Jet Propulsion Laboratory
California Institute of Technology

A few results from radiation transport tool comparison study at JPL

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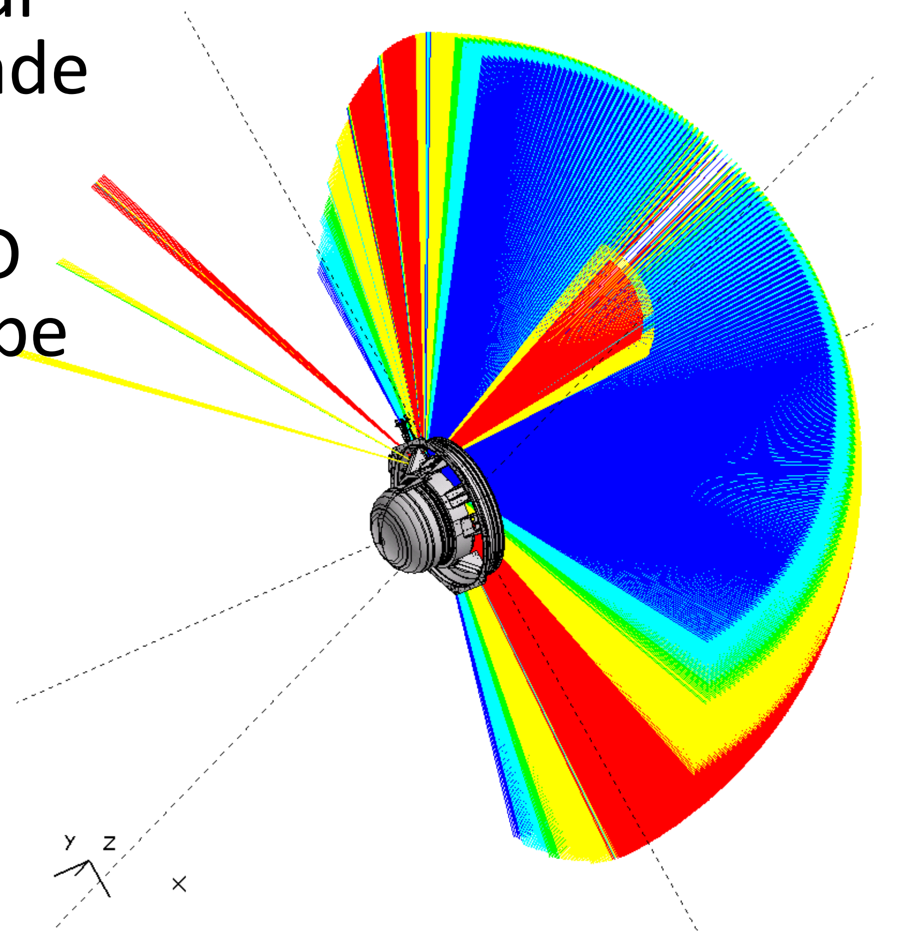
Topics

- Survey of radiation shielding tools
  - Introduction of widely used radiation shielding tools
  - Primary applications of radiation transport tools
- NOVICE vs. FASTRAD for TID
- NOVICE vs. MCNPX for Dose-Depth Curve
- Geant4 vs. MCNPX for Pulse-height Simulation in a Thin Silicon Layer

Ray Tracing Codes

- Ray tracing codes are useful to perform system level trade studies fast
- Ray-tracing codes with CAD interface capability would be very useful
- Tools available:
  - FASTRAD: http://trad.fr/
  - MEVDP: http://www-rsicc.ornl.gov/
  - “SIGMA” option in Novice: tj@empc.com



Transport Codes – Species

- Transport codes model actual particle interactions in the material (Ray tracing codes do not)
- It is important to model all particle species when performing transport analyses
  - Electrons
  - Photons
  - Protons
  - Neutrons
  - Heavy Ions
- Each transport code considers only a specific set of particles

Radiation transport analyses will be required to cover a wide range of particle species

Commonly Available Radiation Transport Codes

	Electron	Photon	Proton	Neutron	Heavy Ion
CREME96 creme96.nrl.navy.mil			O		O
TRIM www.srim.org			O		O
ITS3.0 www-rsicc.ornl.gov	O	O			
NOVICE tj@empc.com	O	O	O		O
MCNP(X) mcnpx.lanl.gov	O	O	O	O	O
Geant4 geant4.web.cern.ch/geant4/	O	O	O	O	O

Other radiation transport codes are available: EGS4, CEPXS, HZETRN, PHITS, PENELOPE, FLUKA, MARS, etc.

Transport Codes – Applications

- Transport codes are needed to consider the following
  - Total ionizing dose
  - Displacement damage dose
  - Single event effects
  - Internal charging
  - Secondary particle environment behind shield
- Transport codes can be used for particle detector simulation

Radiation transport analyses are used to cover a wide range of radiation effects

Features of Common Transport Codes

Code	Primary Application	Comments
CREME96	Heavy Ion LET Spectra	Limited to spherical shell aluminum shielding
TRIM	Proton or heavy ion beam simulation	1-dimensional Only Coulomb interaction
ITS3.0 (TIGER)	Electron or photon beam simulation for dose and charging rate profiles	Excellent electron/photon physics Extensively benchmarked
NOVICE	Spacecraft level shielding analysis	“Adjoint” (fast for space environment application) No secondary neutrons Not accurate for secondary electrons
MCNP(X)	Full 3-D detector/sensor simulation Transients calculation	Good physics and extensive development history Slow for space application
Geant4	Full 3-D detector/sensor simulation Transients calculation	Good physics Many Geant4-based “tools” are available Slow for space application

Comments are based on current JPL experience

Michael Cherng

FASTRAD VS. NOVICE

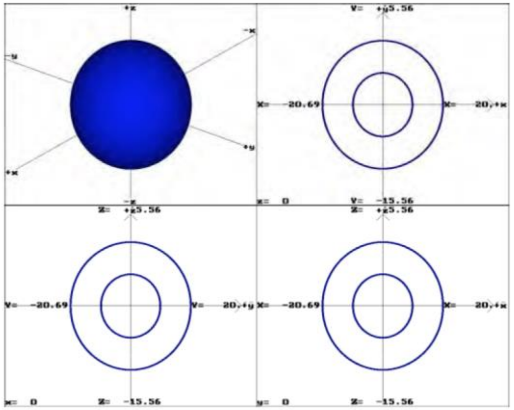
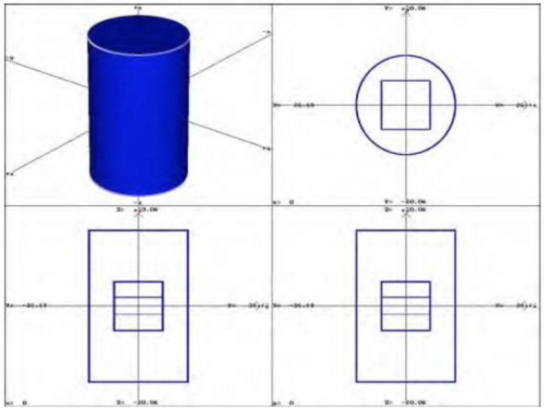


Figure 1. A Spherical Shell in a Spherical shell Container

Table 1. Dose Comparison for a Configuration of Spherical Shell in Spherical Shell Container

3D Mass Model	**Computer Code**	**Ionizing Dose** (krad, Si) [RDF = 1]			
Simple 3D Geometry (A spherical shell in a spherical shell container)		Electron	Photon	Proton	**Total**
• Inner Shell (**Aluminum**, 2.5 mm) • Outer Shell (**Aluminum**, 2.5 mm)	FASTRAD	277.80	2.03	8.91	288.7
	NOVICE	273.0	2.01	8.90	283.9
• Inner Shell (**Tantalum**, 2.5 mm) • Outer Shell (**Aluminum**, 2.5 mm)	FASTRAD	87.03	3.49	0.99	91.5
	NOVICE	41.90	6.86	2.04	50.8
• Inner Shell (**Tantalum**, 2.5 mm) • Outer Shell (**Tantalum**, 2.5 mm)	FASTRAD	36.39	3.93	0.41	40.7
	NOVICE	8.45	7.27	0.96	16.7



A Box Containing Two Boards in a Cylindrical Container

Table 2. Dose Comparison for a Configuration of Box in Cylindrical Container

3D Mass Model	**Computer Code**	**Ionizing Dose** (krad, Si) [RDF = 1]			
Simple 3D Geometry (A Box with 2 boards in a Cylindrical Container)		Electron	Photon	Proton	**Total**
• Box Wall (**Aluminum**, 2.5 mm) • 2 PCB (**Aluminum**, 1.5 mm) • Container Wall (**Aluminum**, 2.5 mm)	FASTRAD	200.94	2.45	4.63	208.0
	NOVICE	210.0	2.50	4.72	217.2
• Box Wall (**Tantalum**, 2.5 mm) • 2 PCB (**Aluminum**, 1.5 mm) • Container Wall (**Aluminum**, 2.5 mm)	FASTRAD	60.08	3.74	0.66	64.5
	NOVICE	33.8	6.74	1.33	41.9
• Box Wall (**Tantalum**, 2.5 mm) • 2 PCB (**Tantalum**, 1.5 mm) • Container Wall (**Tantalum**, 2.5 mm)	FASTRAD	16.02	3.80	0.23	20.1
	NOVICE	3.19	6.25	0.51	10.0

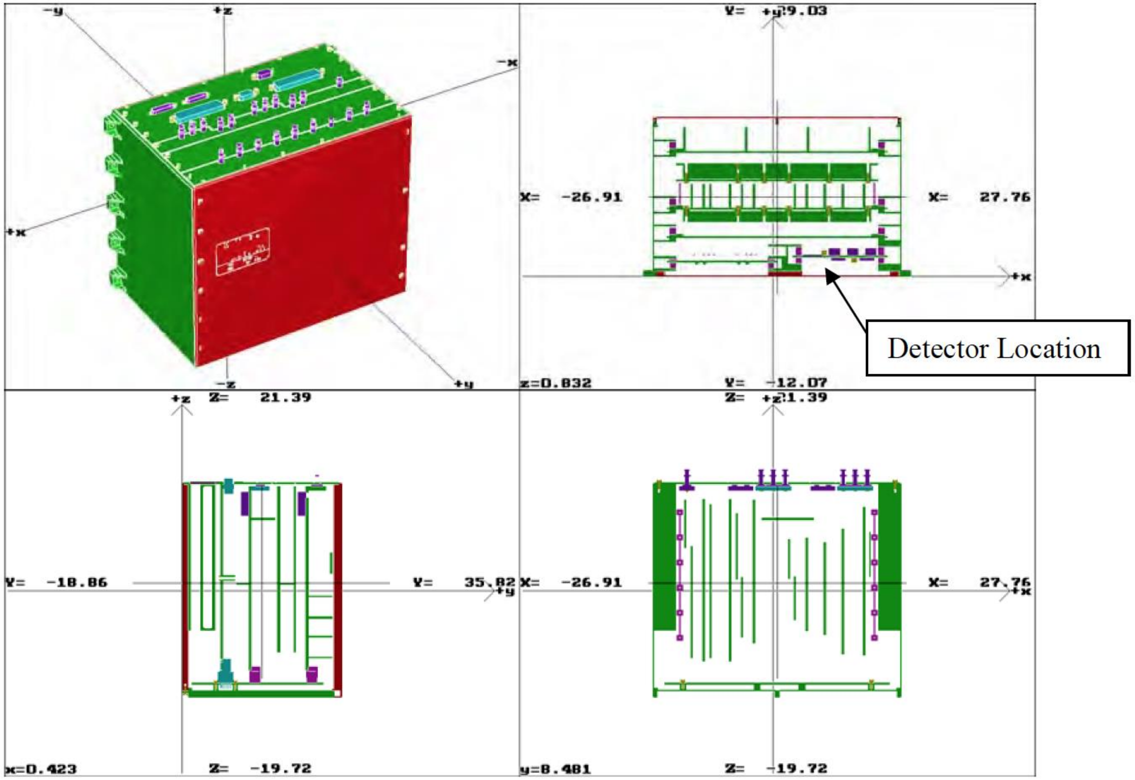
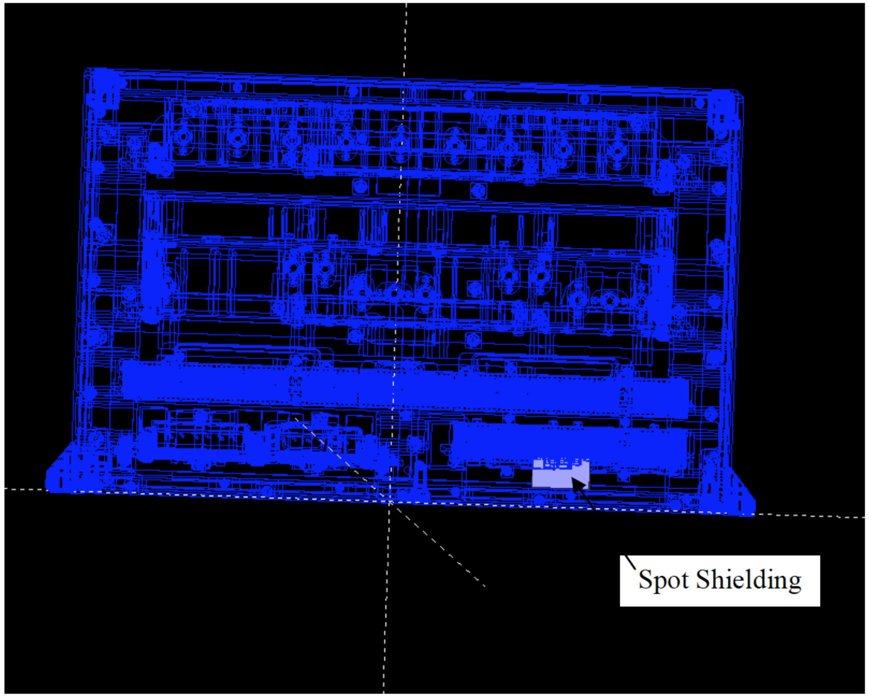


Table 3. Dose Comparison for an Electronics Box CAD Model

3D Mass Model	**Computer Code**	**Ionizing Dose** (krad, Si) [RDF = 1]			
Electronics Box CAD Model		Electron	Photon	Proton	**Total**
• Entire Electronics Box (**Aluminum**)	FASTRAD	365.6	2.69	13.4	381.7
	NOVICE	356	2.93	13.4	372.3
• Entire Electronics Box (**Tantalum**)	FASTRAD	60.02	2.48	1.10	63.6
	NOVICE	54.8	4.29	3.01	62.1



(A picture generated by FASTRAD)
Figure 4. Spot Shielding in Electronics Box CAD Model

Table 4. Dose Comparison for Spot Shielding Inserted in Electronics Box CAD Model

3D Mass Model	**Computer Code**	**Ionizing Dose** (krad, Si) [RDF = 1]			
Electronics Box with a manually inserted spot shielding		Electron	Photon	Proton	**Total**
• Entire Electronics Box (**Aluminum**) • Spot Shielding (**Aluminum**, 4.8 mm thick box wall)	FASTRAD	96.88	3.26	1.78	101.9
	NOVICE	111.0	3.49	1.8	116.3
• Entire Electronics Box (**Aluminum**) • Spot Shielding (**Tungsten**, 4.8 mm thick box wall)	FASTRAD	8.10	3.54	0.15	11.8
	NOVICE	1.96	4.41	0.30	5.67

Summary for NOVICE vs. FASTRAD

- Based on the above calculations and comparisons, FASTRAD is considered a conservative radiation dose estimation tool. Its built-in ray tracing function can generate dose estimate in a very short period of time. Its fast calculation capability significantly outpaces the more sophisticated NOVICE code when complex CAD model was involved. Its real-time visualization capability provides radiation engineers the tool to easily select parts location and perform optimum shielding design and analysis by moving components or adding shielding in the existing CAD file.

- After the “preliminary” radiation dose estimates are done, NOVICE code could be used to calculate the more precise radiation dose values when the hardware design is “finalized”.

Michael Cherng, Insoo Jun, and Tom Jordan

NOVICE VS. MCNPX

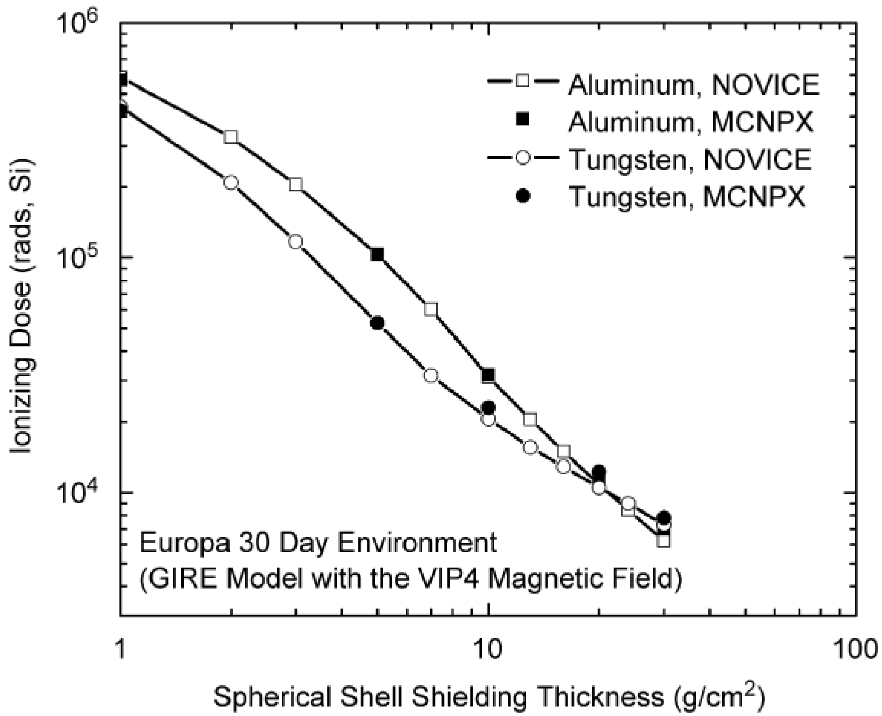


Fig. 2. Ionizing doses calculated for a detector located at the center of spherical shell shielding of aluminum and tungsten in a 30-day Europa mission with NOVICE and MCNPX, respectively. (100 rad = 1 Gray).

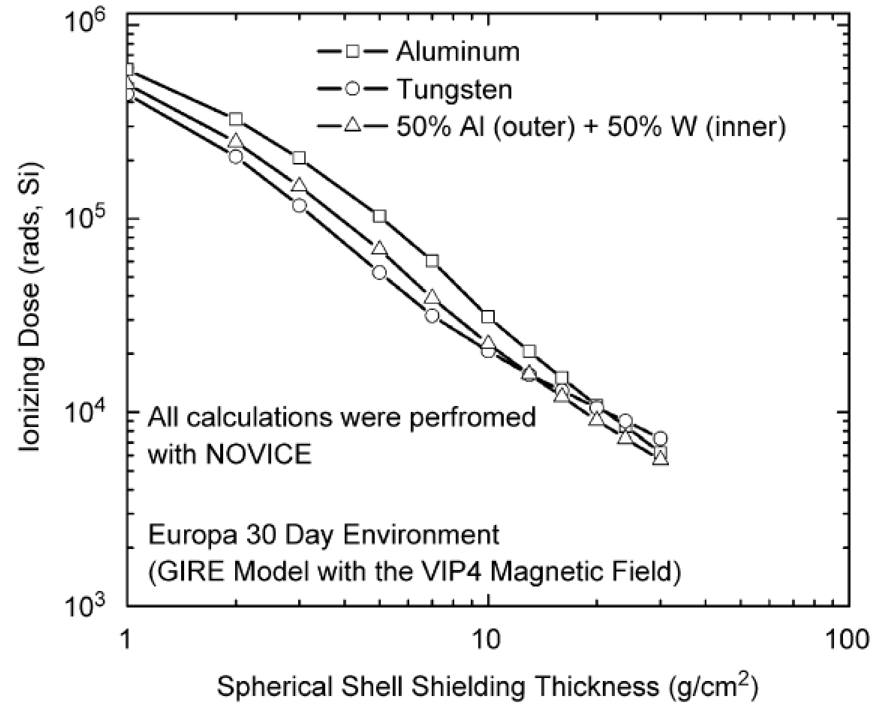


Fig. 3. Ionizing doses calculated with NOVICE for a detector located at the center of the spherical shell shielding of aluminum, tungsten, and 50% areal mass aluminum (outer layer)/50% areal mass tungsten (inner layer) combination in a 30-day Europa mission. (100 rad = 1 Gray).

Cherng et al., NIMA 2007

Bongim Jun, Maria de Soria Santacruz Pich, Insoo Jun, Wousik, Kim, Ed Riedel, and Ryan Park

MCNPX VS. GEANT4

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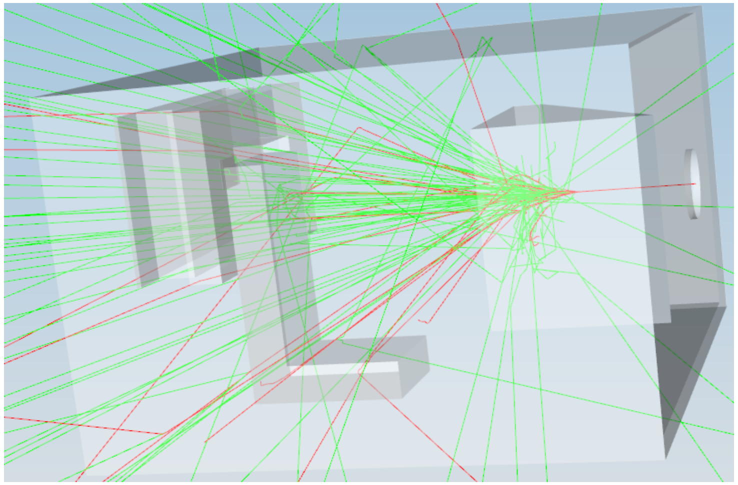
Tests Overview

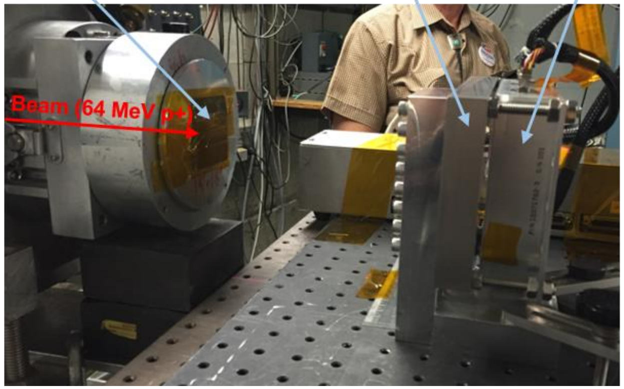
- Electron and proton beam tests of the CMOSIS CMV20000 detector were performed at BNL and UC Davis, respectively
- Electron beam tests were performed at Brookhaven National Laboratory on April 2016:
  - Tests in vacuum with 45 MeV electron beam operated at 1.5 Hz
  - The exposure time was 300 ms at 3 frame per second (fps)
  - Total of 33 runs in different configurations: Two shielding materials (Al and W-Cu) with different thicknesses, four beam charges, two orientations
- Proton beam tests happened at the UC Davis Crocker Nuclear Laboratory on June 2016:
  - Tests in air with 64 MeV proton beam
  - The exposure time was 50 ms at 1 fps
  - Total of 29 runs in different configurations: Two shielding materials (Al and W-Cu) of different thicknesses, three flux levels, two orientations

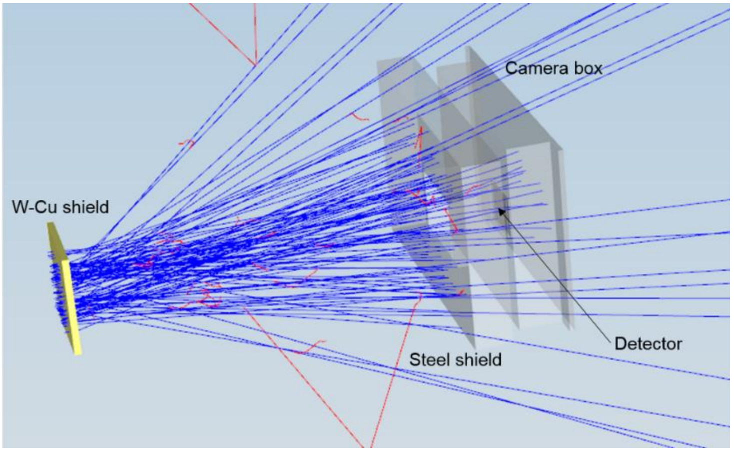
Firefly Beam-Line Tests of Detector

BNL Electron Beam-Line Tests and Simulations



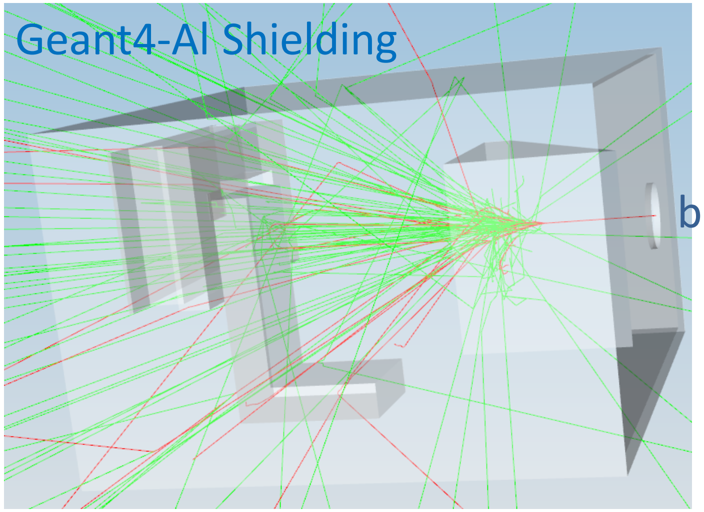
UC Davis Proton Beam-Line Tests and Simulations



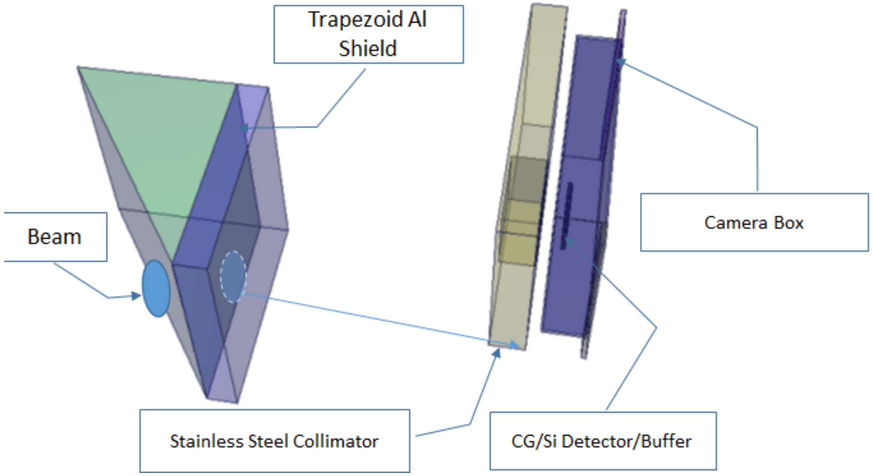


45 MeV Electron Beam Test Result

Test Setup Geometry



MCNP

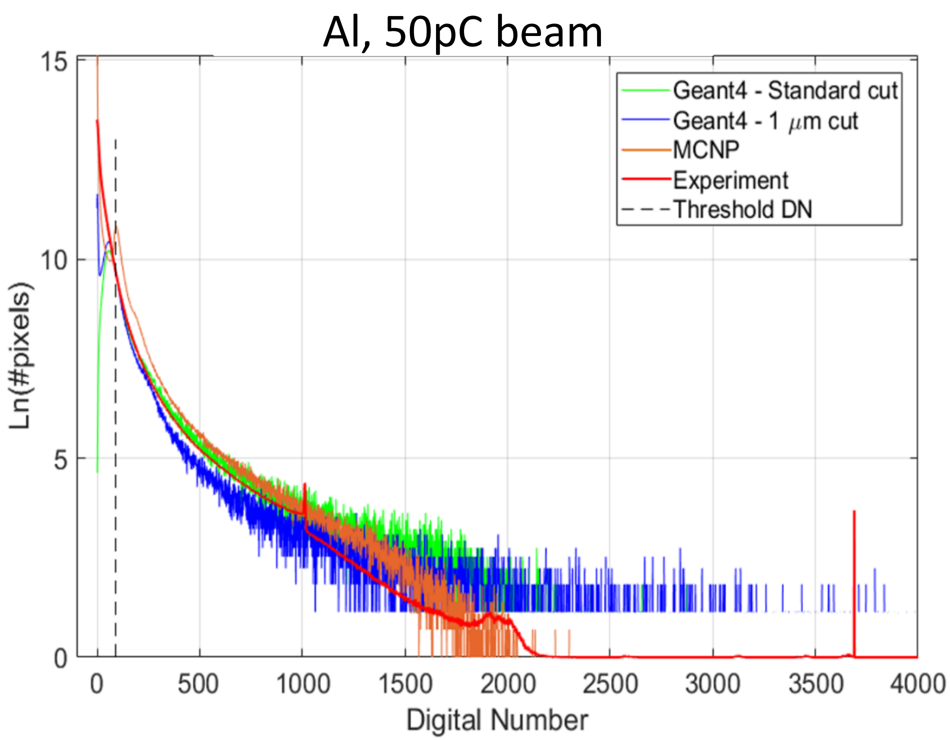


Beam Operation Parameters

Parameter	Al (run12)
Exposure	300 ms
fps	3
Shielding Material	Aluminum, 2.7 g/cm^3
Shielding Thickness	46.74 mm (trapezoid), 12.7 g/cm^2
Beam Energy	45 MeV
Beam Frequency	1.5 Hz
Beam Charge	50 pC
Orientation	Forward

45 MeV Electron Beam Test Result – Al [1/2]

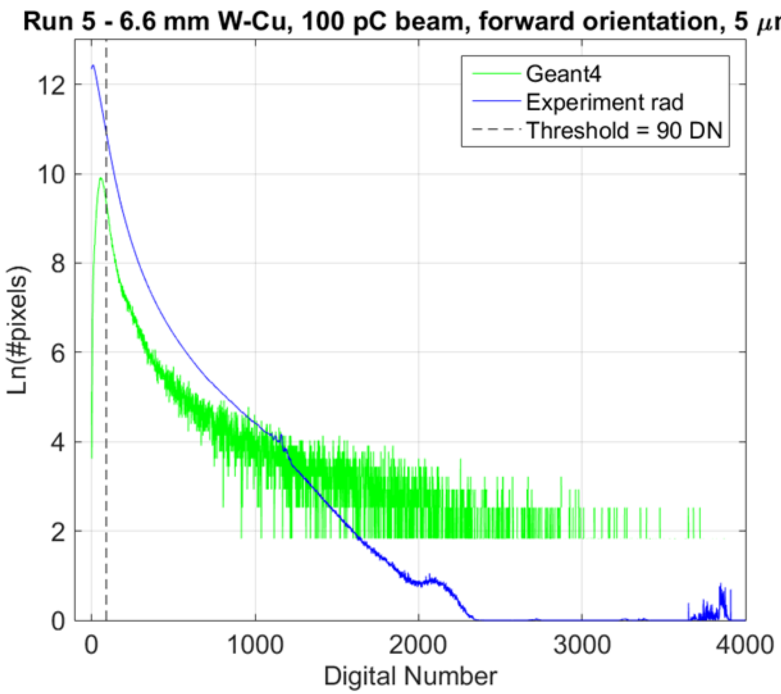
Experiment, Geant4 and MCNP Runs



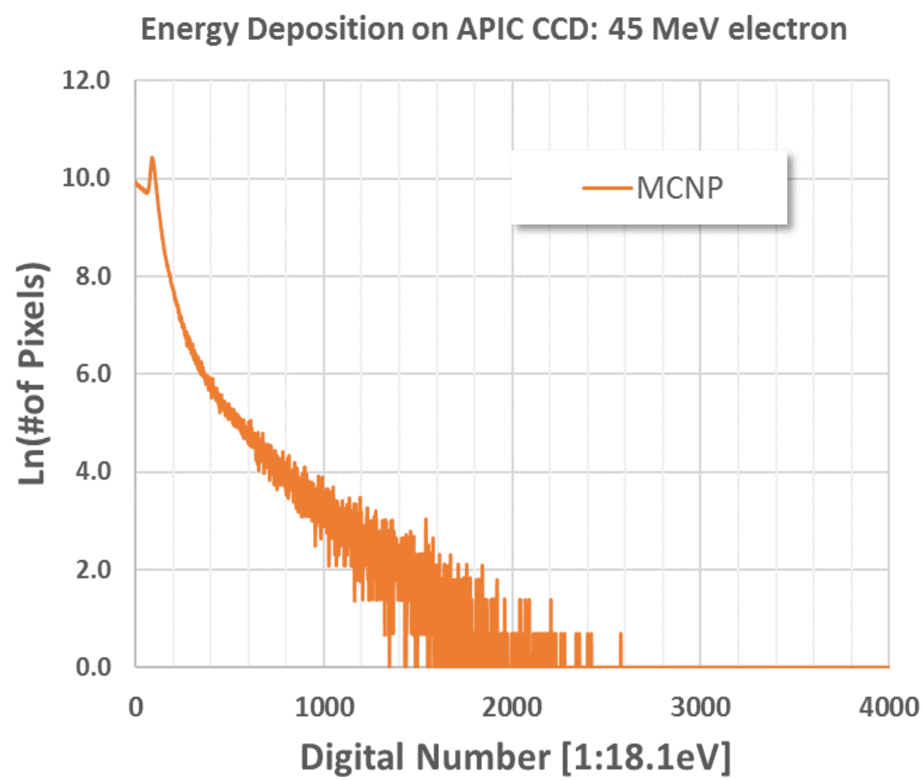
- The results from both Geant4 and MCNP show a good agreement with experiment result
- Peak locations (E_dep@max pixel counts) are slightly different between MCNPX and Geant4
- MCNP prediction is closer to experiment result as DN increases
  - The same number of particles reach the detector when we increase the thickness of the sensitive layer but more energy is deposited per particle, which translates in a flattening and displacement of the Geant4 curve to higher DN

45 MeV Electron Beam Test Result – WCu [2/2]

Experiment and Geant4



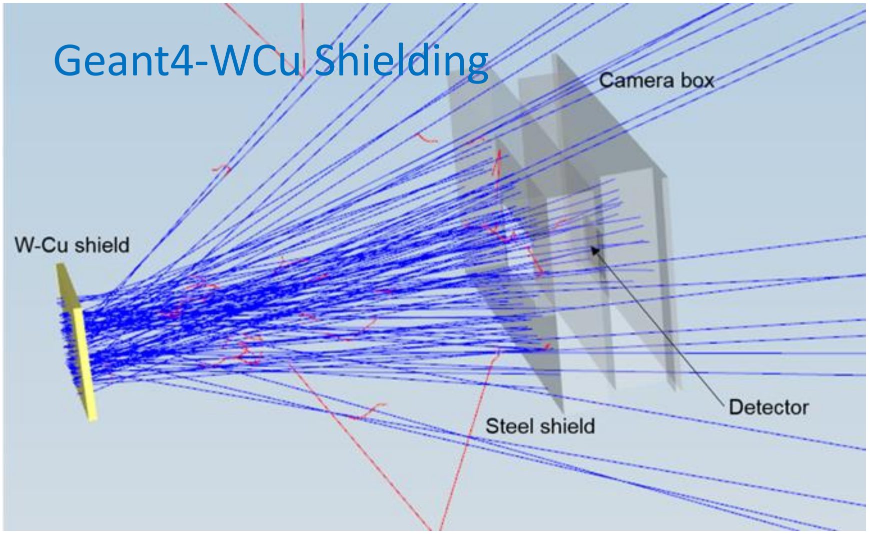
MCNP Runs

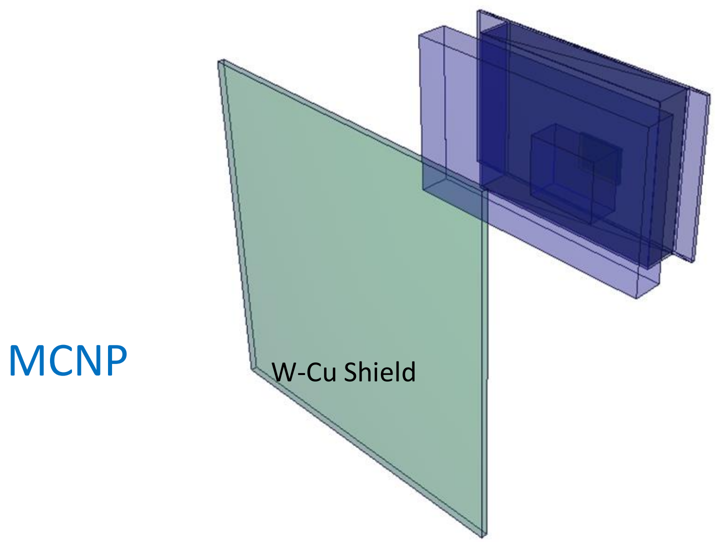


- Peak locations (E_dep@max pixel counts) from Geant4 and MCNP are slightly different
- MCNP prediction is closer to experiment result as DN increases
- Simulation results show a fine agreement but difference is higher with W-Cu shielding

64 MeV Proton Beam Test Result [1/2]

Test Setup Geometry



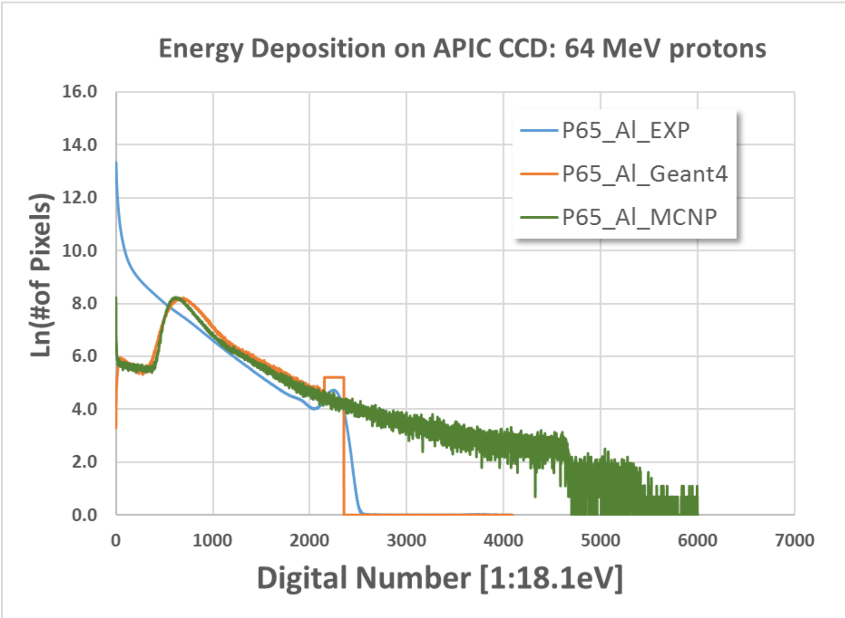


Beam Operation Parameters

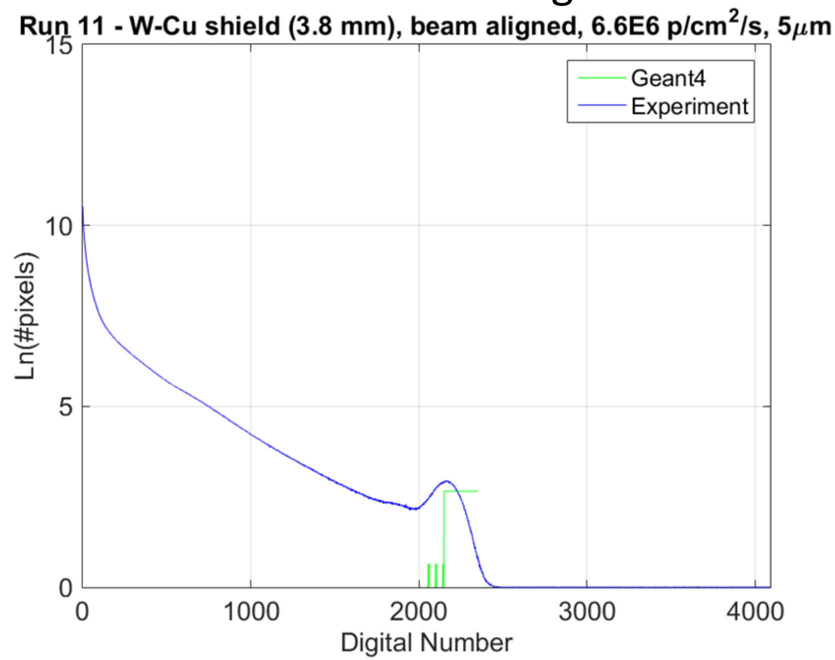
Parameter	Al (run12)
Exposure	300 ms
fps	3
Shielding Material	Aluminum, 2.7 g/cm^3
Shielding Thickness	46.74 mm (trapezoid), 12.7 g/cm^2
Beam Energy	45 MeV
Beam Frequency	1.5 Hz
Beam Charge	50 pC
Orientation	Forward

64 MeV Proton Beam Test Result [2/2]

Al Shielding



WCu Shielding



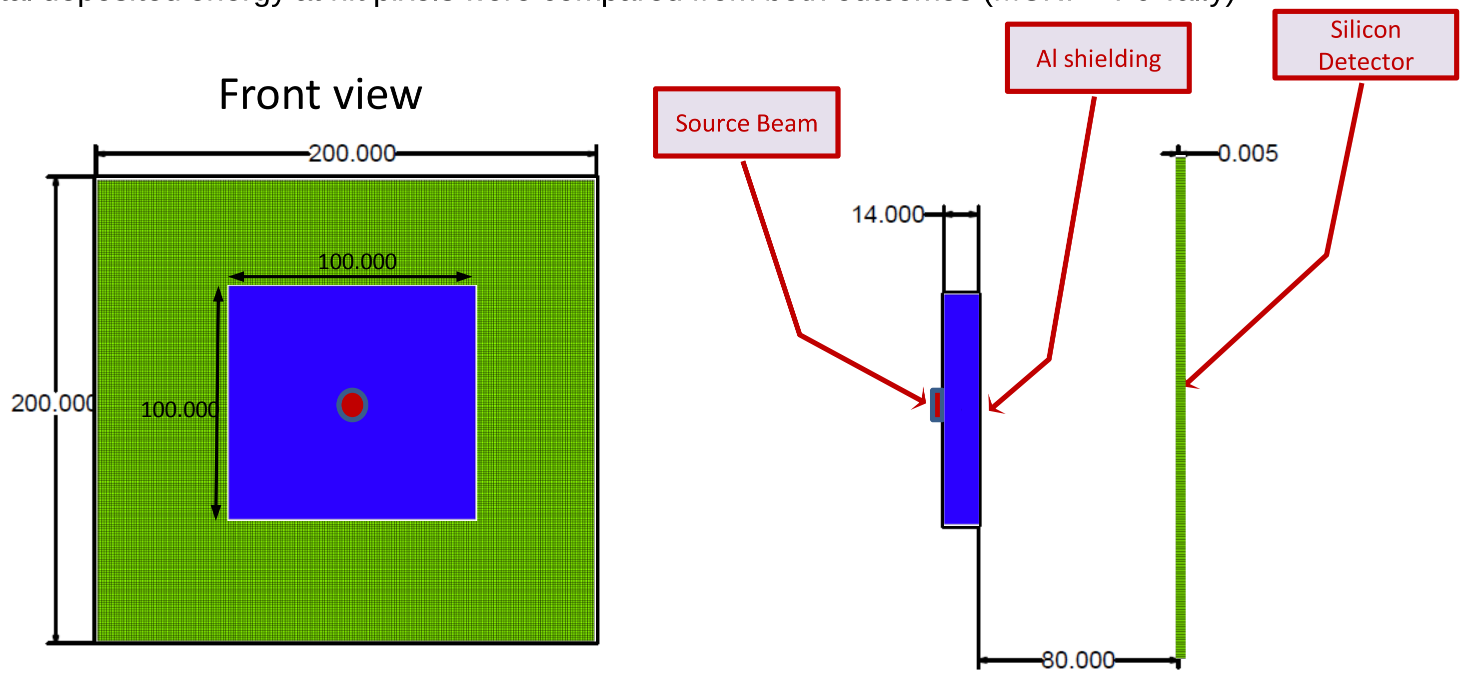
- Geant4 and MCNP simulations show a fair agreement in intermediate energy range with test result performed with Al shielding
- More analysis is on-going with MCNP to understand the abnormal characteristics shown on W-Cu shielding result from Geant4

Bongim Jun and Insoo Jun

MORE MONTE CARLO SIMULATION WITH SIMPLE GEOMETRY

Starting with the Simplest Geometry (Version 0)

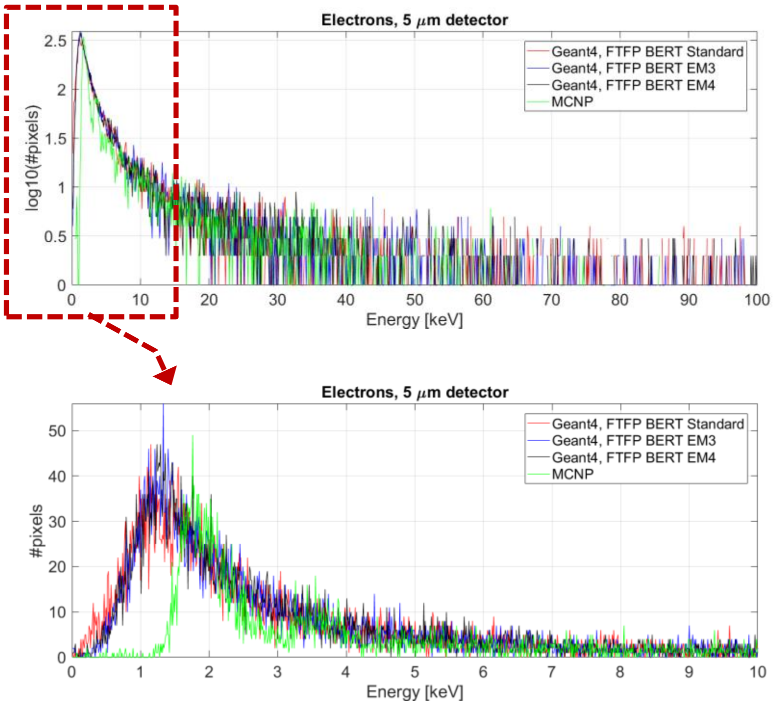
- For easier and better understanding of results from two simulation tools, following simple geometry was introduced to minimize variables
  - Geometry/Source Beam
    - Al Shielding/Si detector(active region only)
    - **Detector is 200x200 pixels (1mm x 1mm size)**
    - Source: Circular beam (r=0.5 cm) centered behind the shielding in vacuum
  - Electron Run: 45 MeV beam with 30000 source particles in vacuum
  - Proton Run: 64 MeV beam with150000 source particles in vacuum
  - Source particle quantities are optimized not to saturate the detector (~16% of pixels with deposited energy)
  - Total deposited energy at hit pixels were compared from both outcomes (MCNP +F6 Tally)



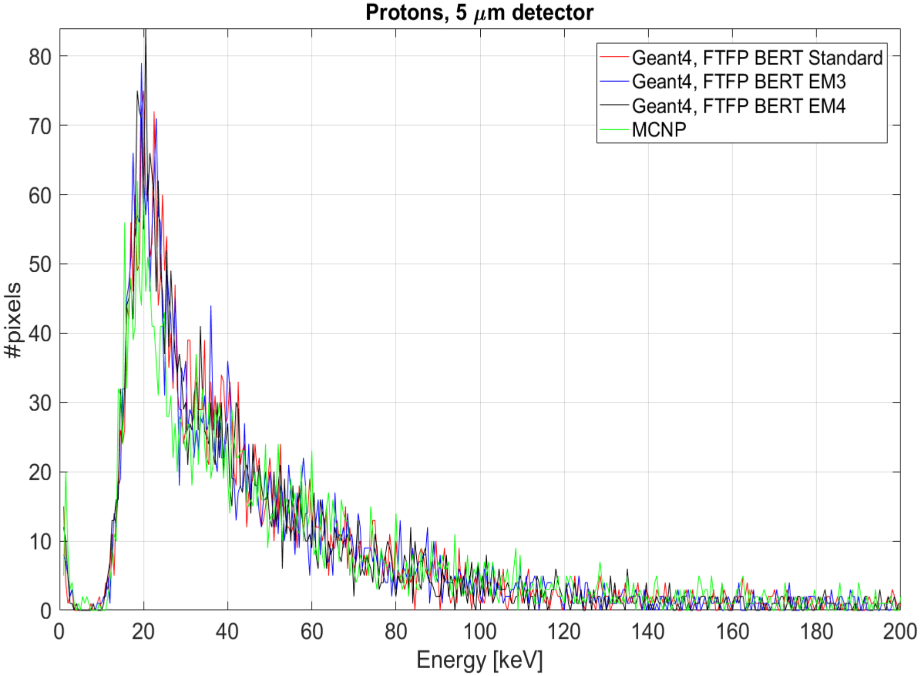
Unit: mm

Deposited Energy in Si Active Region

Electron Run Result



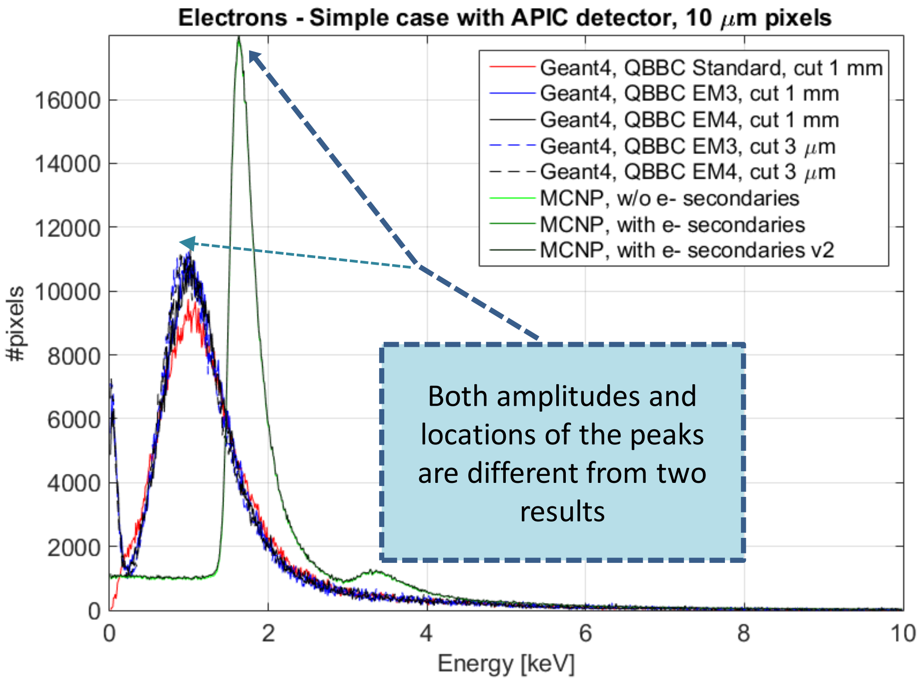
Proton Run Result

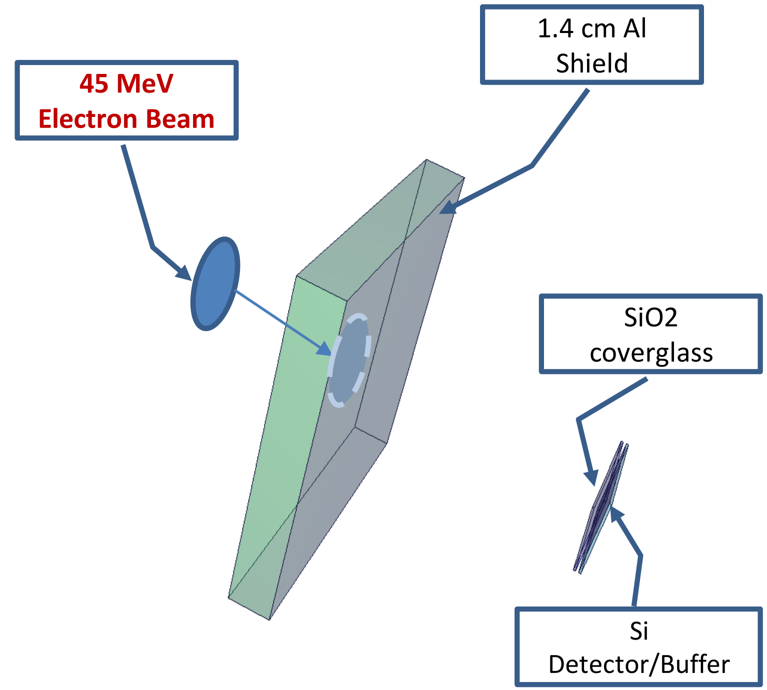


- Output: total energy deposition at Si Detector with all Geant4 physics options and MCNP (F6 tally)
- For electron simulation, results show a poor agreement at low energies (<5 keV) between Geant4 and MCNP
- Simulation results show a good agreement for 64MeV proton

Geometry and Beam Setup (Version 1)

- Circular Beam/Al Shield/Coverglass/Si-detector/Si-Buffer

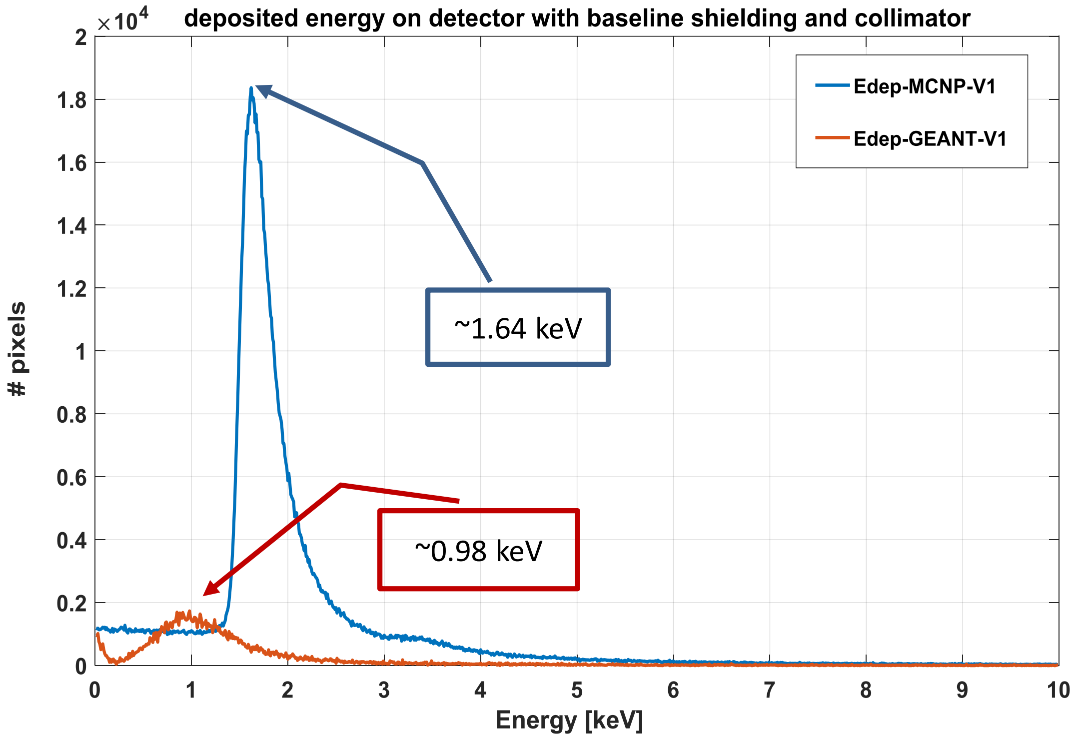


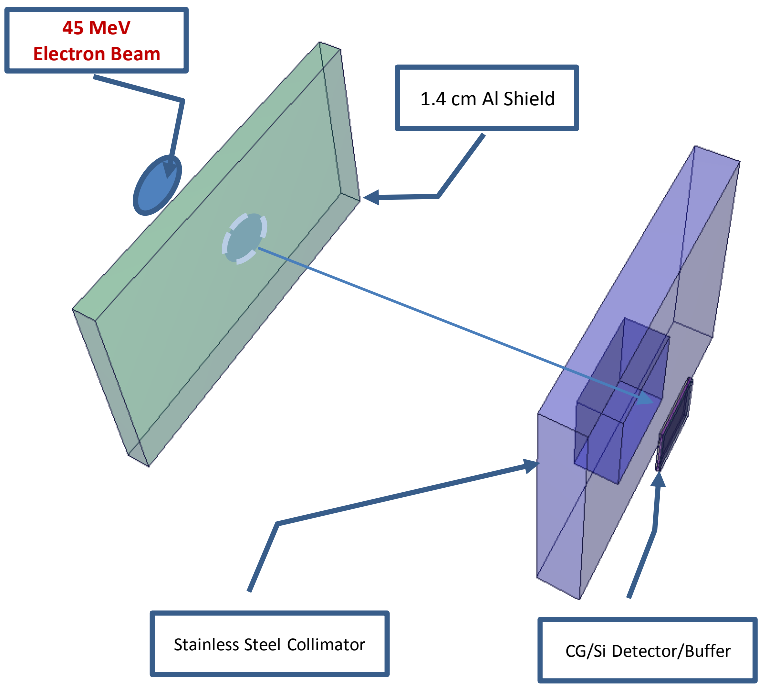


- Geant4:
  - QBBC Standard is not capable of reproducing the low energies
  - EM3 and EM4 seem to capture the secondaries (independently of the cut)
- MCNP runs with varying physics options (other than default) do not change the main feature of the result
- MCNP and G4 QBBC electron physics give very different results for all cuts

Geometry and Beam Setup (Version 2)

- Circular Beam/Al Shield/**Collimator**/**Coverglass**/Si-detector/**Si-Buffer**

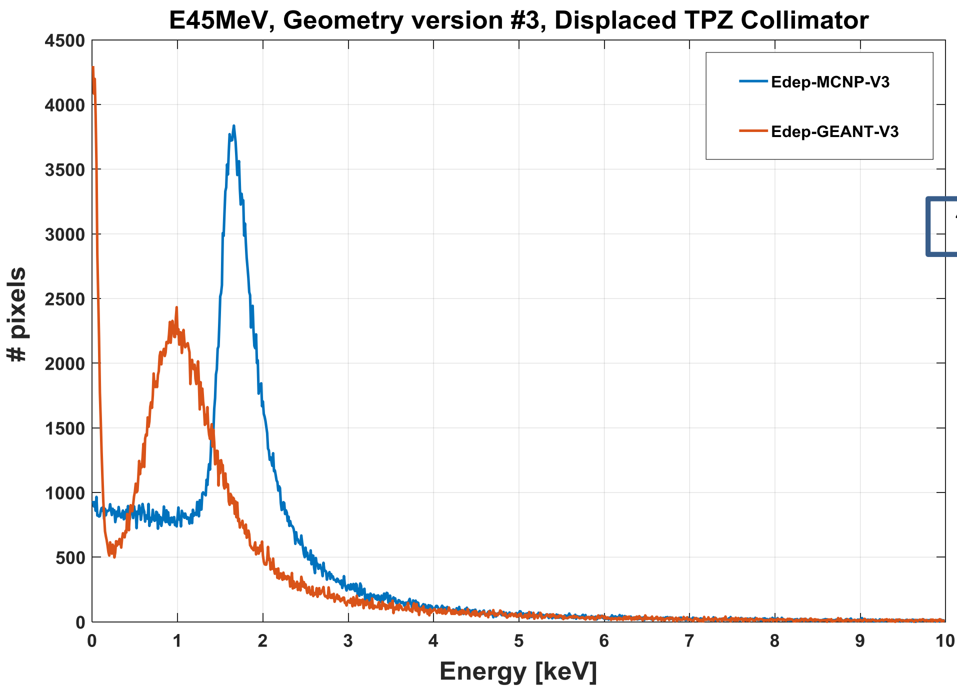


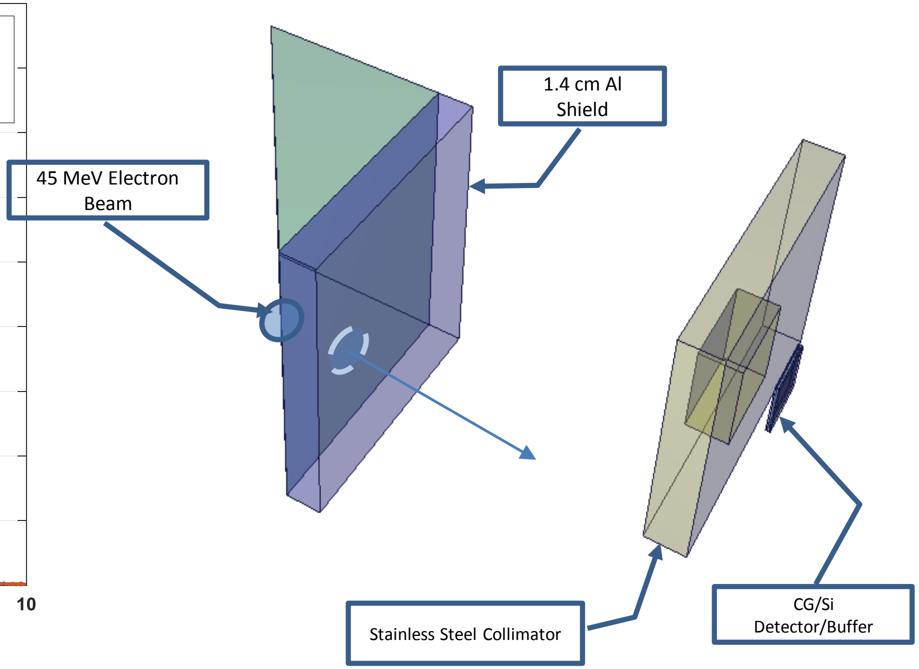


- Collimator is added into the geometry version 1
- Peak split remains unchanged

Geometry and Beam Setup (Version 3)

- Circular Beam/Al **Trapezoid Displaced Shielding** /**Collimator**/**Coverglass**/Si-detector/**Si-Buffer**





- Shield geometry is added into the geometry version 0
- Peak split remains unchanged with different shielding design
- Regardless of complexity in geometry, difference in peak energy from Geant4 and MCNP remain unchanged
- Better understanding of Geant4 and MCNP on particle transport physics is needed

Lessons-Learned from Beam Testing

- Testing is important to understand the detector behavior when irradiated and the capability of radiation transport tools

- Simulation of detector behavior also requires deep understanding of how the tool(s) treats radiation transport, especially when secondary particles are important (e.g., thick shield)

- Good knowledge of the detector’s geometrical/material makeup, driving electronics, potential sources of dark noises, and operation is essential to correctly interpret firefly test and simulation results

Summary

- Radiation transport codes are needed to:
  - Estimate doses and other radiation effects
  - Design radiation shield
  - Understand instrument's response to radiation
- Different codes should be used for different applications and for different radiation type
- Benchmark study (including beam testing) is recommended to validate simulation results for specific hardware application
  - This is especially true for science instrument simulations

THANK YOU!

QUESTIONS?