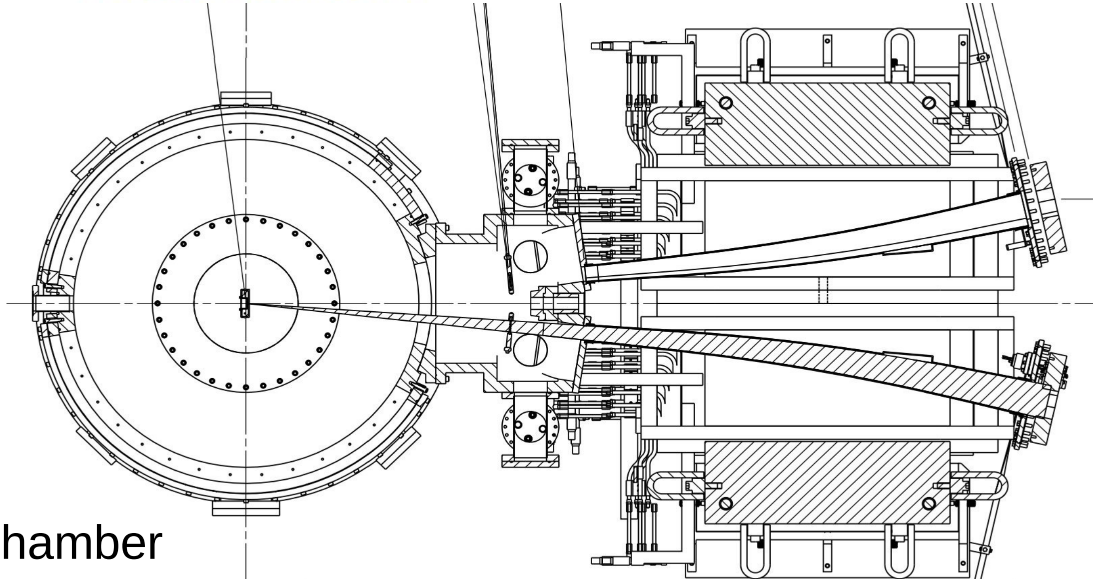


PREX Radiation Issues



HRS Control and Power Electronics

Septum area



Target Chamber