Novel Active Interrogation Techniques for the Detection of Special Nuclear Material

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Outline

- Motivation
- Background
- Monte Carlo Modeling
  - Model for organic scintillators
  - Pulse height distributions
  - Photonuclear physics
- Comparisons with Experimental Data
- Conclusions and Future Work

Motivation

Weapons of Mass Destruction are the Greatest Terrorism Threat to the World

"Today, the gravest danger in the war on terror, **the gravest danger facing America and the world, is outlaw regimes that seek and possess nuclear**, chemical, and biological **weapons**. These regimes could use such weapons **for blackmail, terror and mass murder**. They could also give those weapons to terrorist allies, who would use them without hesitation."

Motivation

A Multifaceted Solution is Required

- Intelligence Gathering
- International Cooperation
- Law Enforcement (local, state, federal)
- <u>New and Advanced Detection Technologies</u>

Motivation

Screening for HEU at Potential Points of Entry

Background

Research & Development Needs are Mission Driven

Fixed

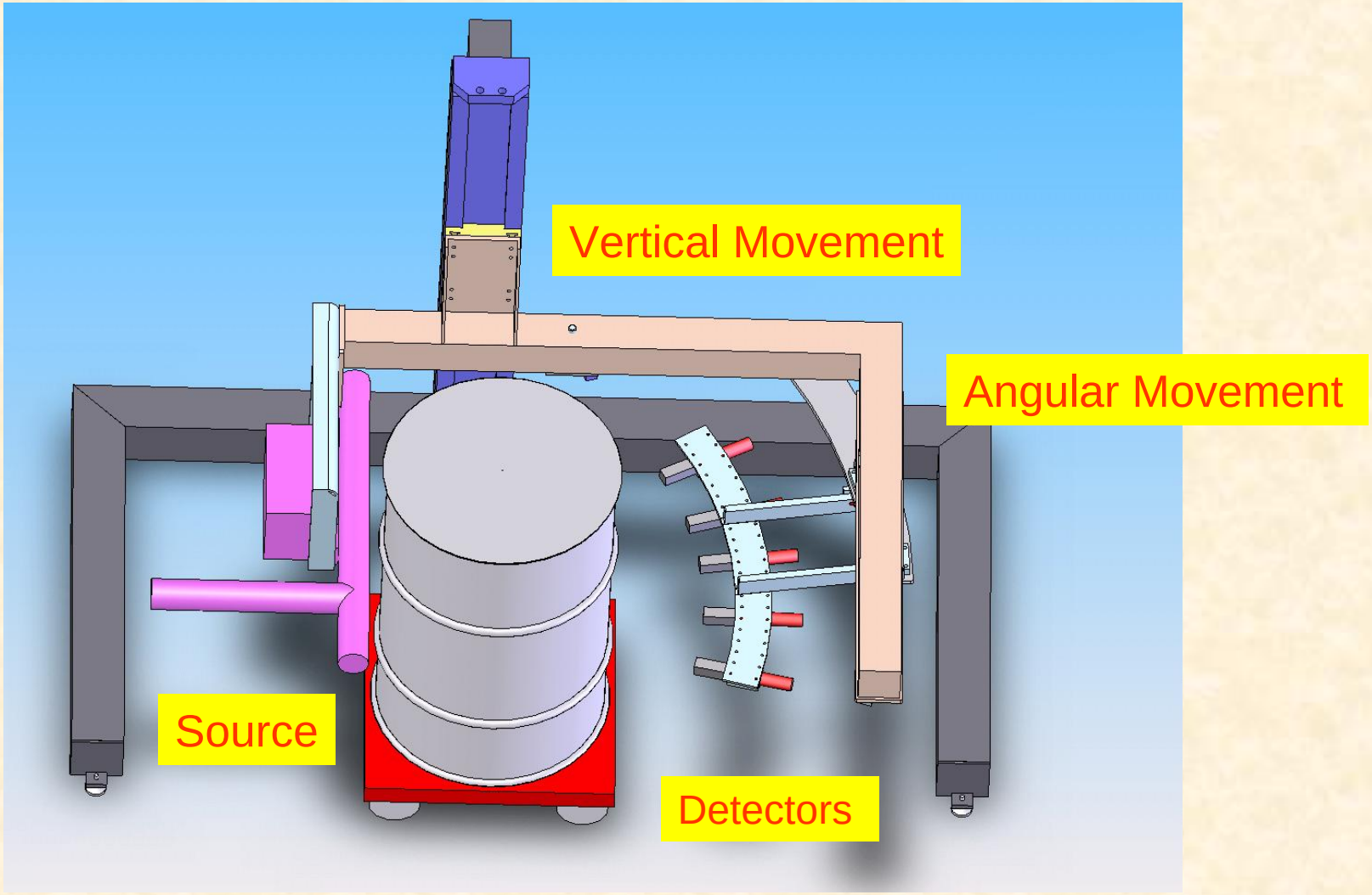
Portable

Monte Carlo Modeling

- Simulate the neutron and photon flux in nuclear and nonnuclear materials
- Simulate detector response
- Analyze data from existing measurement systems
- Plan novel measurement systems

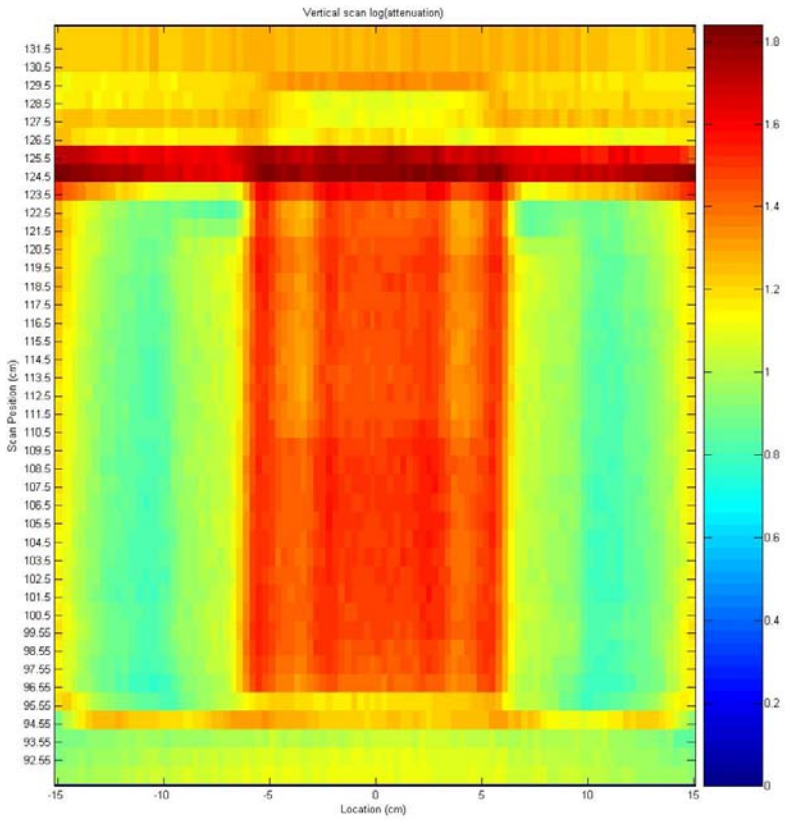
Application of Monte Carlo Modeling

Imaging for Secondary Inspection: Tomography

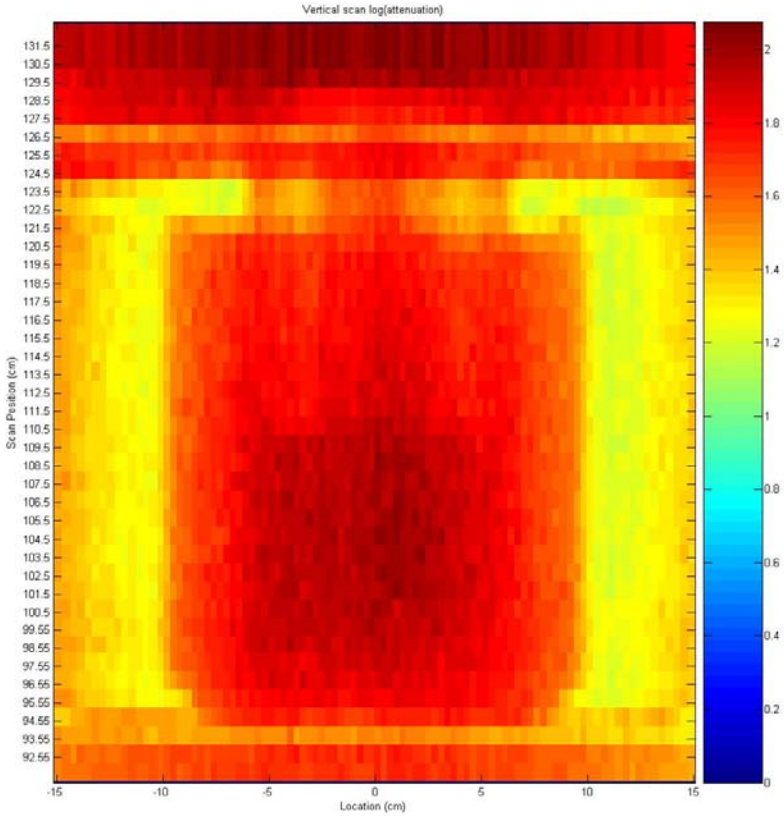


Application of Monte Carlo Modeling

3-D Images Built from Many Horizontal Slices: Cf-252 Gamma and Neutron Measurements



Gamma Image



Neutron Image

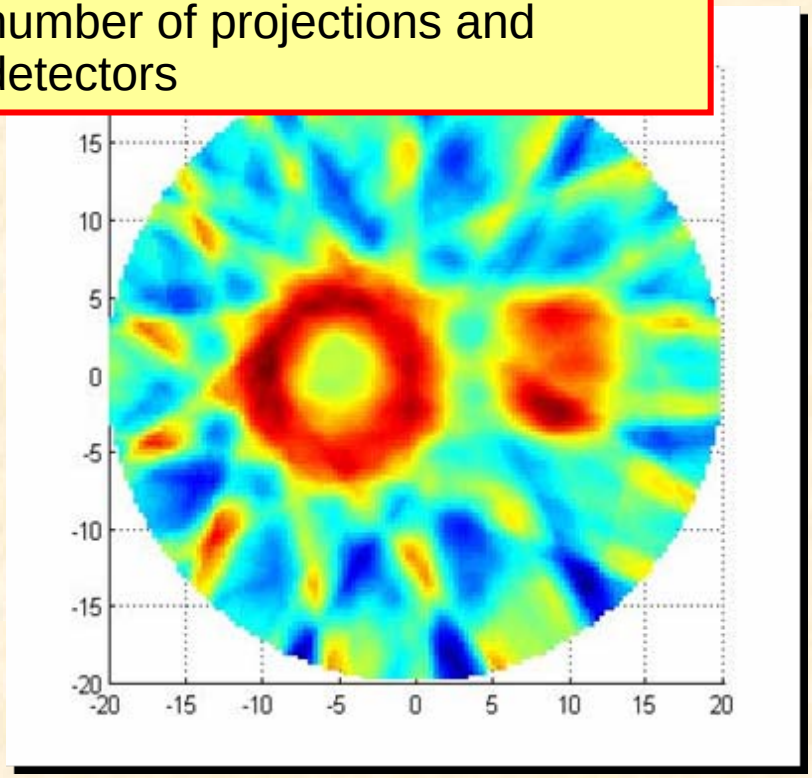
Application of Monte Carlo Modeling

Imaging for Secondary Inspection: Low-Resolution Tomographic Images

Thick container wall is a neutron shield

Depleted uranium casting and water bottle in AT400 container, measured with 14-MeV neutrons

Streaking occurs due to limited number of projections and detectors

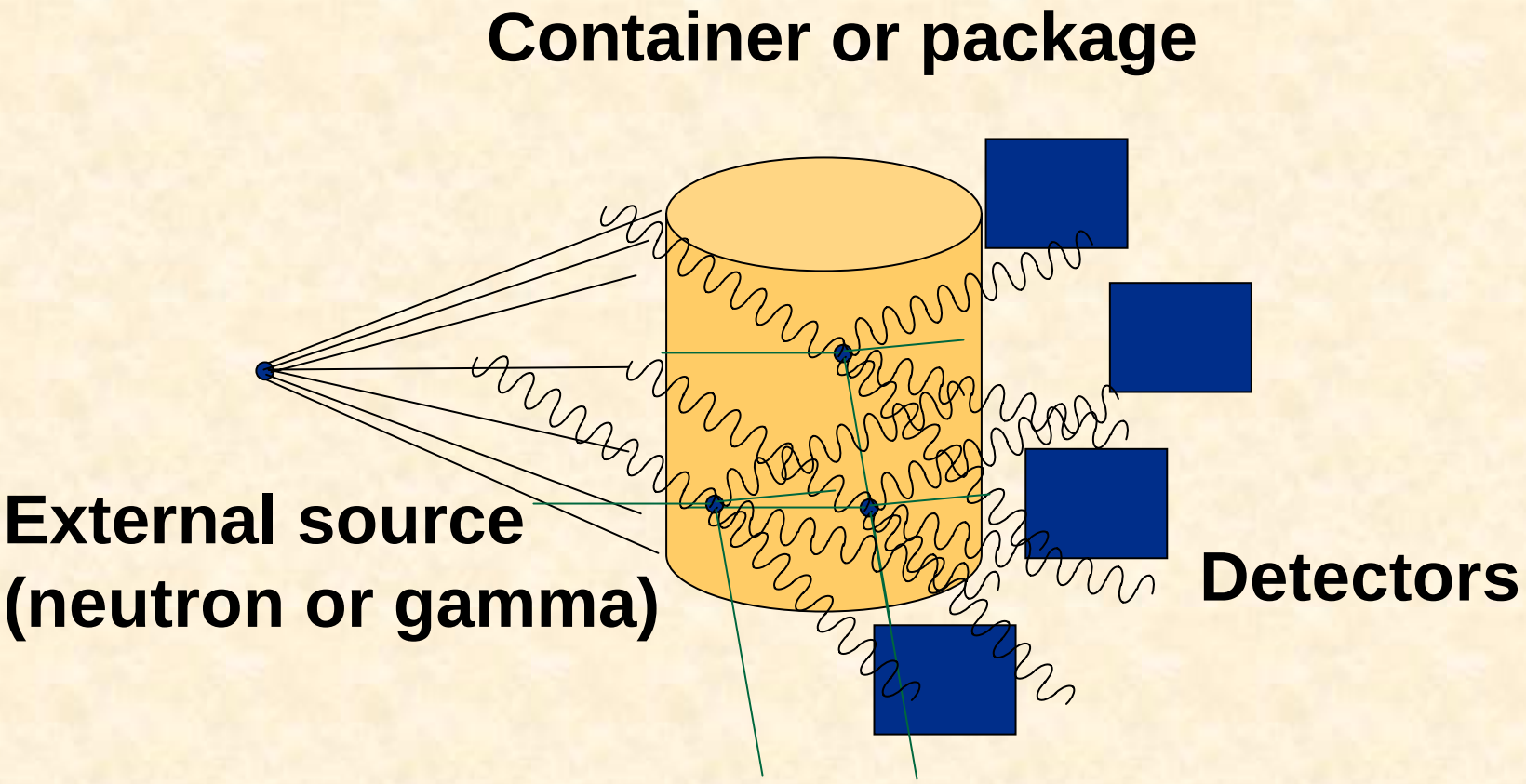


Filtered back-projection of 12 projections (normalized to empty AT400 container)

Active Interrogation

- The most difficult problem is the detection of concealed uranium
  - The low spontaneous fission rate of uranium makes passive interrogation very difficult
- Objectives:
  - Develop a system based on active interrogation with coincidence detection to aid in the identification and attribution of diverted fissile nuclear material
  - Model and analyze the conceptual system with new Monte Carlo codes to determine feasibility and limitations

Active Interrogation Schematic Diagram

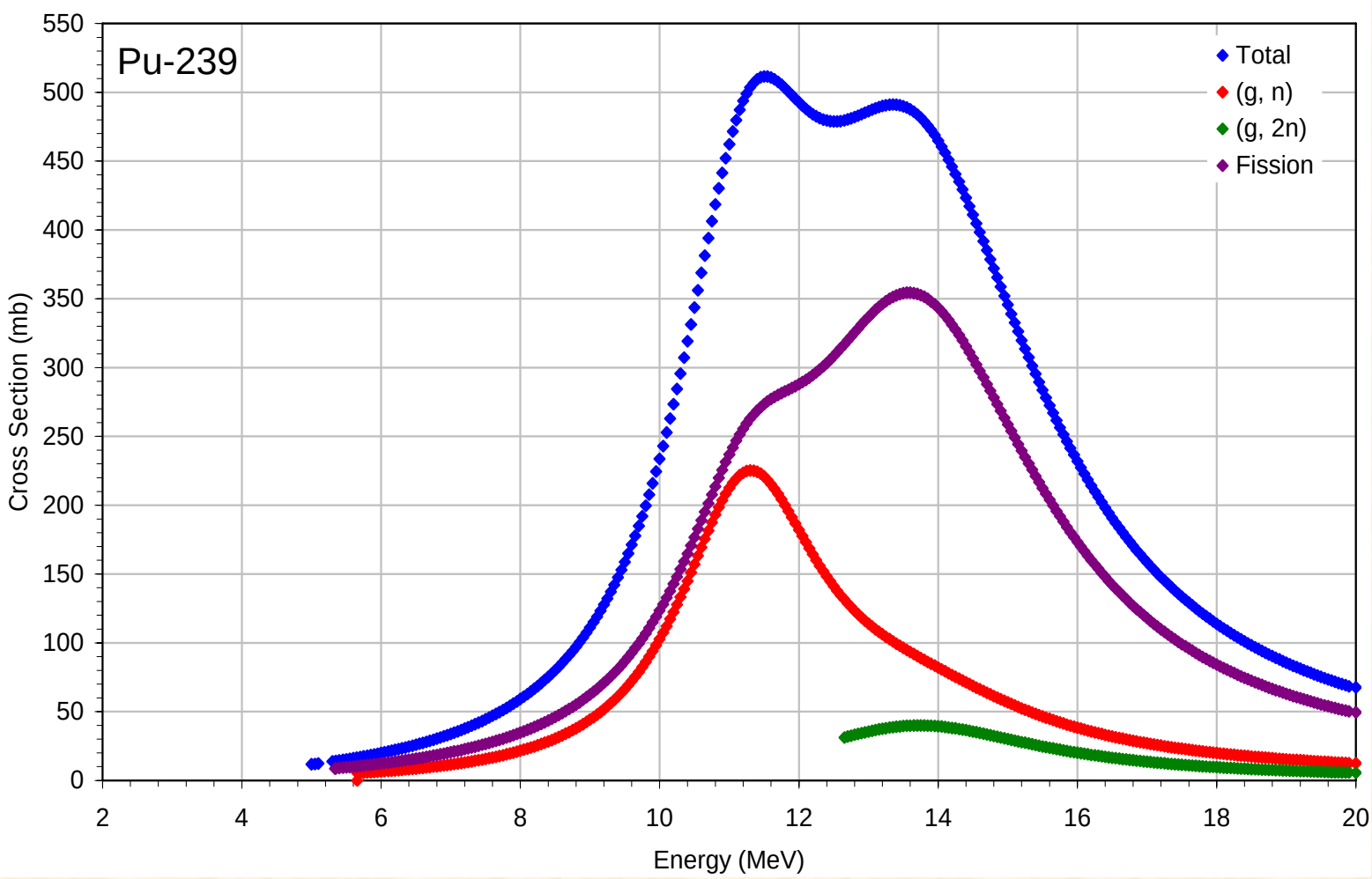


Active Interrogation Sources

- Active interrogation sources are typically high-energy neutrons or photons
- There are trade-offs between these two particle types
  - Neutrons have higher penetrability in high-Z materials
  - Photons have higher penetrability in low-Z materials
- Low-Z materials are commonly used in industrial packaging: photons were selected for this application

Background

Photonuclear Cross Sections



Background

Correlation Measurements

- Particles are detected within a time-delay window between two detectors
- Correlated particles provide a reliable indication of fission occurrence
- Particles from other reactions arrive randomly and are largely uncorrelated

Background

Monte Carlo Simulations

- Used to evaluate new measurement techniques: provide useful insights on what works in different scenarios
- Need codes that reliably simulate the physics of photonuclear interactions on an event-by-event basis
- Data libraries of large codes such as MCNP lack basic data

Main Features of Modified MCNP-X and MCNP-PoliMi codes

Modifications can be grouped into two subsets:

- Physics of particle transport
- Physics of detection

Physics of Particle Transport

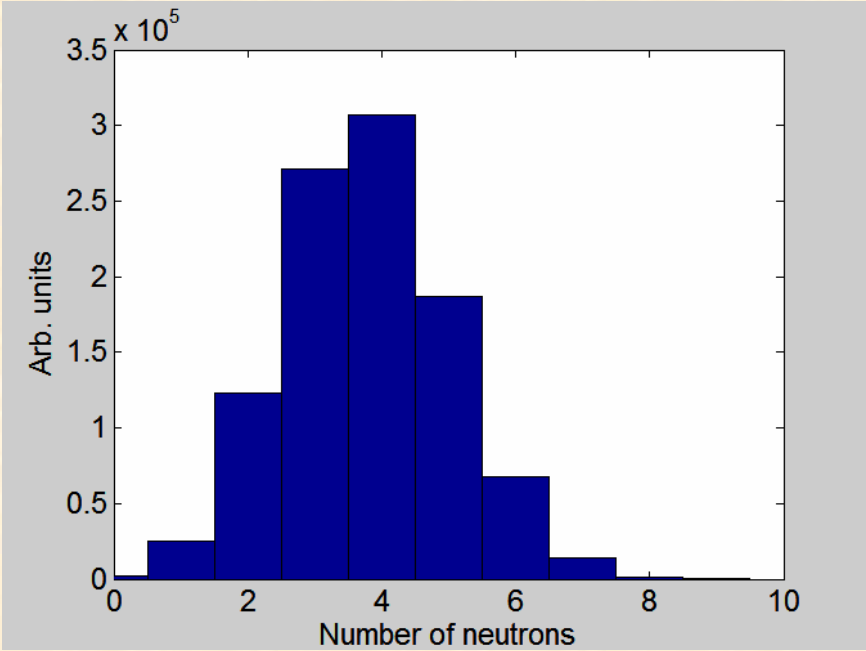
Overview

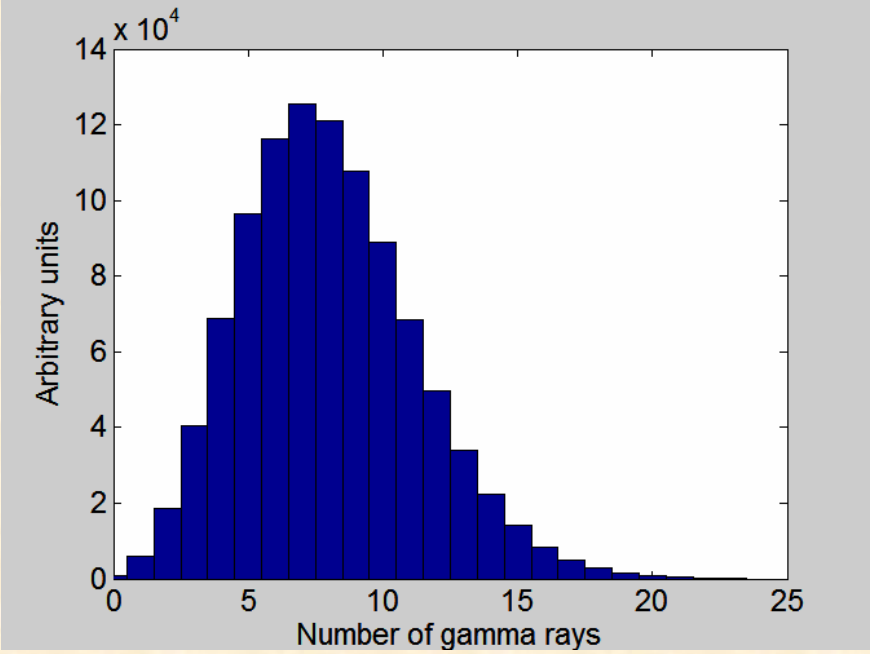
1. Neutron interaction and secondary neutron and gamma production are correctly linked
2. Photon interaction and secondary neutron and gamma production are correctly linked
3. Neutron and gamma fission multiplicity distributions have been implemented

Correct simulation of the neutron and photon field in a multiplying (or nonmultiplying) medium on an event-by-event basis: this is a unique capability of our code system

Physics of Particle Transport

Multiplicity of Neutrons and Gamma Rays from Fission



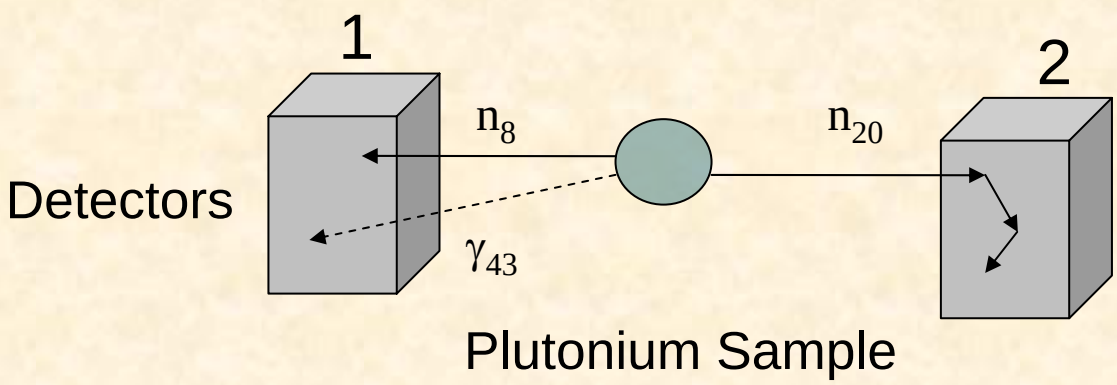


Physics of Detection

MCNP-PoliMi Collision Output File

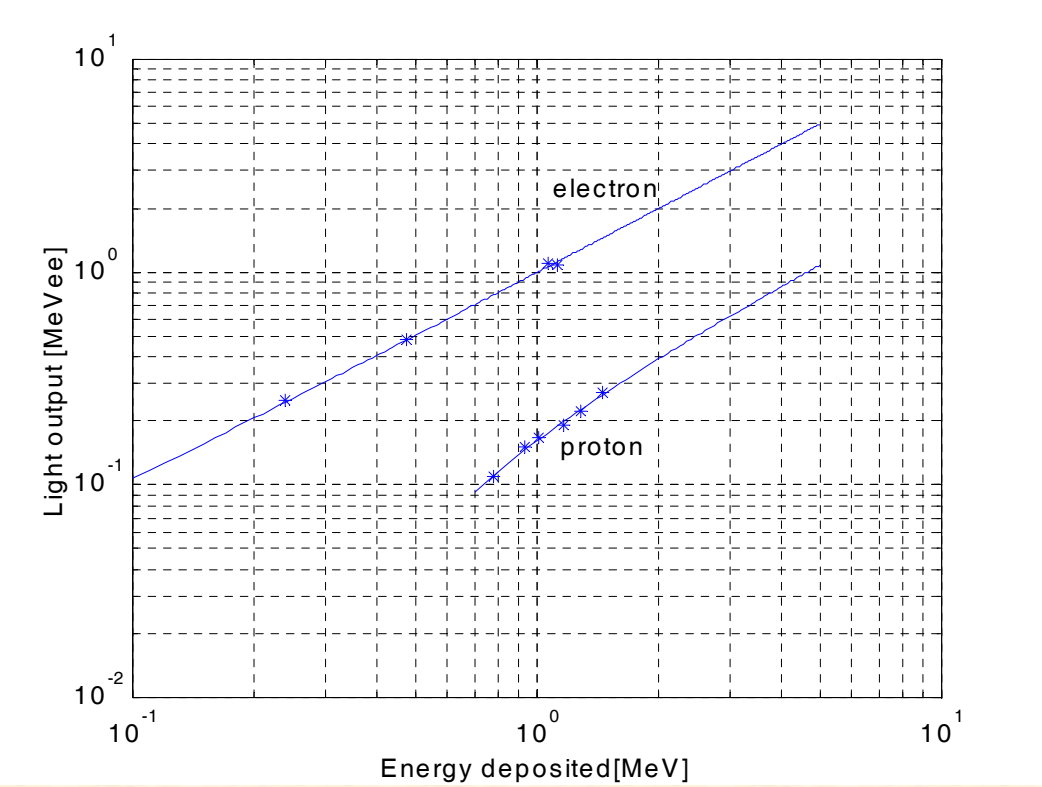
History number	Particle number	Projectile type*	Interaction type$^{\Delta}$	Target nucleus•	Cell number of collision event	Energy deposited in collision (MeV)	Time (shakes)	Collision position (X)	(Y)	(Z)	Particle weight	Generation number	Number scatterings
...													
29	20	1	-99	1001	2	0.3105	2.743	-25.64	14.37	8.7	1	2	2
29	20	1	-99	1001	2	0.1894	2.846	-26.01	-14.8	9.48	1	2	3
29	20	1	-99	1001	2	0.1617	3.045	-27.27	15.07	10.1	1	2	4
29	43	2	1	6	1	0.7734	6.514	31.83	7.07	11.2	1	2	1
29	8	1	-99	1001	1	0.3731	3.965	27.84	18.82	-0.6	1	0	1
...													

* 1 = neutron; 2 = photon
Δ -99 = elastic scattering; 1 = Compton scattering
• 1001 = hydrogen; 6 = carbon



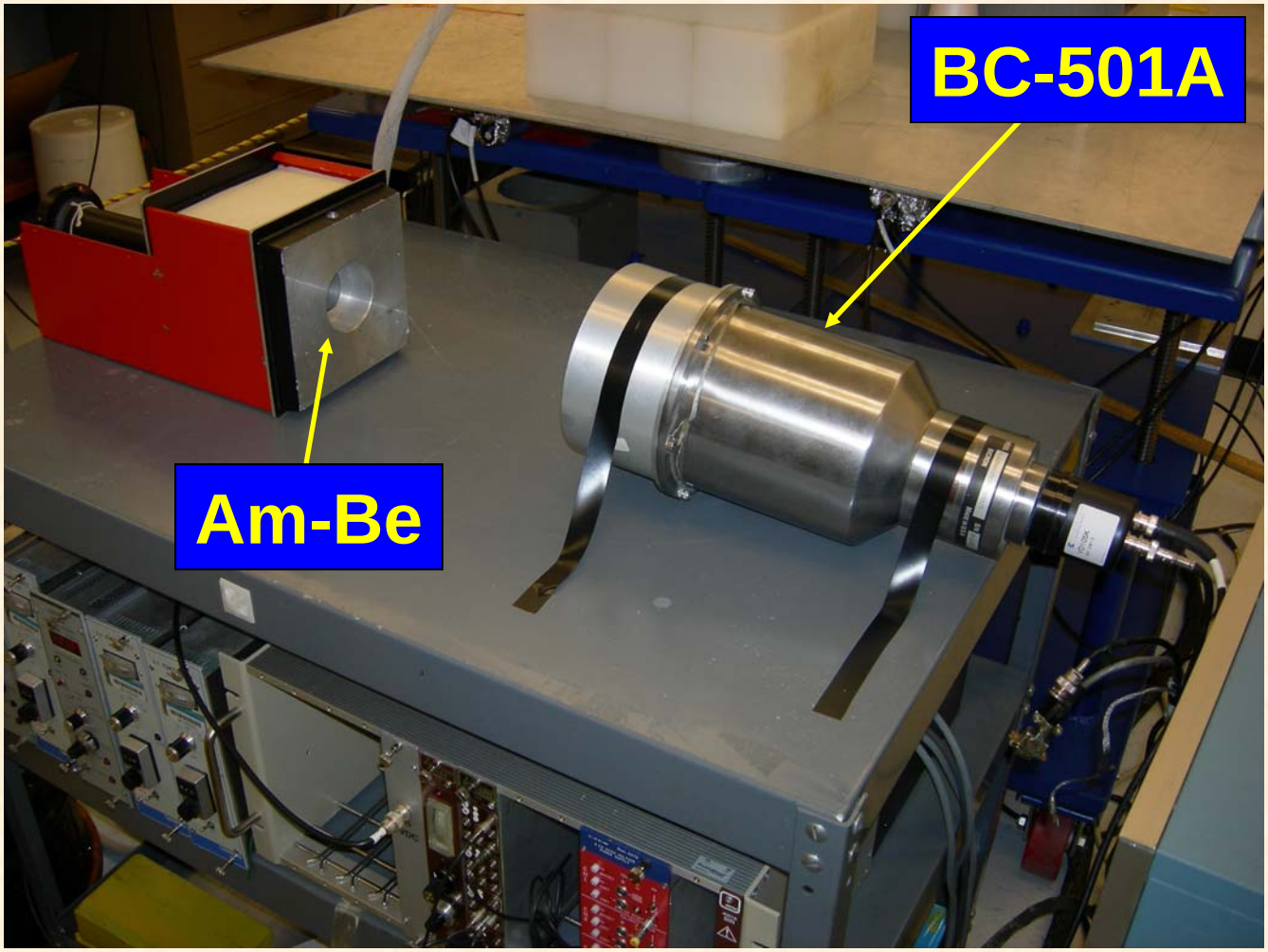
Post-Processing Code for MCNP-PoliMi Collision Output File

Scintillation Detectors



Experimental calibration of scintillator to determine the light output for neutron interactions on H and the light output for γ interactions on e-

Neutron Pulse Height Analysis



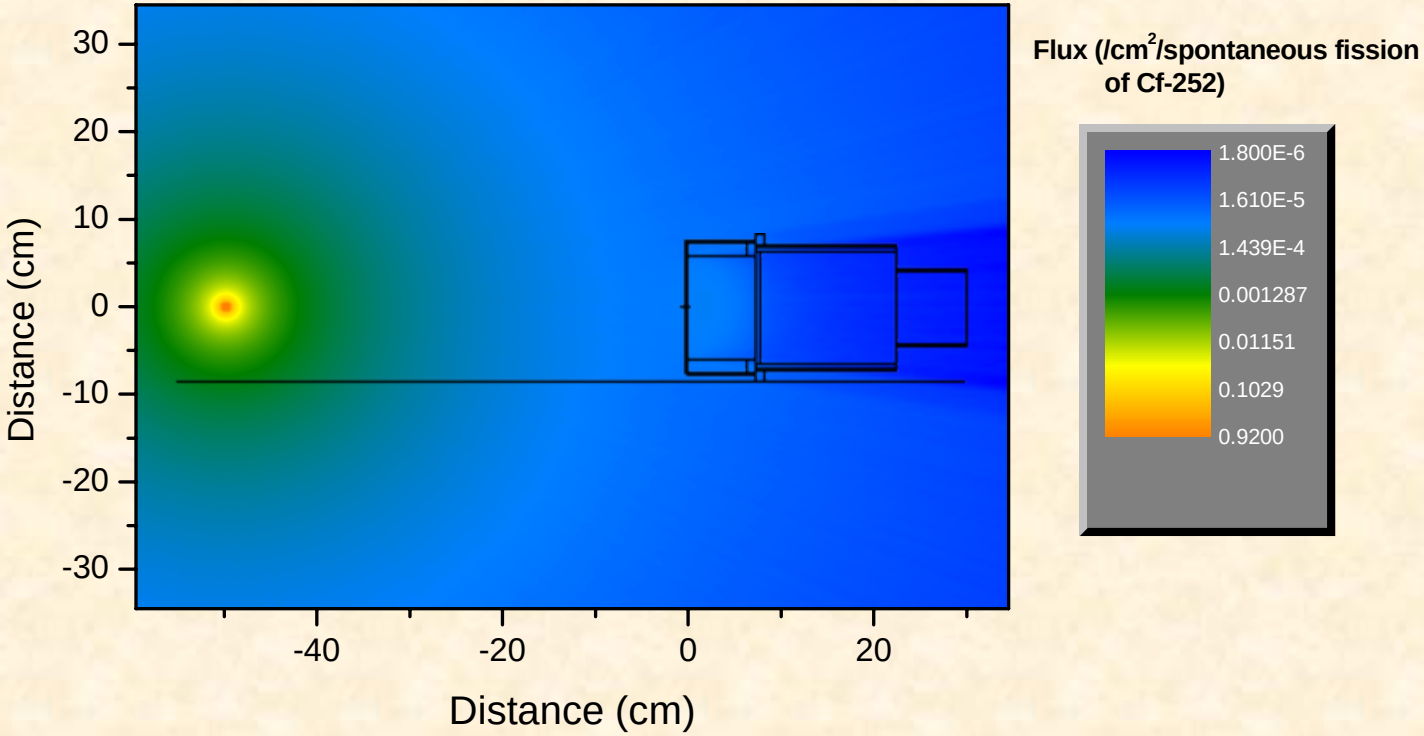
Neutron sources:
Cf-252 (~60e3 n/s)
Am-Be (~10e5 n/s)
Am-Li

Shielding:
1-inch Pb block
1-inch PE block

Source Distance:
50 cm

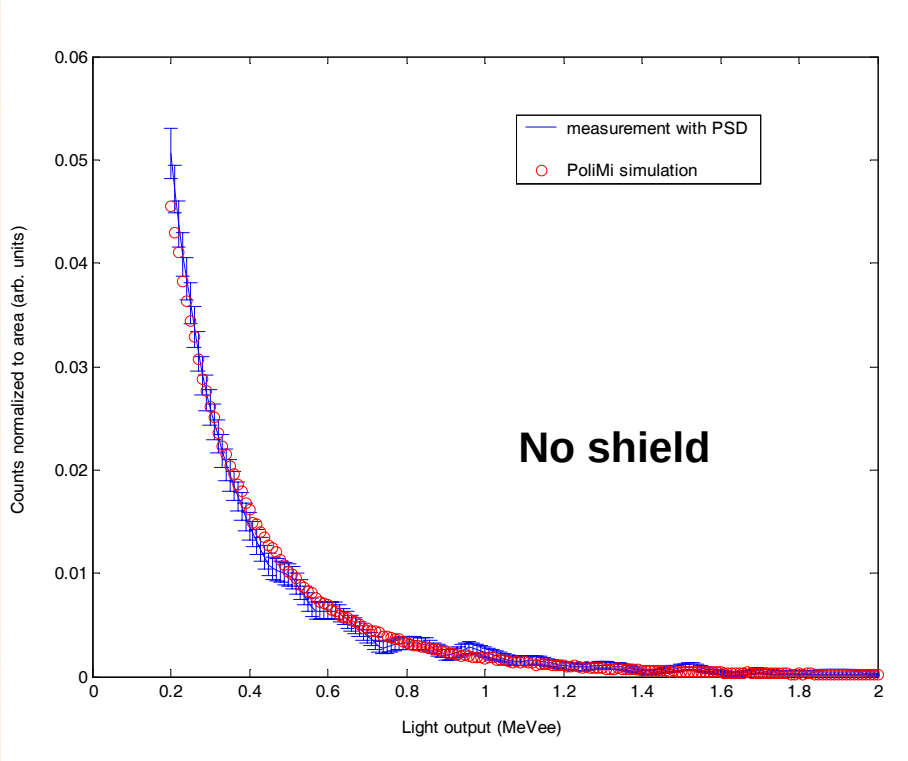
Data structure:
200 ns/pulse
~4500 pulses/ acquisition

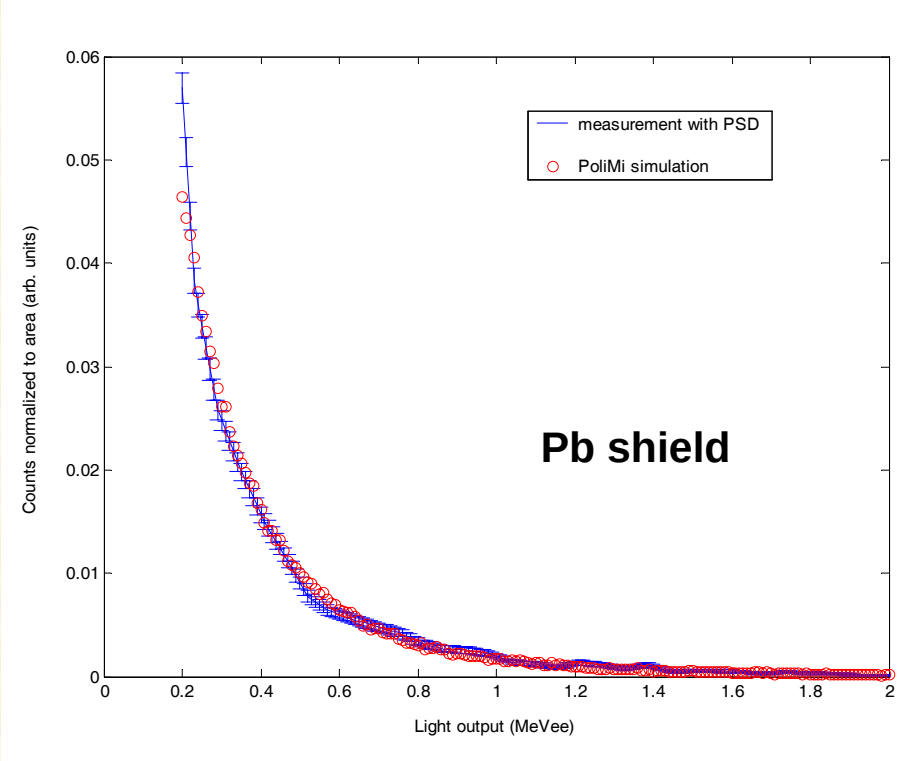
Simulating Neutron Pulse Height Distributions



- Isotropic sources placed 50 cm from BC-501A
- Attenuation in the detector
- Neutron pulse height distributions calculated

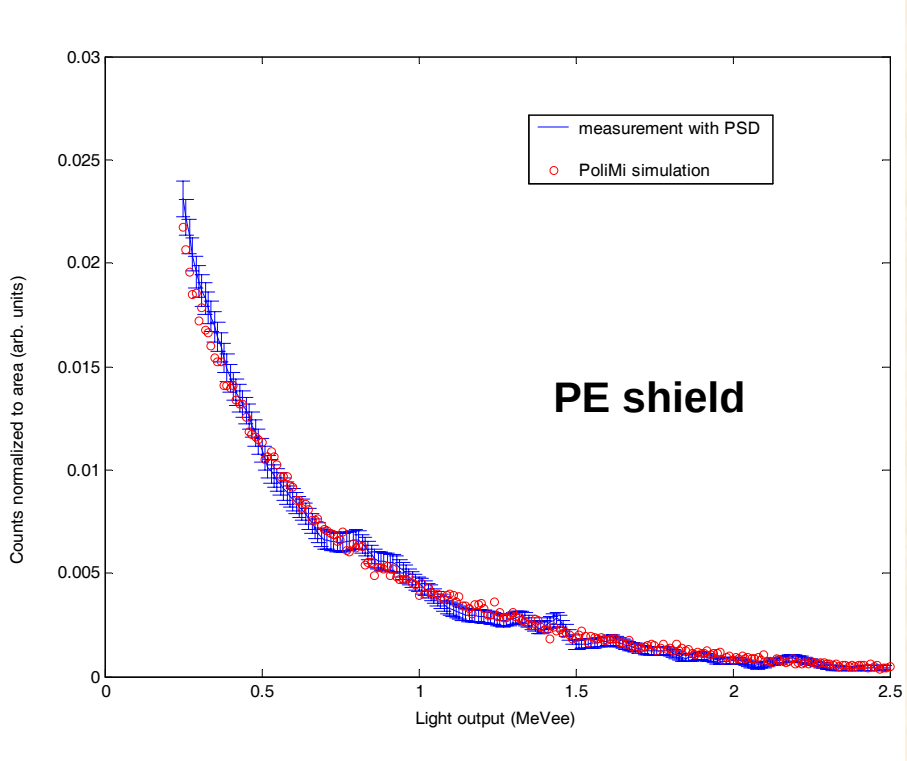
Pulse-Height Distributions–Cf-252

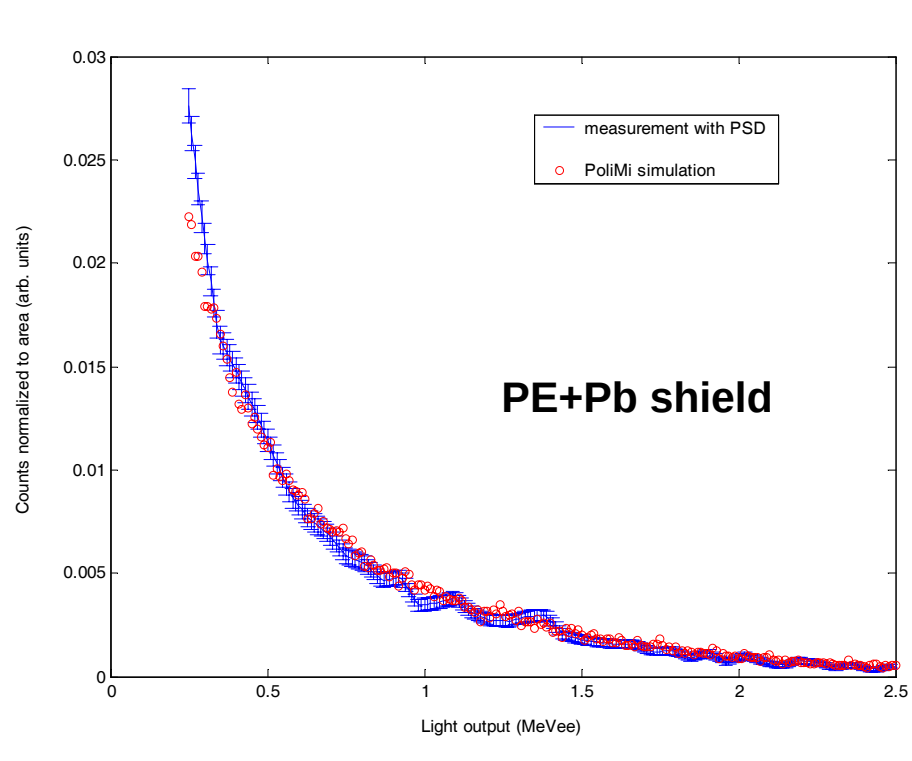




- Very good agreement between the measurement and PoliMi
- Pb shielding results in more neutron pulses per acquisition, which improves statistics of neutron data
- Detection threshold of 0.094 MeVee

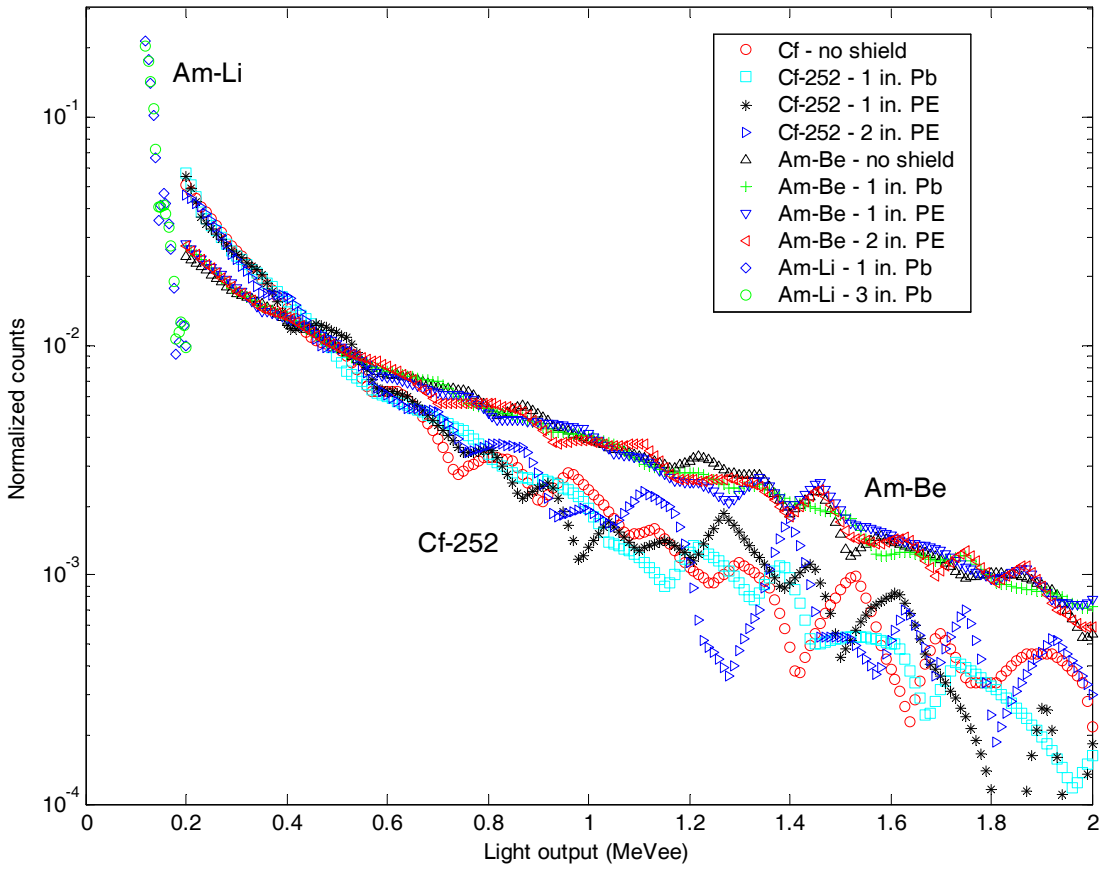
Pulse-Height Distributions–Am-Be





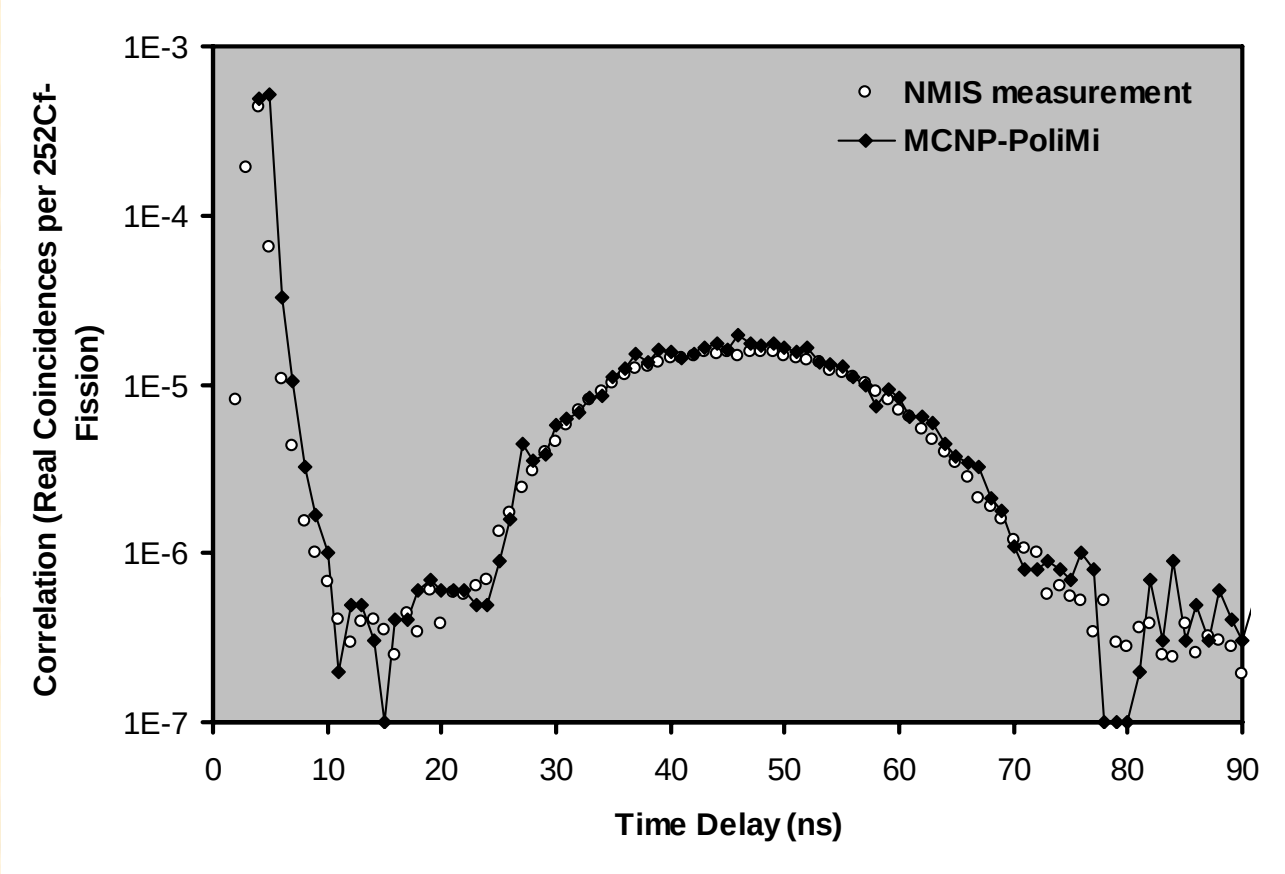
- Combination of PE and Pb gives more low-energy counts

Source Identification by Analysis of Neutron Pulse-Height Distributions



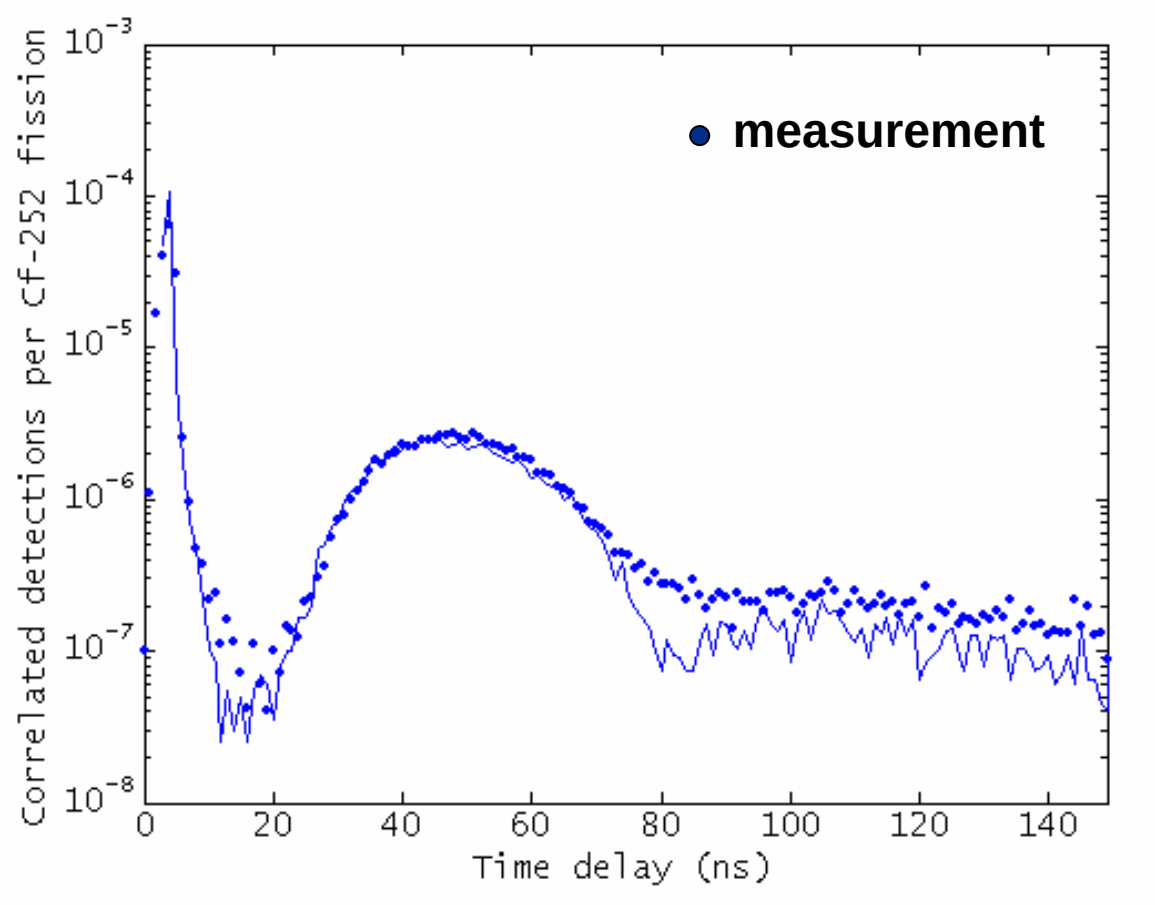
Comparison of Measurement and MCNP-PoliMi Simulation: Time-of-Flight in Air

Plastic scintillator 10.1 × 10.1 × 10.1 cm



Comparison of Measurement and MCNP-PoliMi Simulation: Time-of-Flight in Air

Plastic scintillator 2.54 × 2.54 × 15.0 cm



Objectives of Monte Carlo Studies

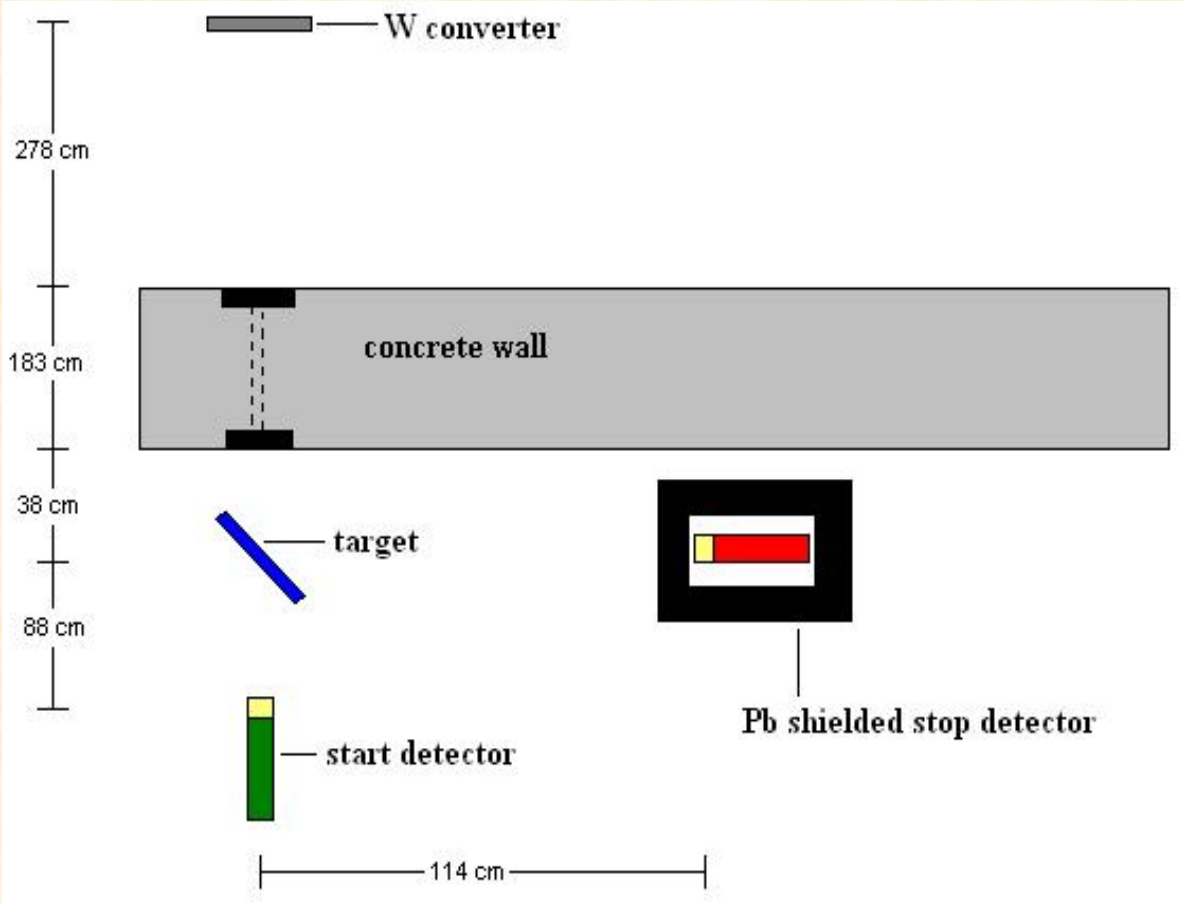
- Understand the basic physics interactions occurring in the target and the detectors
- Plan experiments to be performed with a variety of detectors in a variety of scenarios
  1. Gamma-ray measurements using gamma detectors
  2. Neutron and gamma-ray correlation and multiplicity measurements using liquid and plastic scintillators
- Analyze the effect of accidental coincidences in correlation measurements

MCNP-X/MCNP-PoliMi Code System

- Simulate photonuclear events and their progeny in fissile assembly and cargo material:
  - (γ, fission), (γ, n), and (γ, 2n)
- Simulate the flux of neutrons and photons generated in the target and in the surroundings
- Simulate detector response to fast neutrons and photons
- Compute correlation and multiplicity measurements among detectors

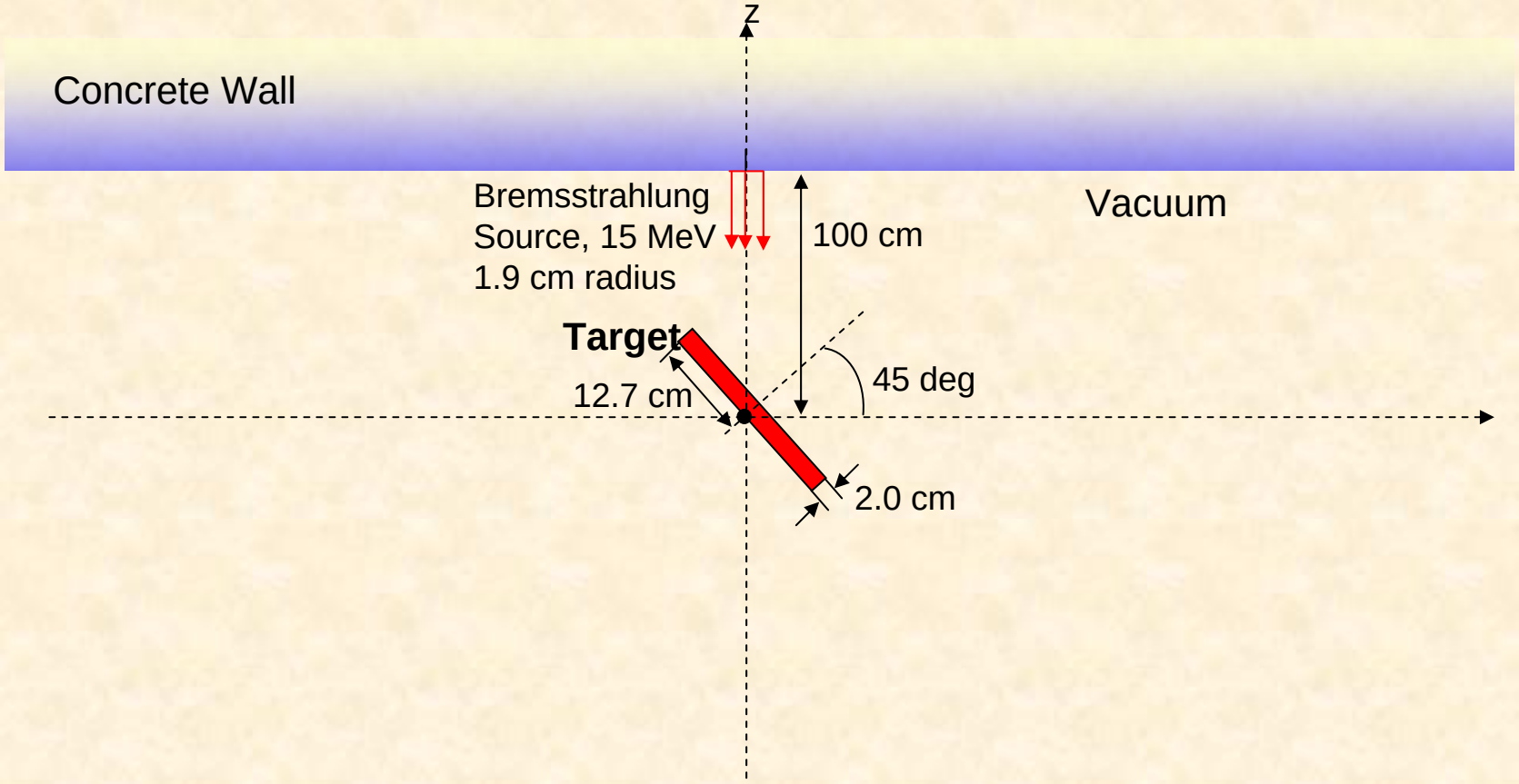
Idaho Accelerator Center

Experimental Setup



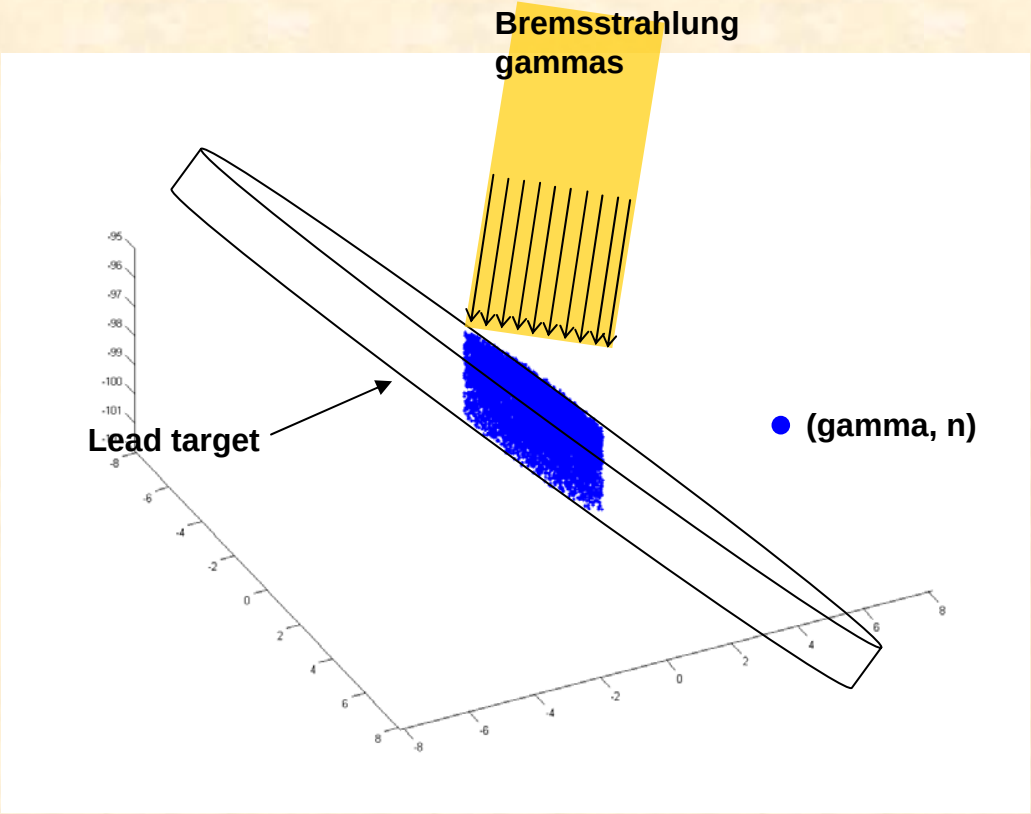
MCNP-PoliMi Model: Target Close-Up

Lead, depleted uranium (DU), and highly enriched uranium (HEU) targets modeled with realistic densities and fixed geometry



MCNP-PoliMi 3-D Distribution of Photonuclear Events in the Lead Target

15 MeV endpoint energy Bremsstrahlung spectrum

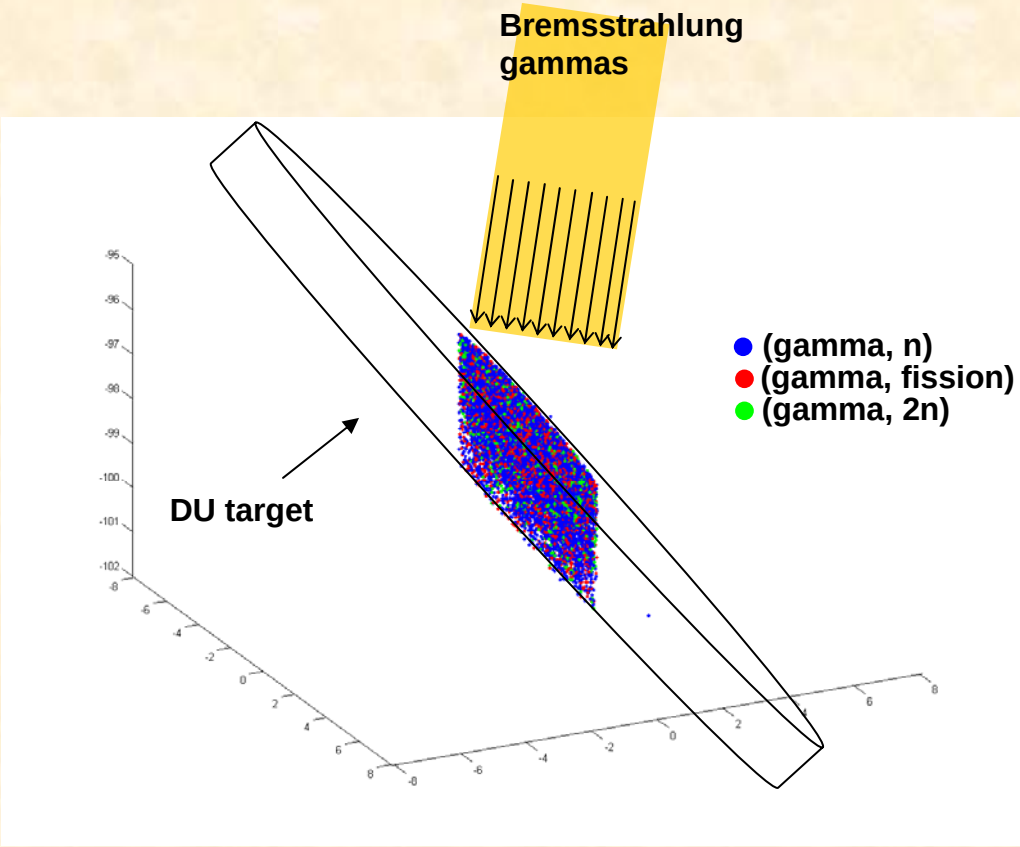


Note: Not to scale; the target disk is actually larger

- Shows positions of the photonuclear interactions within the lead target
- All photonuclear events are confined to the region directly hit by the beam: gamma Compton scatterings do not play a role

MCNP-PoliMi 3-D Distribution of Photonuclear Events in the DU Target

15 MeV endpoint energy Bremsstrahlung spectrum

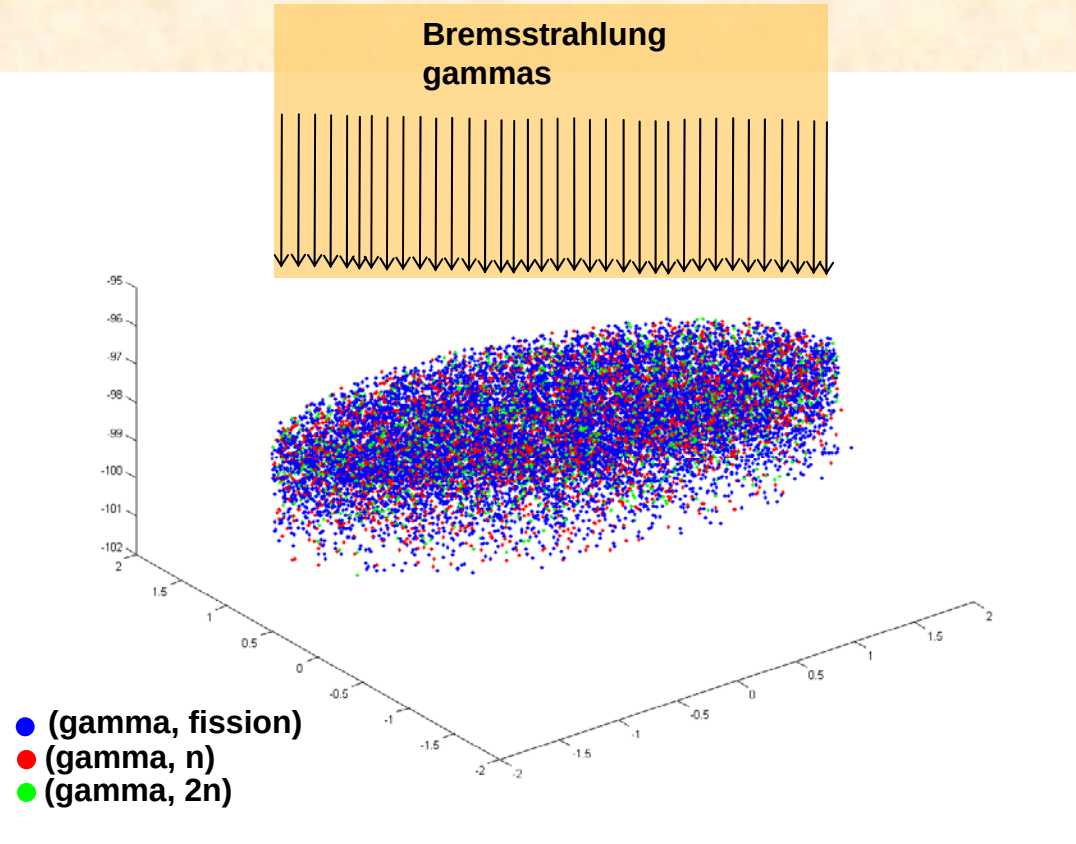


Note: Not to scale; the target disk is actually larger

- Shows positions of the photonuclear interactions within the DU target
- Almost all photonuclear events are confined to the region directly hit by the beam: gamma Compton scatterings do not play a large role

MCNP-PoliMi 3-D Distribution of Photonuclear Events in the DU Target: Close-Up on Region Hit by the Beam

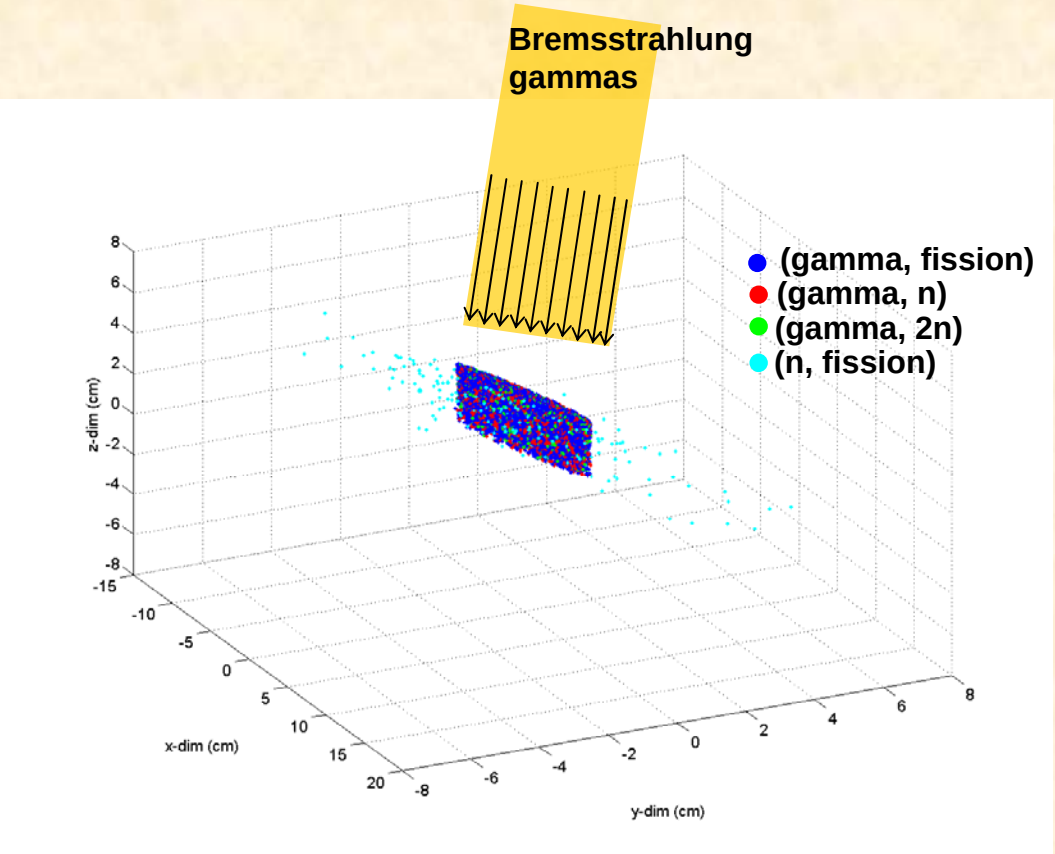
15 MeV endpoint energy Bremsstrahlung spectrum



- Shows positions of the three primary photonuclear interactions within the target
- Top portion of the target shows higher density of photonuclear events

MCNP-PoliMi 3-D Distribution of Interactions in DU Target: Secondary, Neutron-Induced Fissions

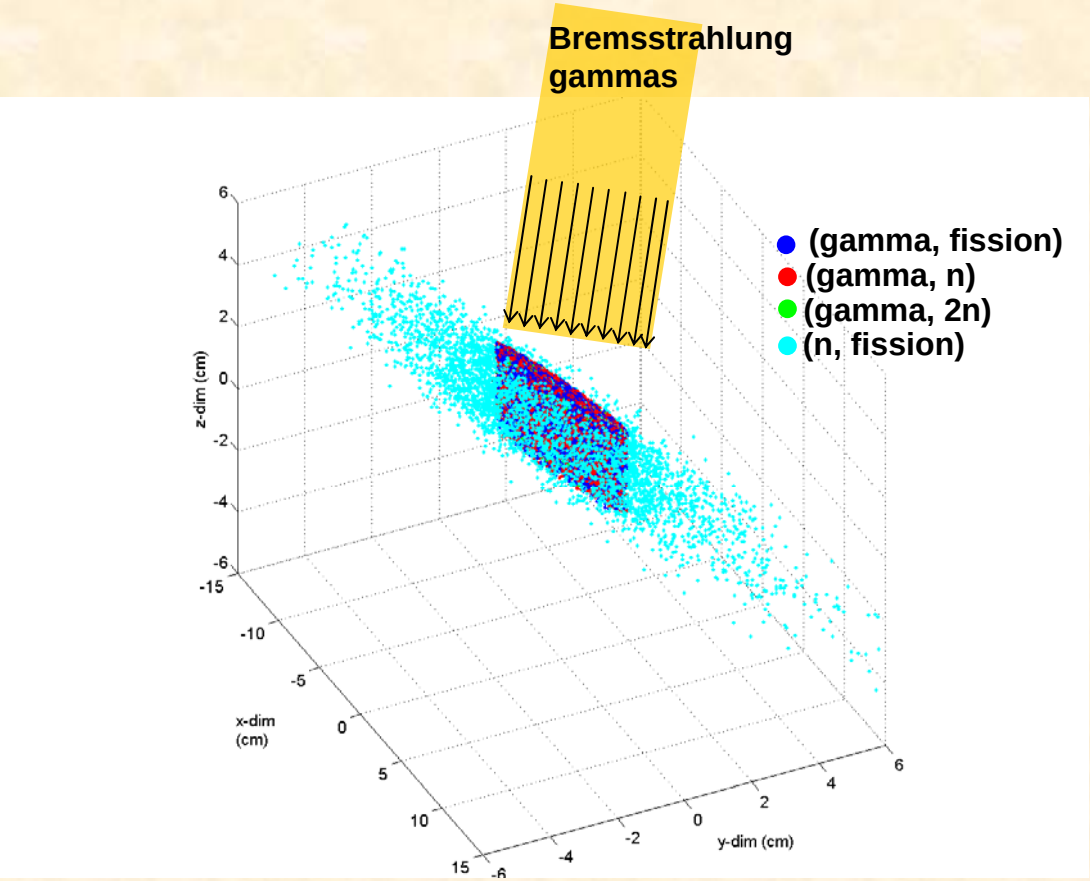
15 MeV endpoint energy Bremsstrahlung spectrum



- Shows positions of the three primary photonuclear interactions within the target
- Shows positions of the secondary, neutron-induced fissions in the DU (not many)
- DU composition:
  99.8 wt% U-238
  0.2 wt% U-235

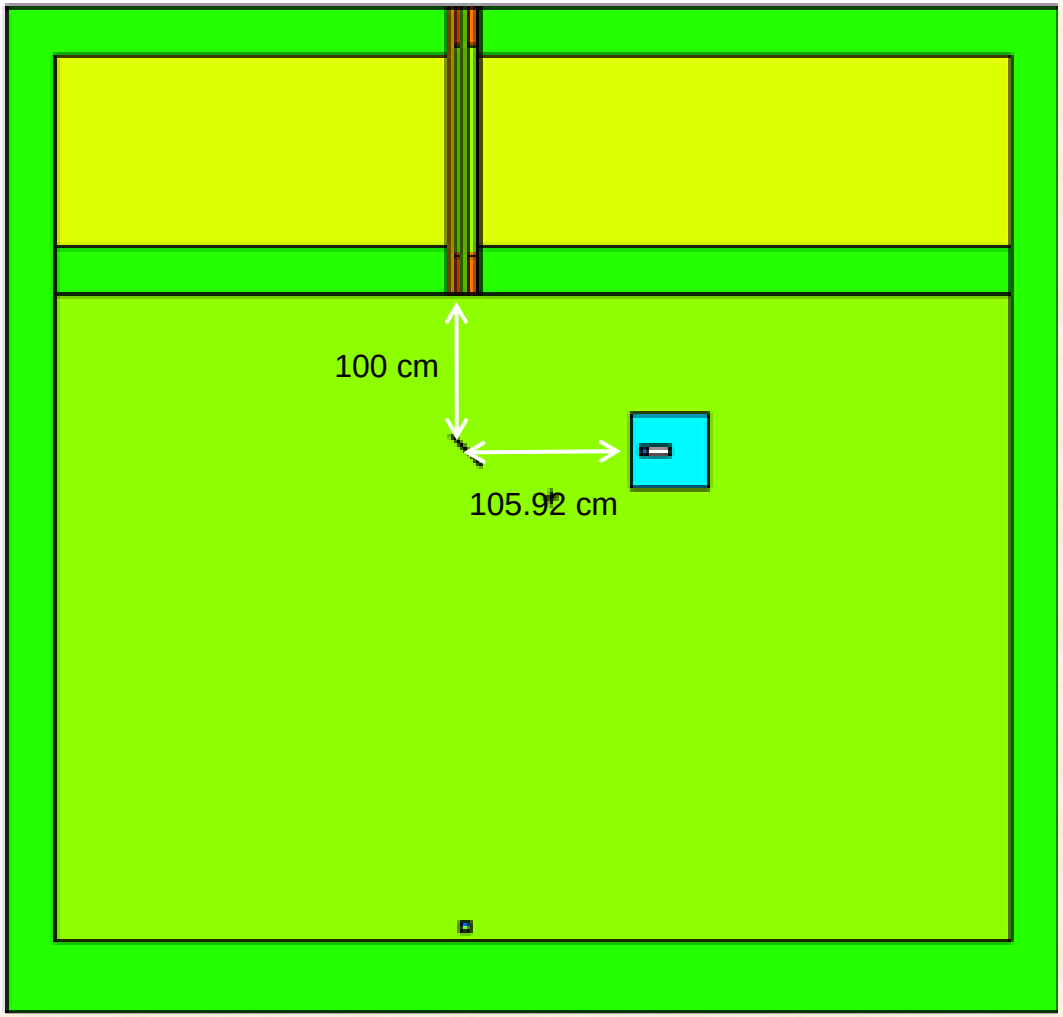
MCNP-PoliMi 3-D Distribution of Interactions in HEU Target: Secondary, Neutron-Induced Fissions

15 MeV endpoint energy Bremsstrahlung spectrum



- Shows positions of the three primary photonuclear interactions within the target
- Shows positions of the secondary, neutron-induced fissions in the HEU (many more than the DU)
- HEU composition:
  92 wt% U-235
  8 wt% U-238

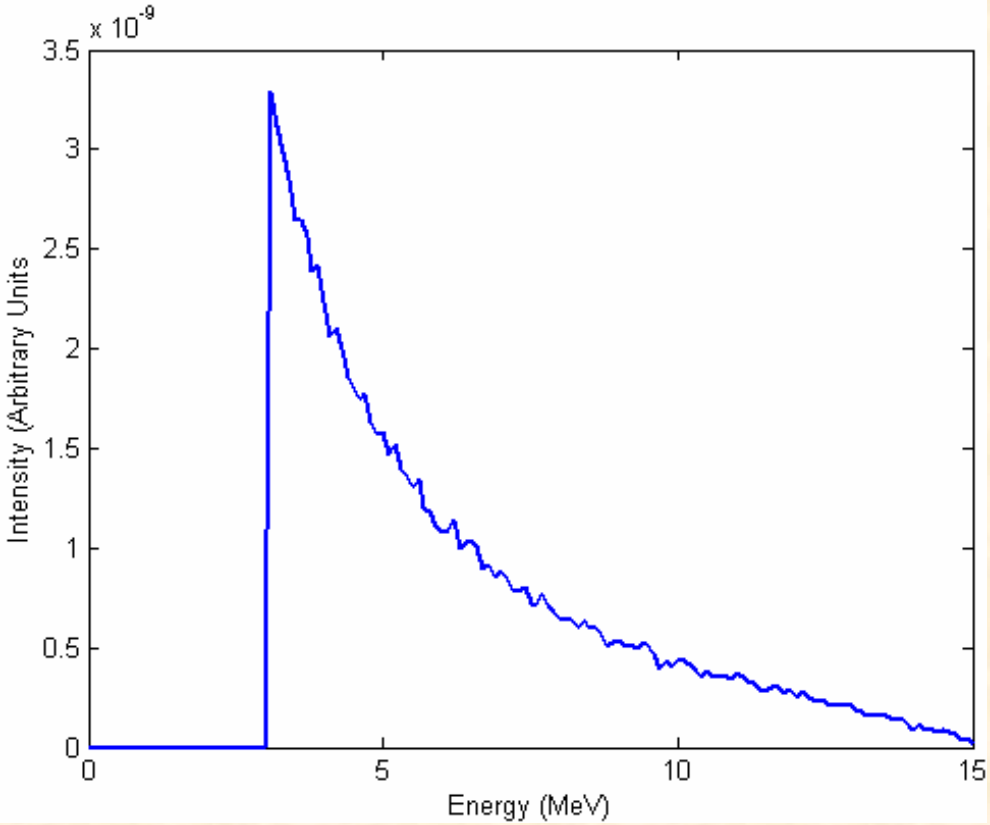
MCNP-X/MCNP-PoliMi Geometry



Input Photon Spectrum

MCNP-X Model Results from IAC

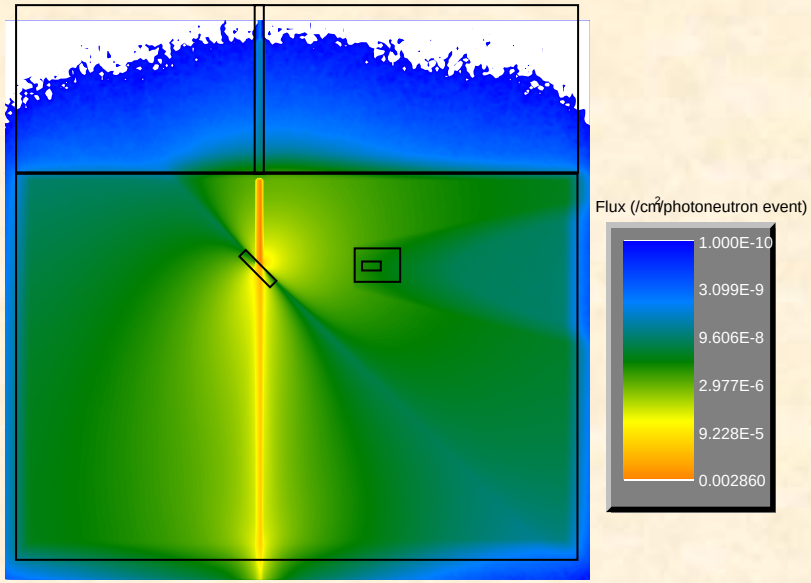
- Energy distribution of Bremsstrahlung source was obtained by IAC via an MCNP-X model
- These results were used as the input for our simulations



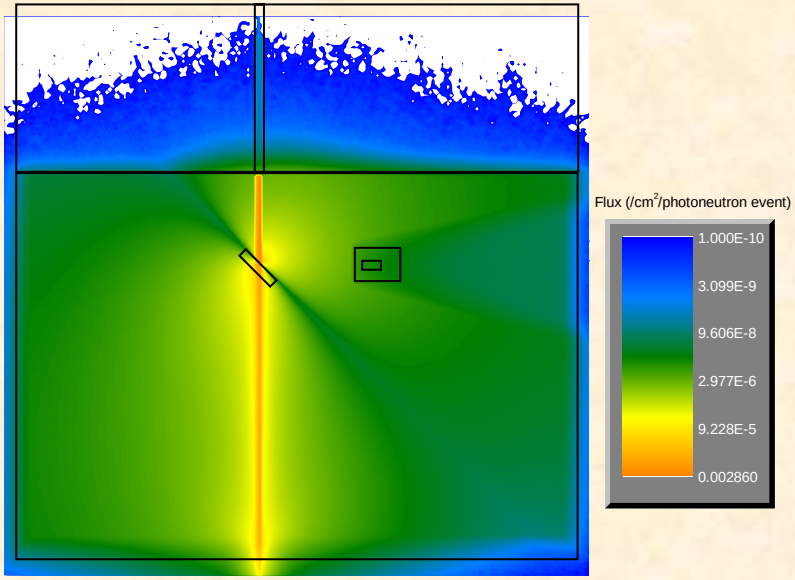
MCNP-X Photon Flux in Target and Room

15 MeV endpoint energy Bremsstrahlung spectrum

Depleted uranium target



Lead target

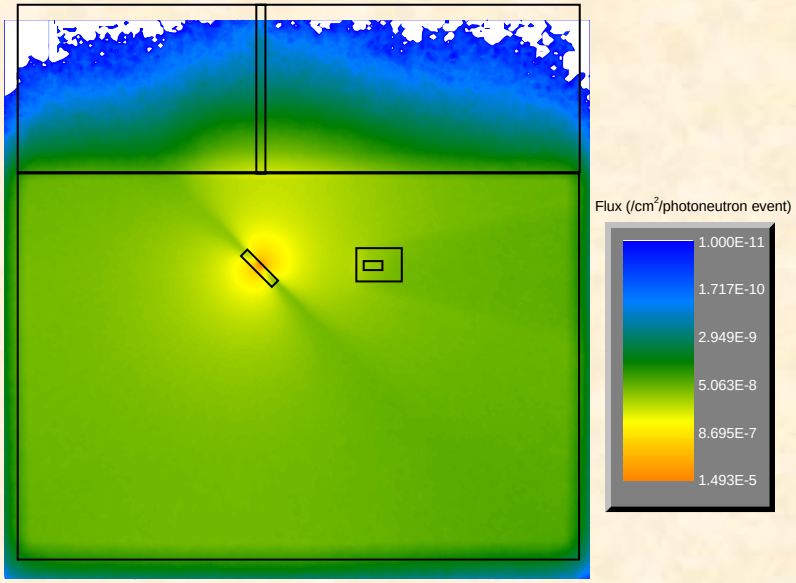


- Shows photon flux beam attenuation from target (more for depleted uranium than lead)
- Does not include secondary photons from photonuclear events
- Shadow behind the detector (note: it begins at the lead shield)
- Self-attenuation along the target axis

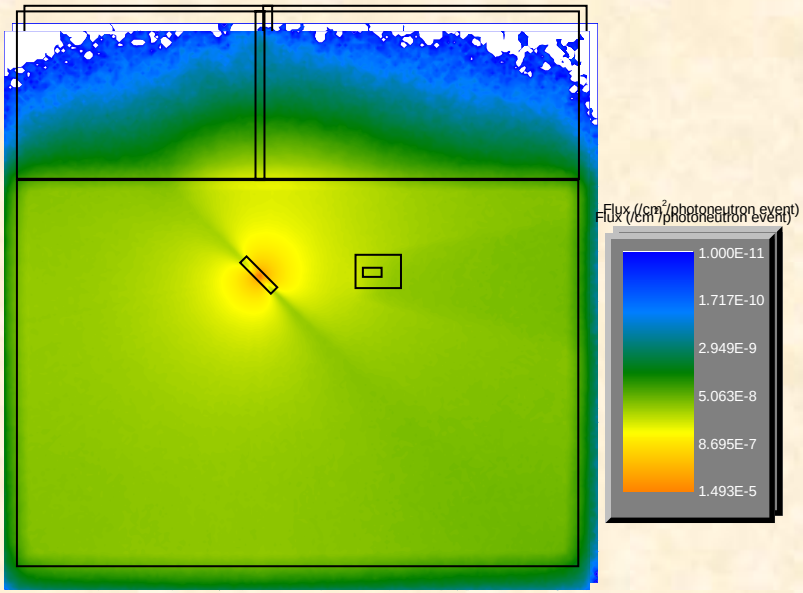
MCNP-X Neutron Flux in Target and Room

15 MeV endpoint energy Bremsstrahlung spectrum

Depleted Uranium target



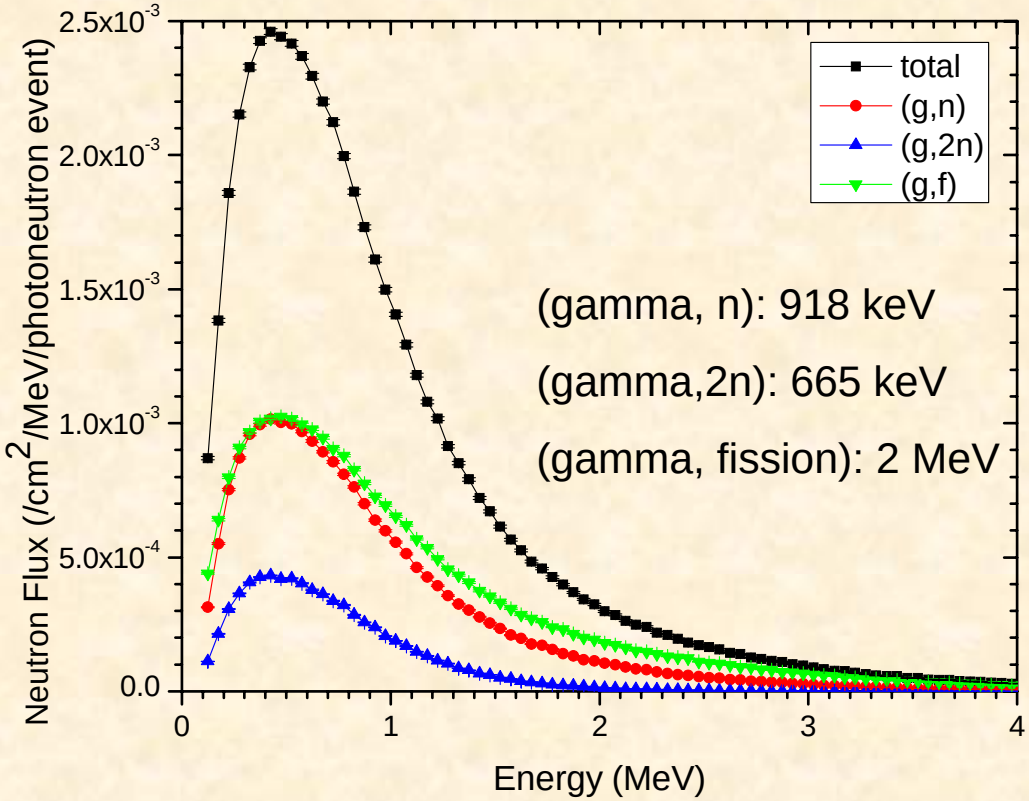
Lead target

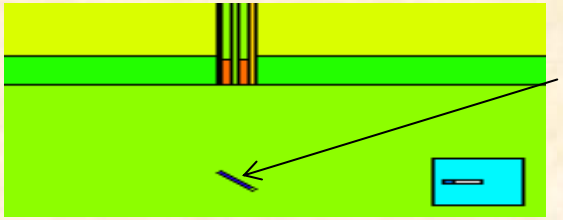


- Shows photoneutron production in the target (red)
- Neutron flux in the room (more neutrons from the depleted uranium target than the lead target)
- Self-attenuation along the target axis

MCNP-PoliMi Neutron Flux Across the DU Sample's Top Surface

15 MeV endpoint energy Bremsstrahlung spectrum

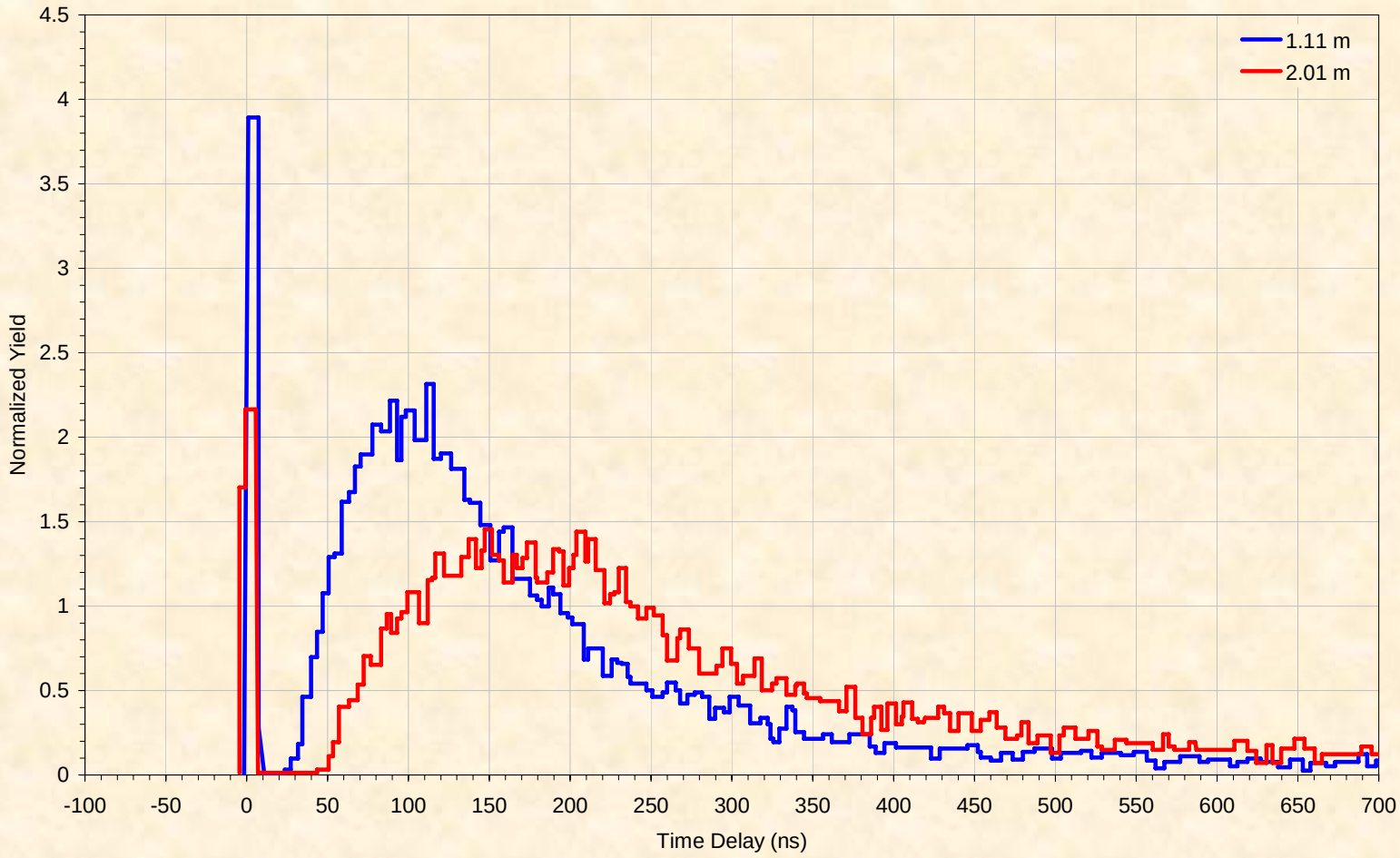




- Neutron flux from photonuclear events generated in the DU sample
- Total flux and separate contributions are shown
- Shows that (g, fission) neutron spectrum is richer in high-energy neutrons, but the shape of the spectrum is very similar to (g, n) and (g, 2n) neutrons

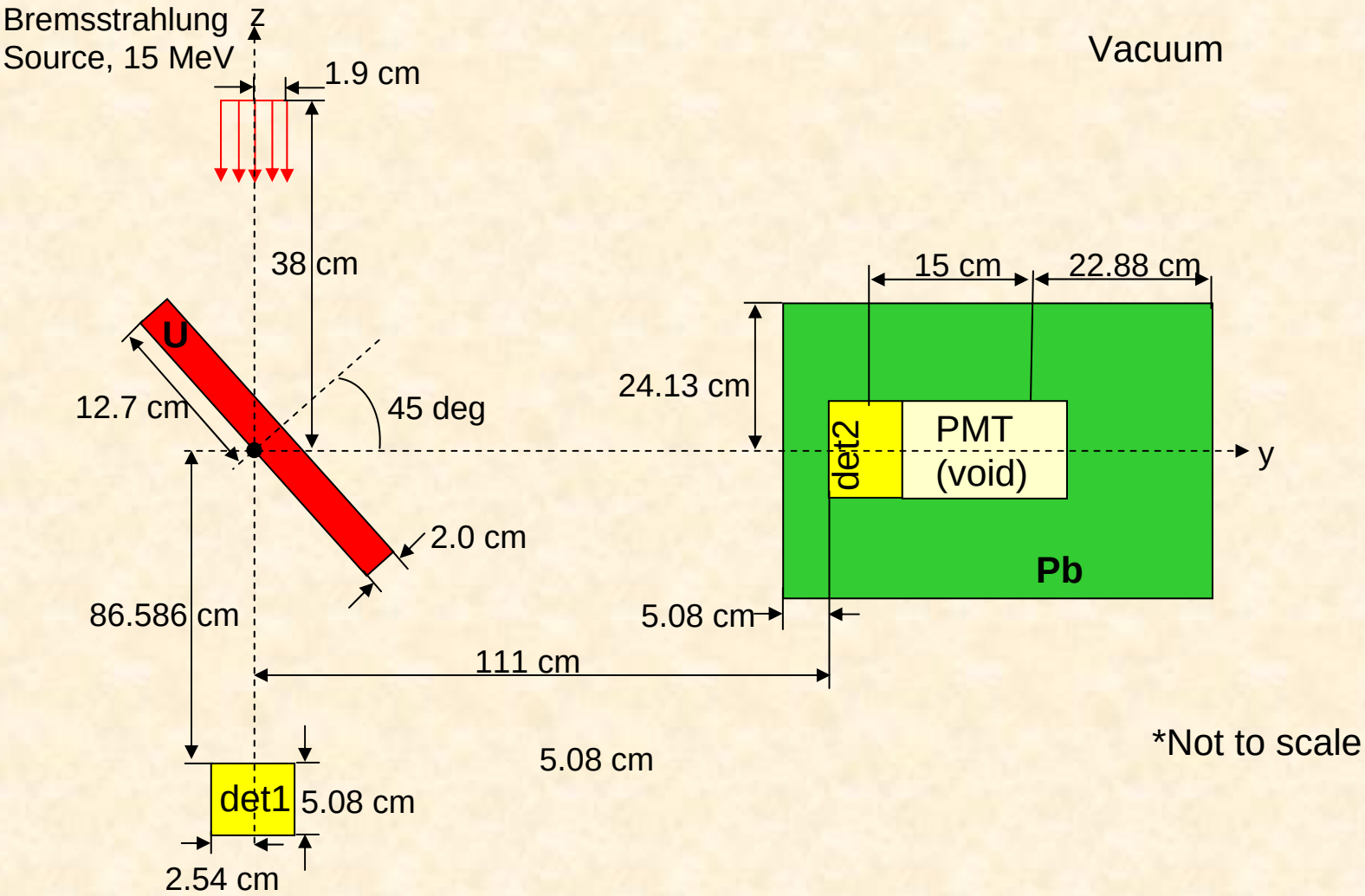
Measurement Data from IAC

15-MeV Bremsstrahlung Input Spectrum



MCNP-PoliMi Model

Geometrical Setup



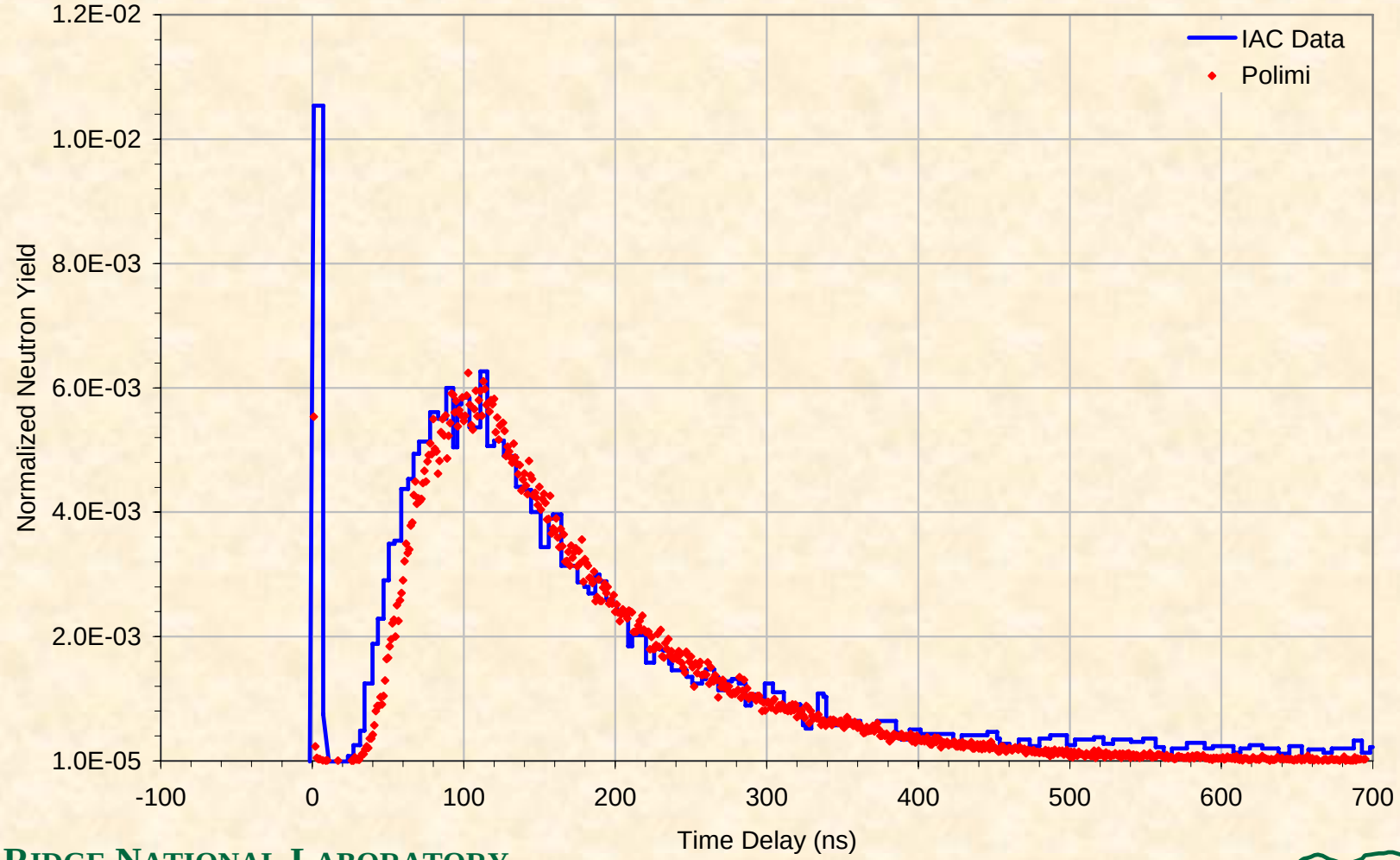
Data Post-Processing

Necessary Assumptions

- Detection threshold is a characteristic of the particular system and is determined through measurement
  - We were not provided this information, so a value of 0.006 MeVee was assumed
- MCNP-PoliMi results and the experimental data were normalized for direct comparison
  - Each set of data was normalized to the integral of the neutron region
  - The photon peak should be neglected in the absence of a “start” detector for this setup

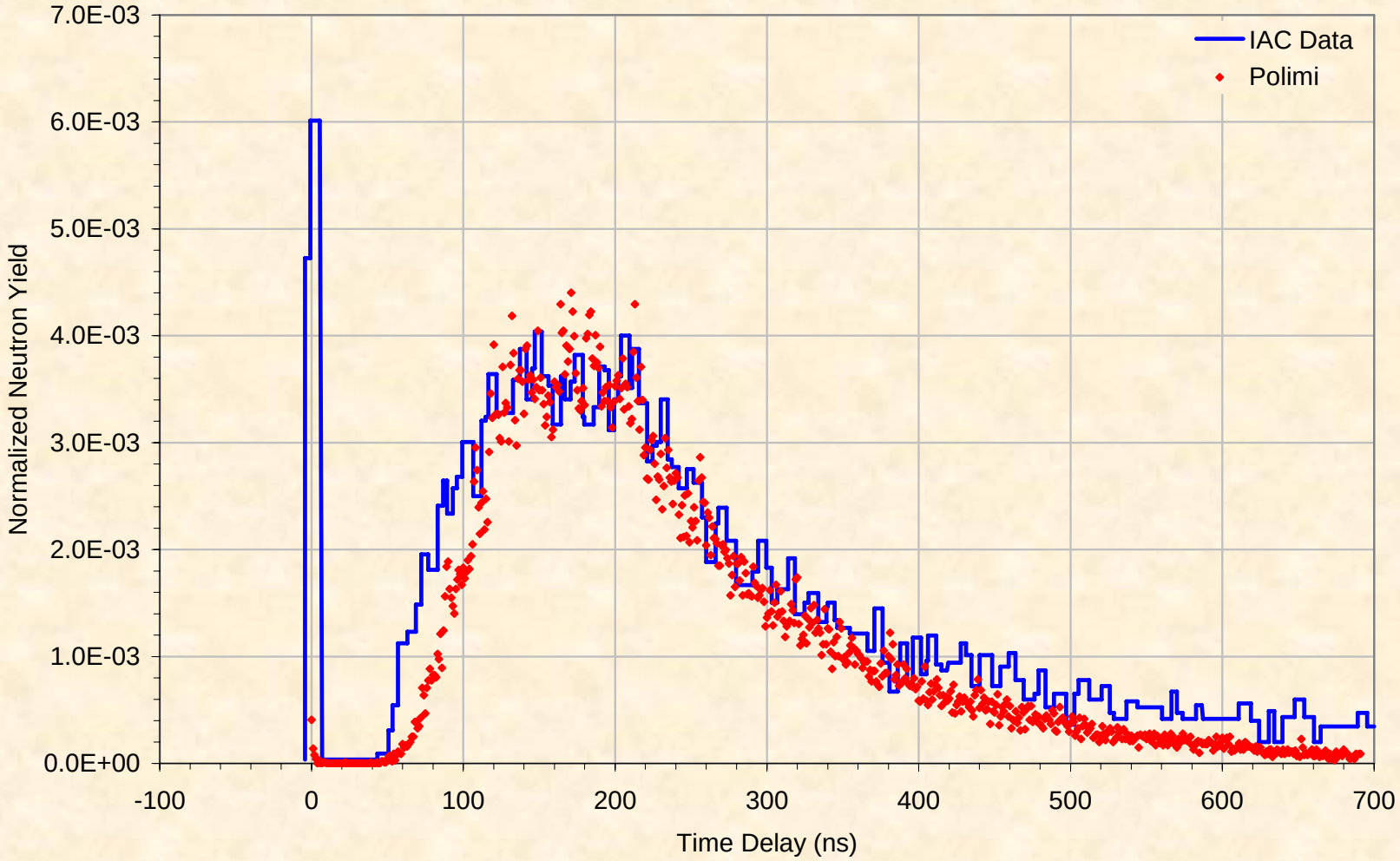
MCNP-PoliMi Results

Comparison to IAC Data for 1.11-m Case



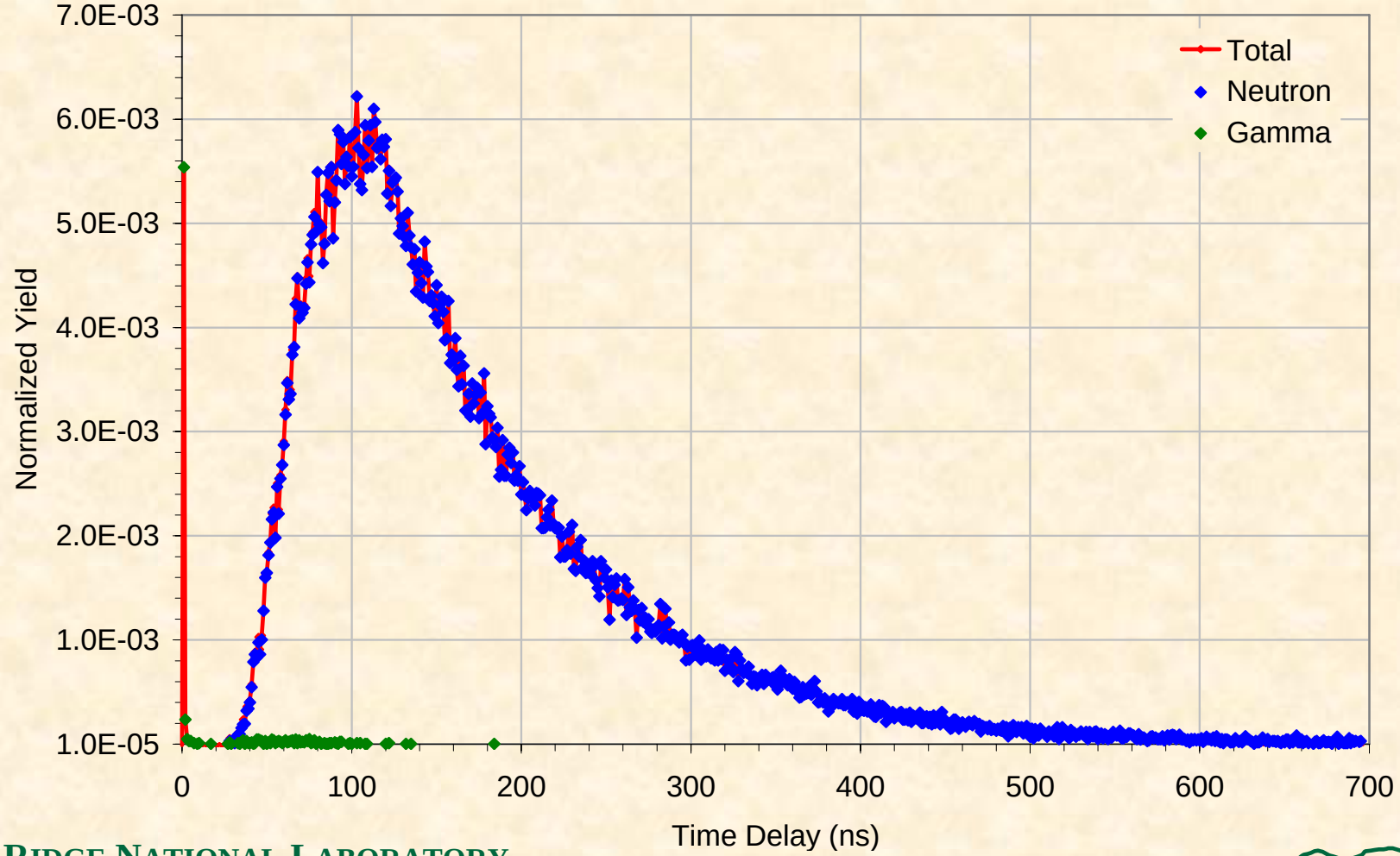
MCNP-PoliMi Results

Comparison to IAC Data for 2.01-m Case



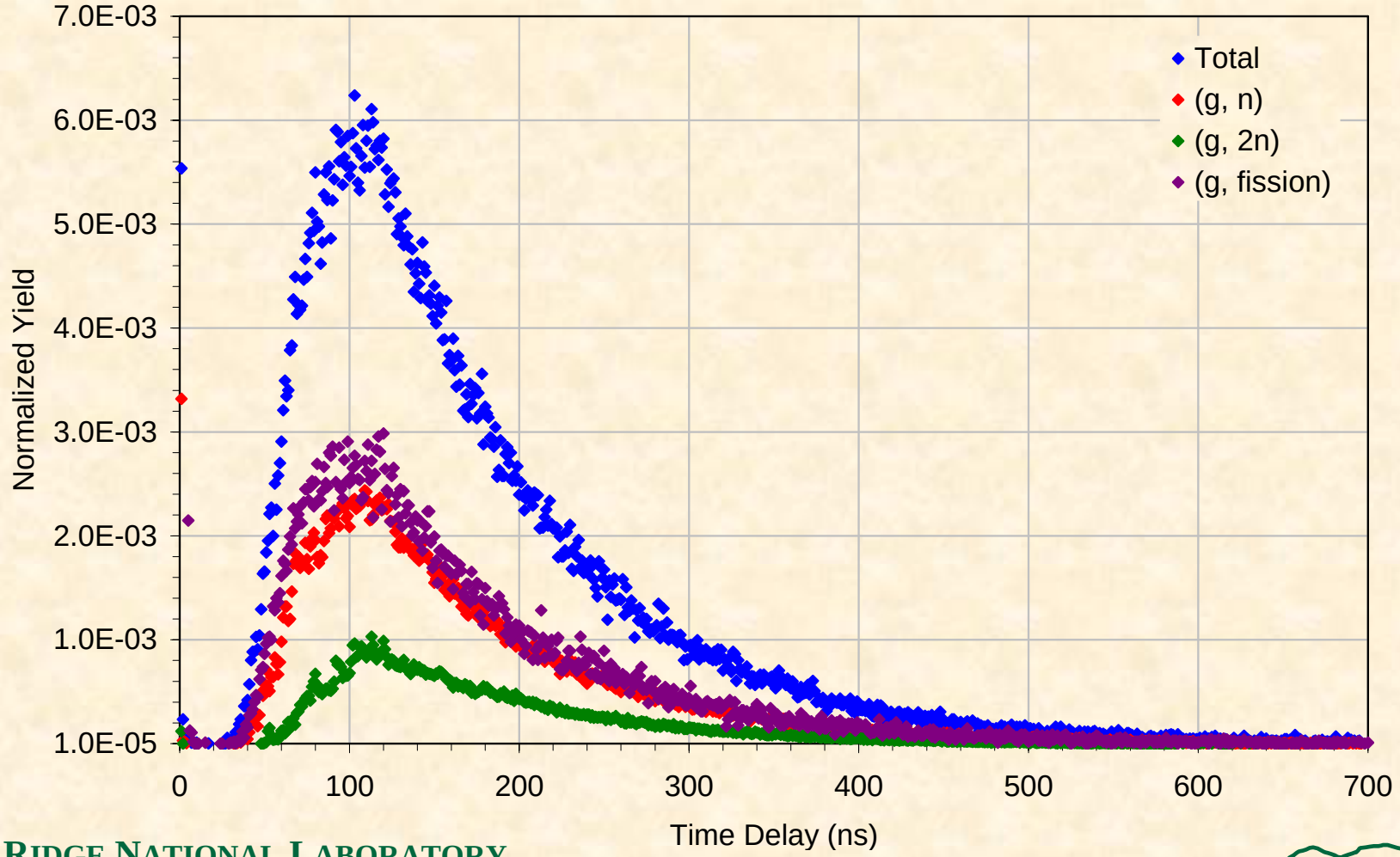
MCNP-PoliMi Results

Separate Neutron and Gamma Contributions



MCNP-PoliMi Results

Separate Reaction Contributions

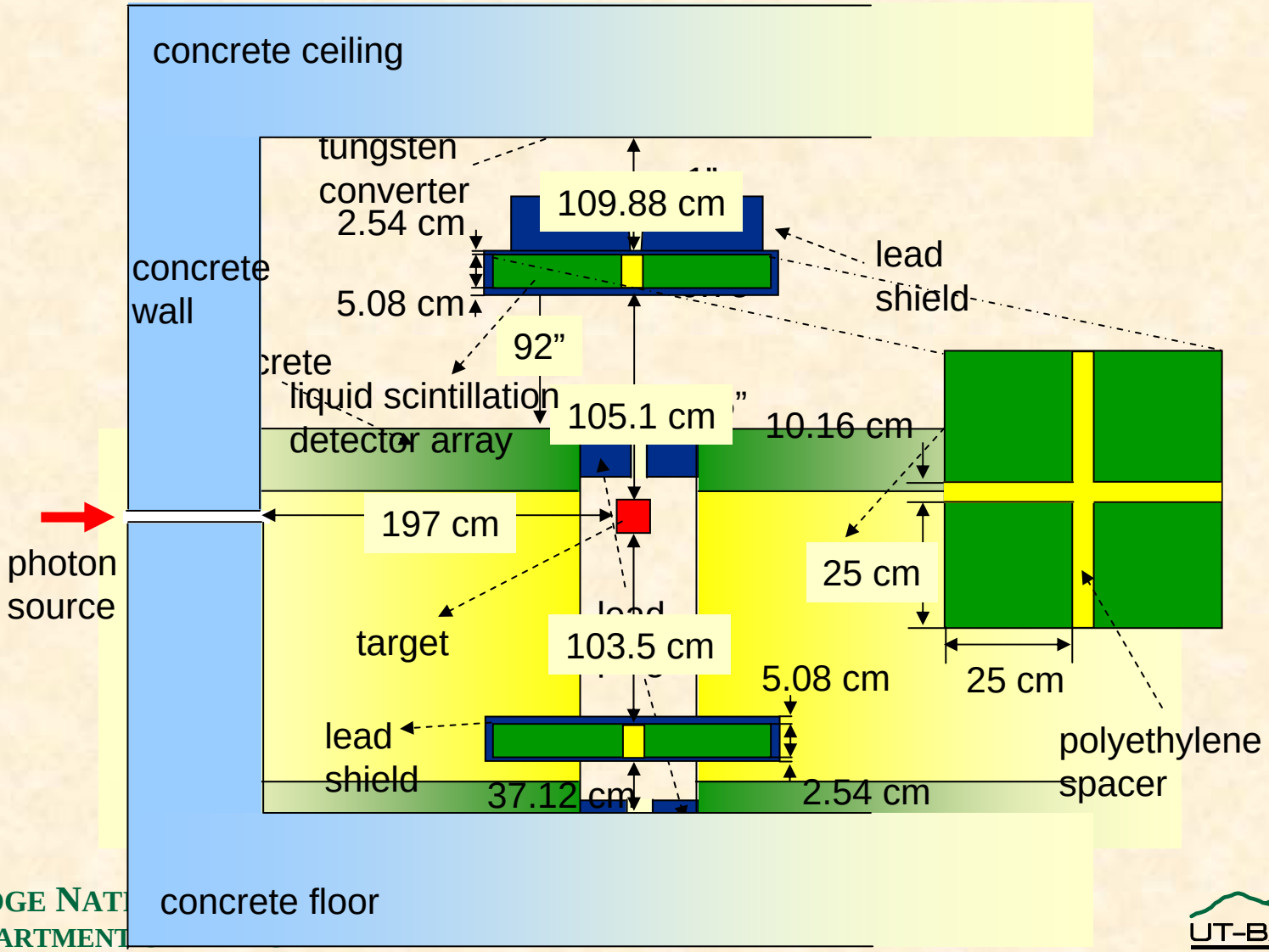


Analysis of Simulation Results

- There is a small (~10 ns) time delay in the leading edge of the correlation function
  - There could still be some disagreement in exact system geometry
- Further discrepancy at later times can be attributed to scattering sources not represented by our model such as the table and floor
  - Detection at later times is limited by the detector threshold, which also required some assumptions here
- Additional information needed
  - Accelerator pulse time width (not modeled in the simulations)
  - Threshold of the detectors
  - Timing of detector photomultiplier tubes

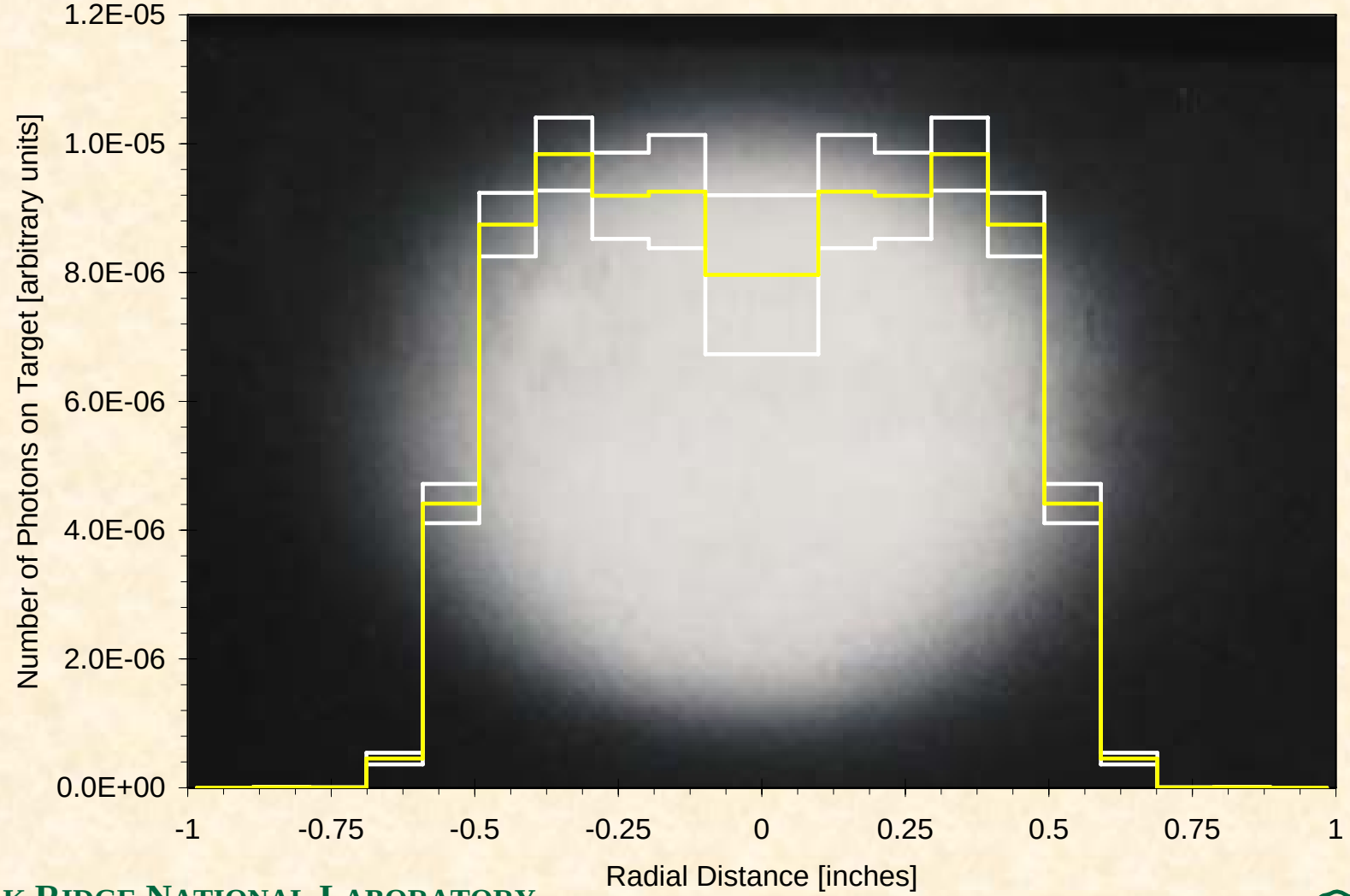
New Experimental Setup

Collimator Model



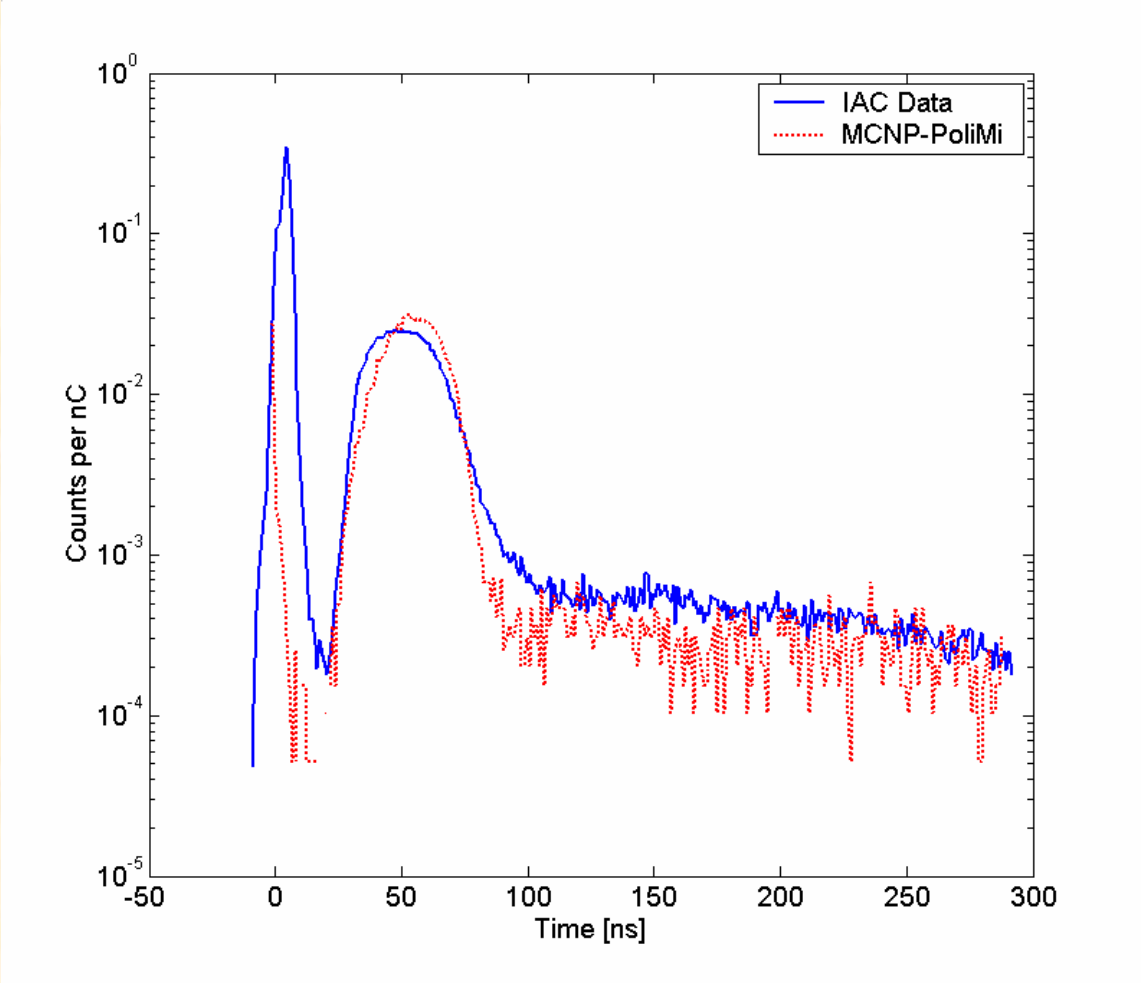
Collimator Model

MCNPX Result



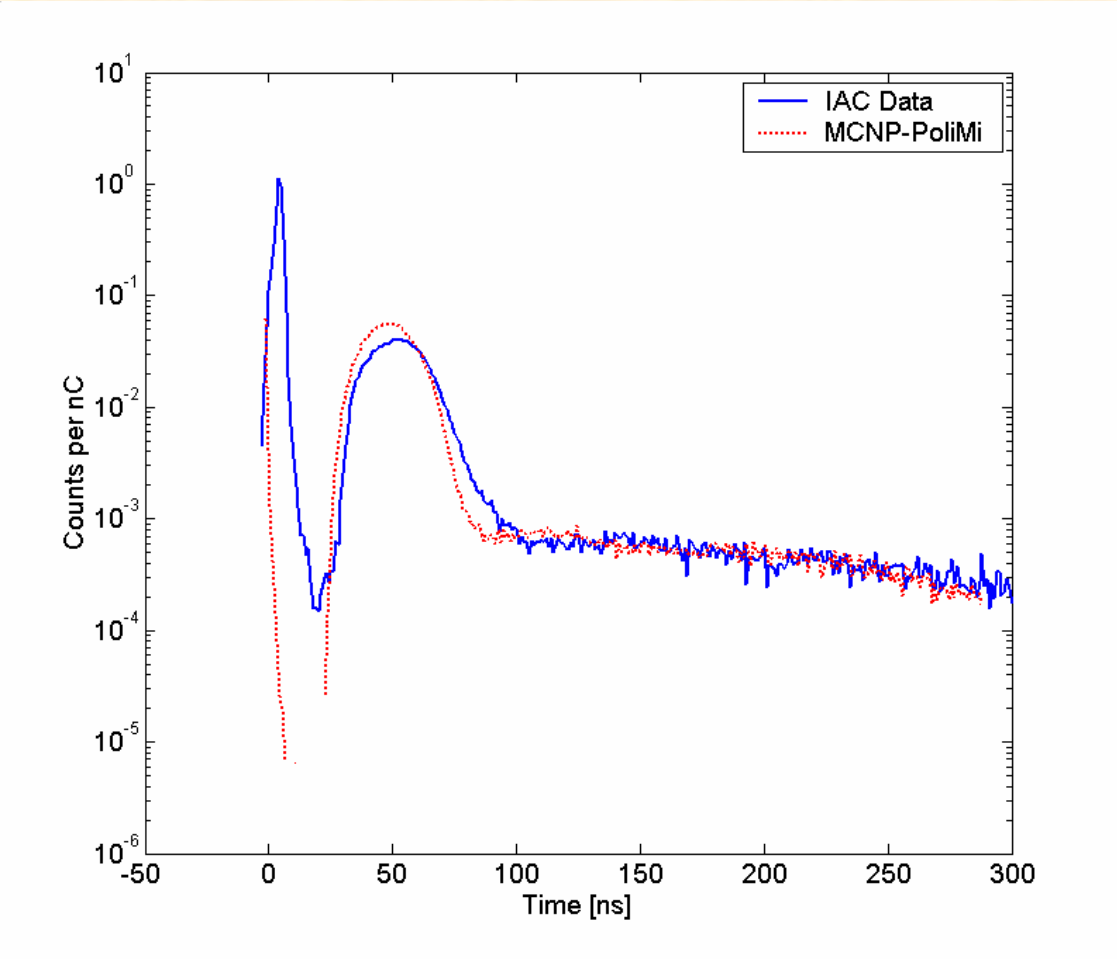
Depleted Uranium Sample

Correlated Counts per nC



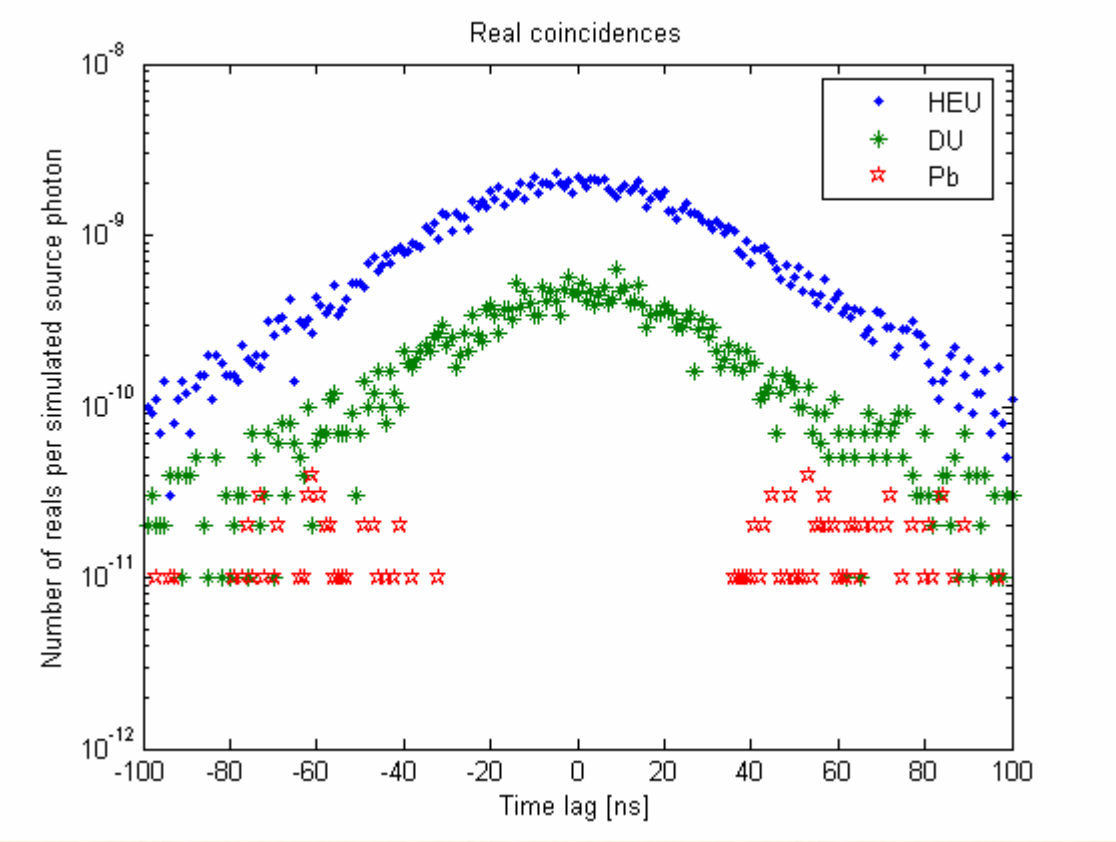
Lead Sample

Correlated Counts per nC



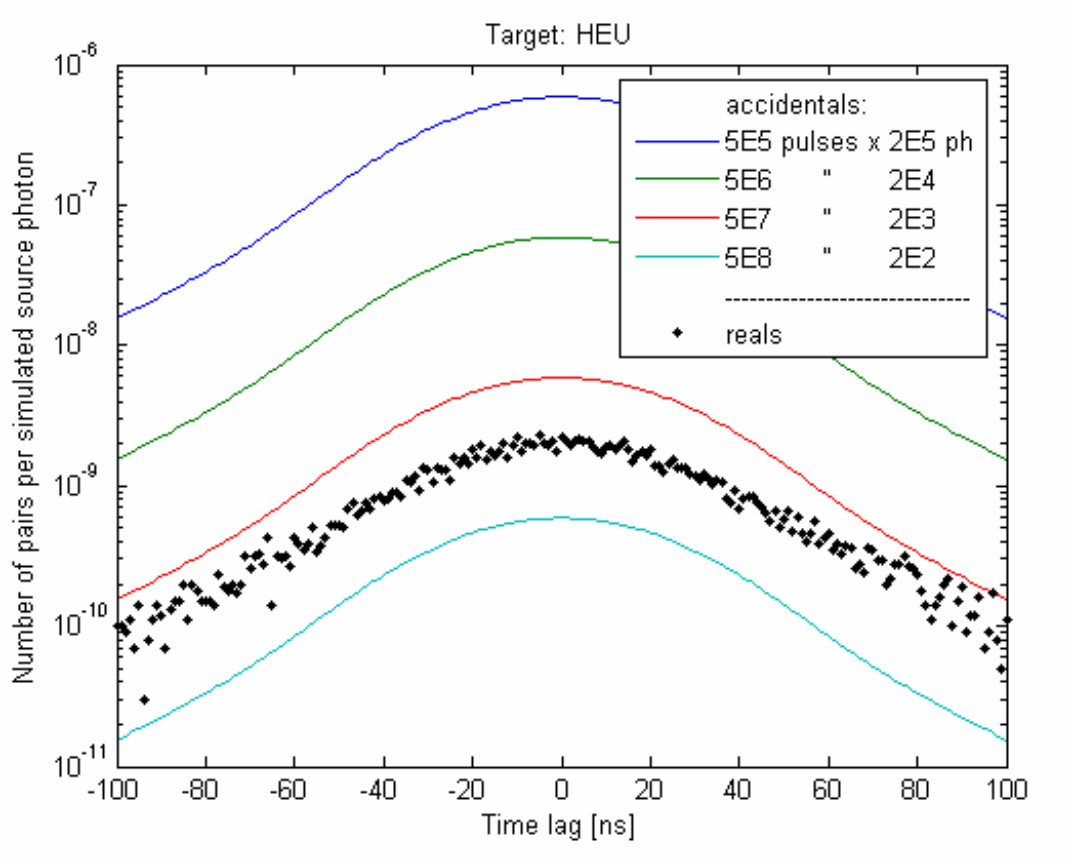
Detector-Detector Time Correlation Distribution of Particles

Real Coincidences: HEU, DU, and Pb



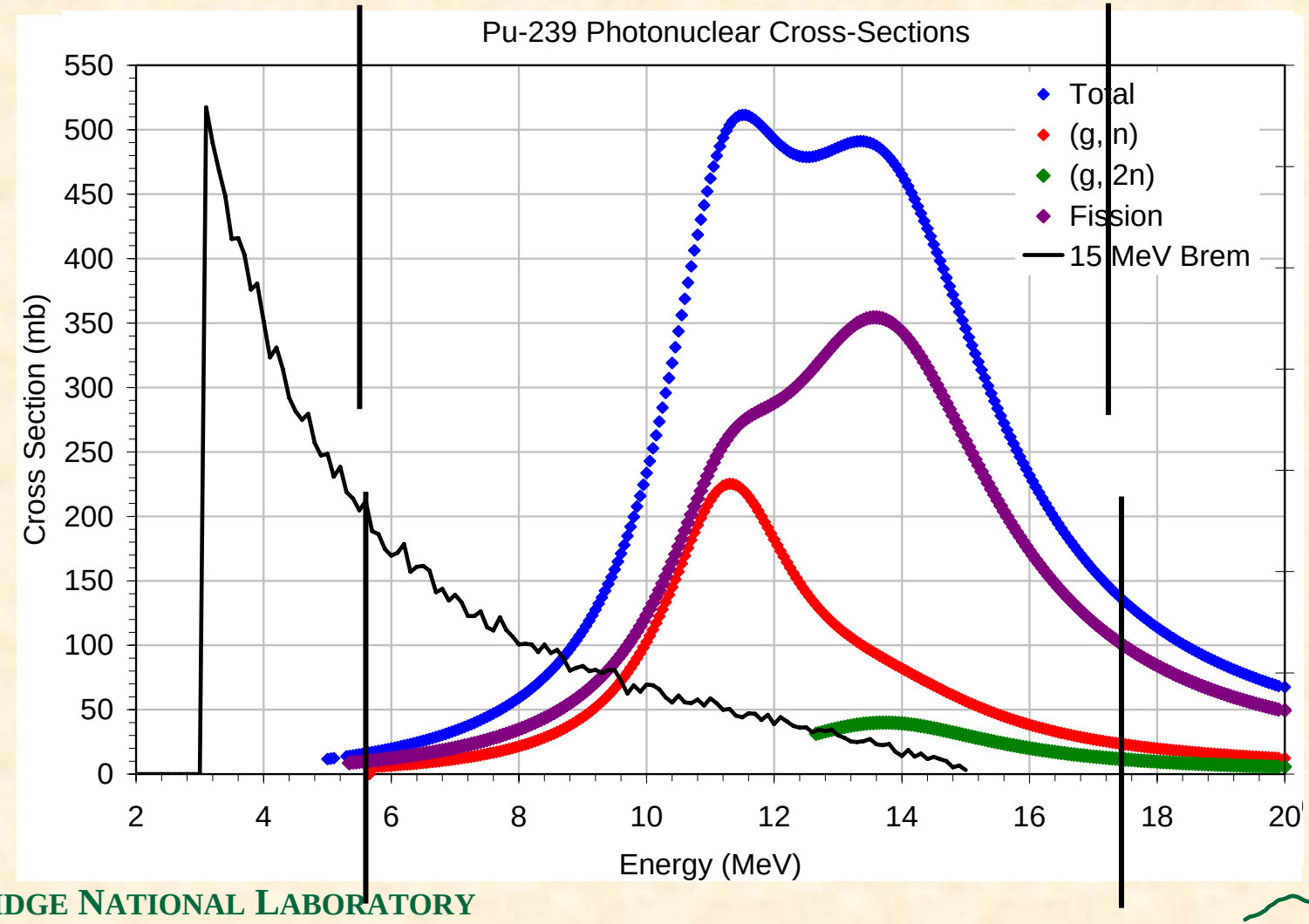
- Shows the distribution of real coincidences in the two detectors for targets composed of HEU, DU, and Pb
- Note, the real coincidences in the HEU are approximately a factor of 10 greater than in the DU
- Accidental coincidences are calculated separately

Distribution of Accidental Coincidences: HEU Target

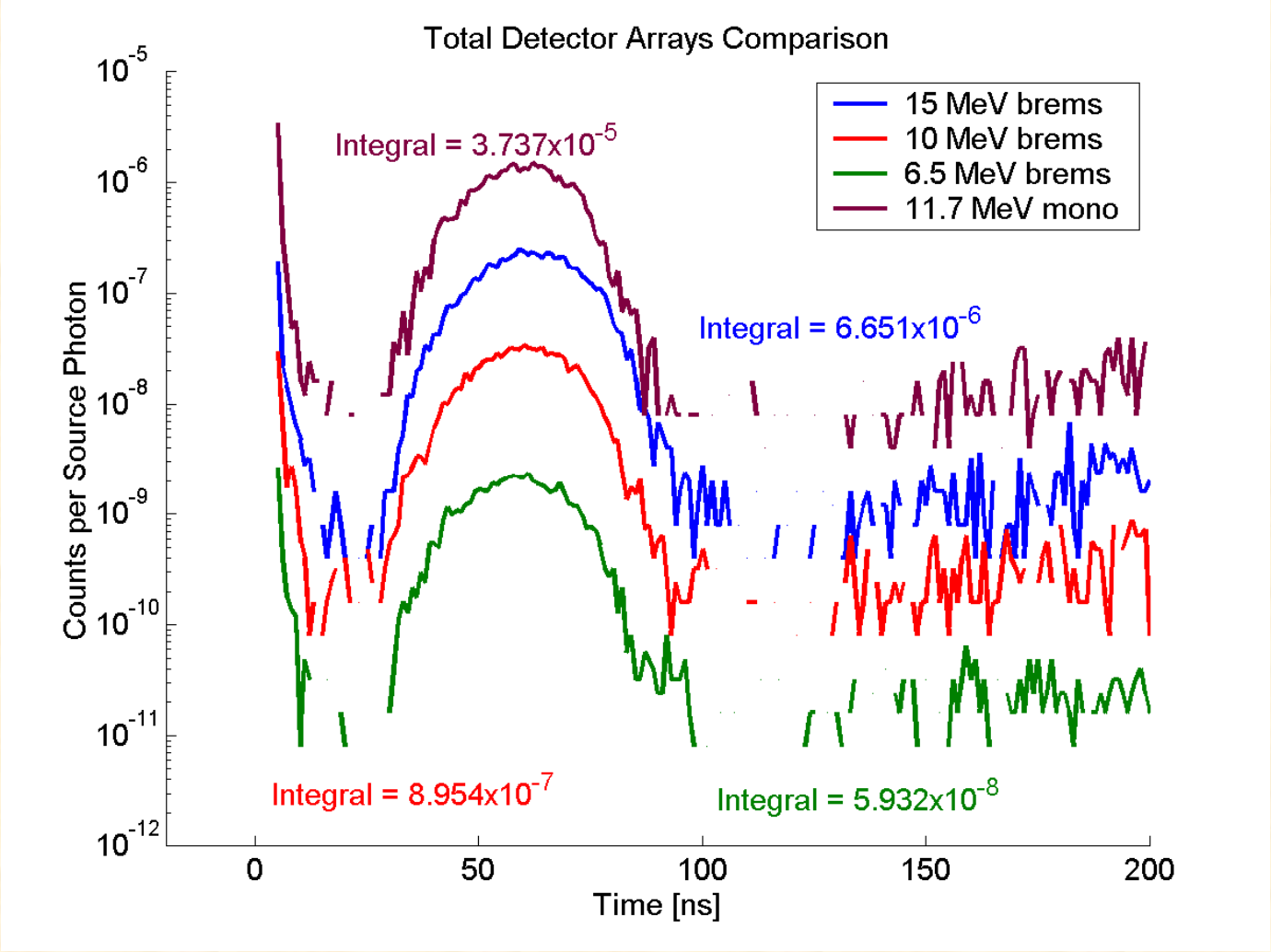


- Real coincidences are more than the HEU, but accidental coincidences go up, too
- Only the case with N=5e8 pulses each of M=200 photons shows a distribution of accidentals that is **less than** the real coincidences
- At a rep rate of 120 Hz, the measurement would last 48 days
- At a rep rate of 100 kHz, the measurement would last ~80 mins

Advantages of a Monoenergetic Source



Advantages of a Monoenergetic Source HEU Target



Conclusions

- Modified MCNP-X/MCNP-PoliMi codes are unique tools that are instrumental in the simulation of scenarios that are of interest to homeland security and nuclear nonproliferation
  - Can correctly simulate the neutron and photon field generated in active interrogation using neutrons and photons
  - Not only average quantities, such as fluxes, but also higher order statistics: correlations, multiplicities, etc.
- A specialized post-processing code is used to accurately model detector response
- Comparisons of experimental data and code results show good agreement

Future Work

- Evaluate and implement data for delayed secondary gamma rays from photofission events to use with MCNP-X/MCNP-PoliMi
- Evaluate the feasibility of neutron and gamma-ray multiplicity measurements with multiple detectors (up to 8)

Future Work (cont.)

- Combine the modified MCNP-X and MCNP-PoliMi codes and modify the new MCNP-X version
  - Parallel version of modified MCNP-X
- Extend and validate the post-processing code for more detector types: germanium, capture-gated organic scintillators, helium-3, etc.

Research Team

This work is the result of a vibrant collaboration among institutions within and outside the United States

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Collaborations with other Institutions:

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- Alan Hunt, Idaho State University

Novel Active Interrogation Techniques for the Detection of Special Nuclear Material

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Oak Ridge National Laboratory

February 8, 2007
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