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Development of an Optimized Converter Layer for a Silicon-Carbide-Based Neutron Sensor for the Detection of Fissionable Materials

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Motivation

We are developing a thin neutron detector for applications including decommissioning at Fukushima Daiichi. We are developing a system based to detect fast and thermal neutrons using a SiC detector and SiC front-end amplifier. Here we evaluate candidate converter layers for thermal neutron detection by means of Monte Carlo simulation using MCNP 6.2. We also make preliminary investigation of gamma rejection as well as comparison with simulations using Geant4 10.05.01.

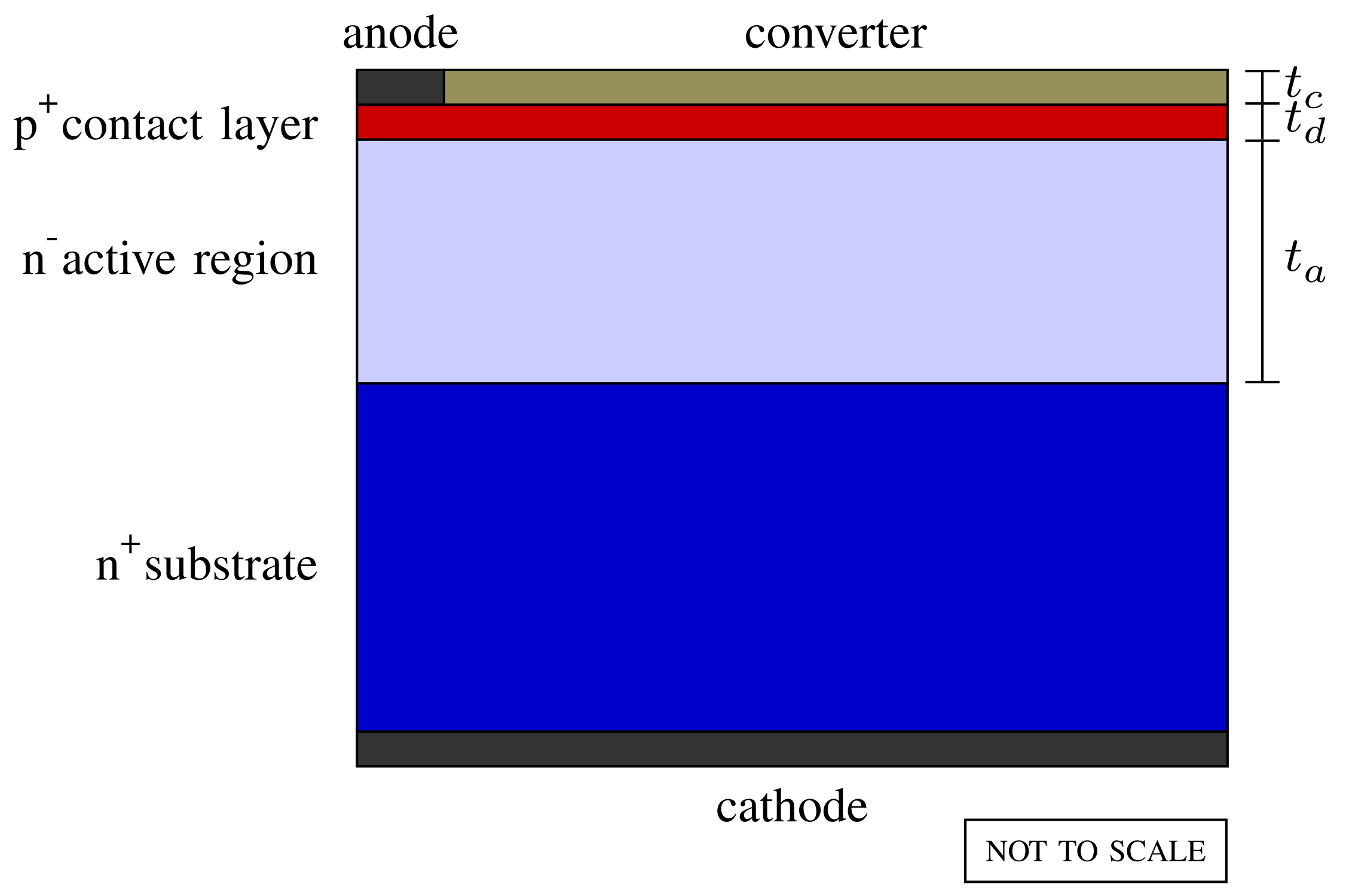
Key requirements

We require neutron sensitivity and gamma rejection in a very small device.

	nominal	localised worst case	
neutron fluence rate	10^7	10^{13}	$cm^{-2}\,s^{-1}$
gamma dose rate	0.1	1000	$Gy\,h^{-1}$
temperature	>60		°C
humidity		100	%
thickness	<3		mm

SiC detector construction

Our detector is a SiC PN diode with mesa structure and a planar converter layer, operated with reverse bias to full depletion. We consider active region thickness t_a in the range from 5 μm to 20 μm.

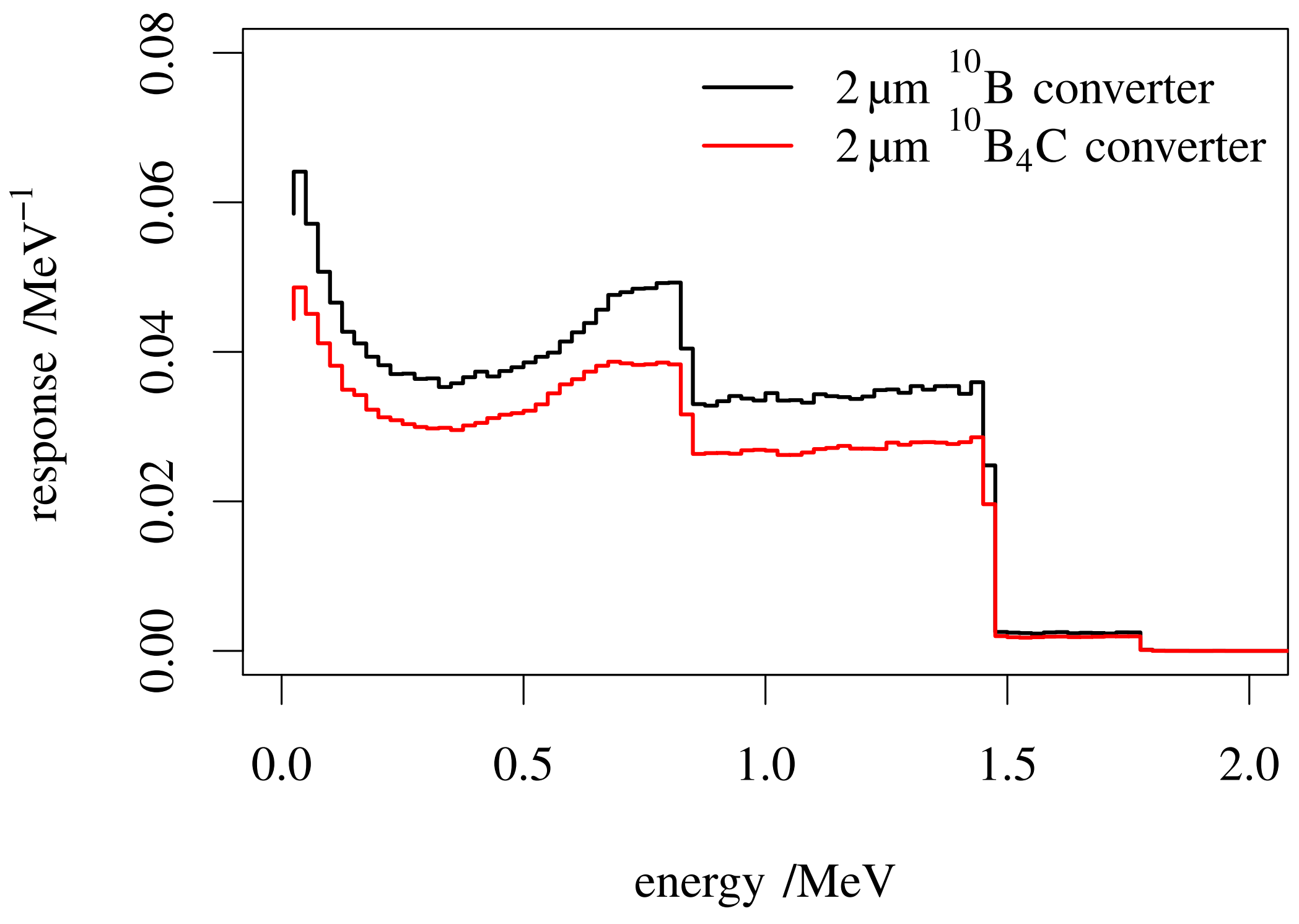


Detector area up to 1 cm×1 cm and active layer depth ∼10 μm gives capacitance ∼1 nF and r.m.s. $\sqrt{kTC}$ noise equivalent to ∼100 keV deposited in the SiC active region. We expect a lower limit of detection $\gtrsim$300 keV.

Candidate converter materials

Converters based on ^{6}Li, ^{10}B, and Gd were considered.

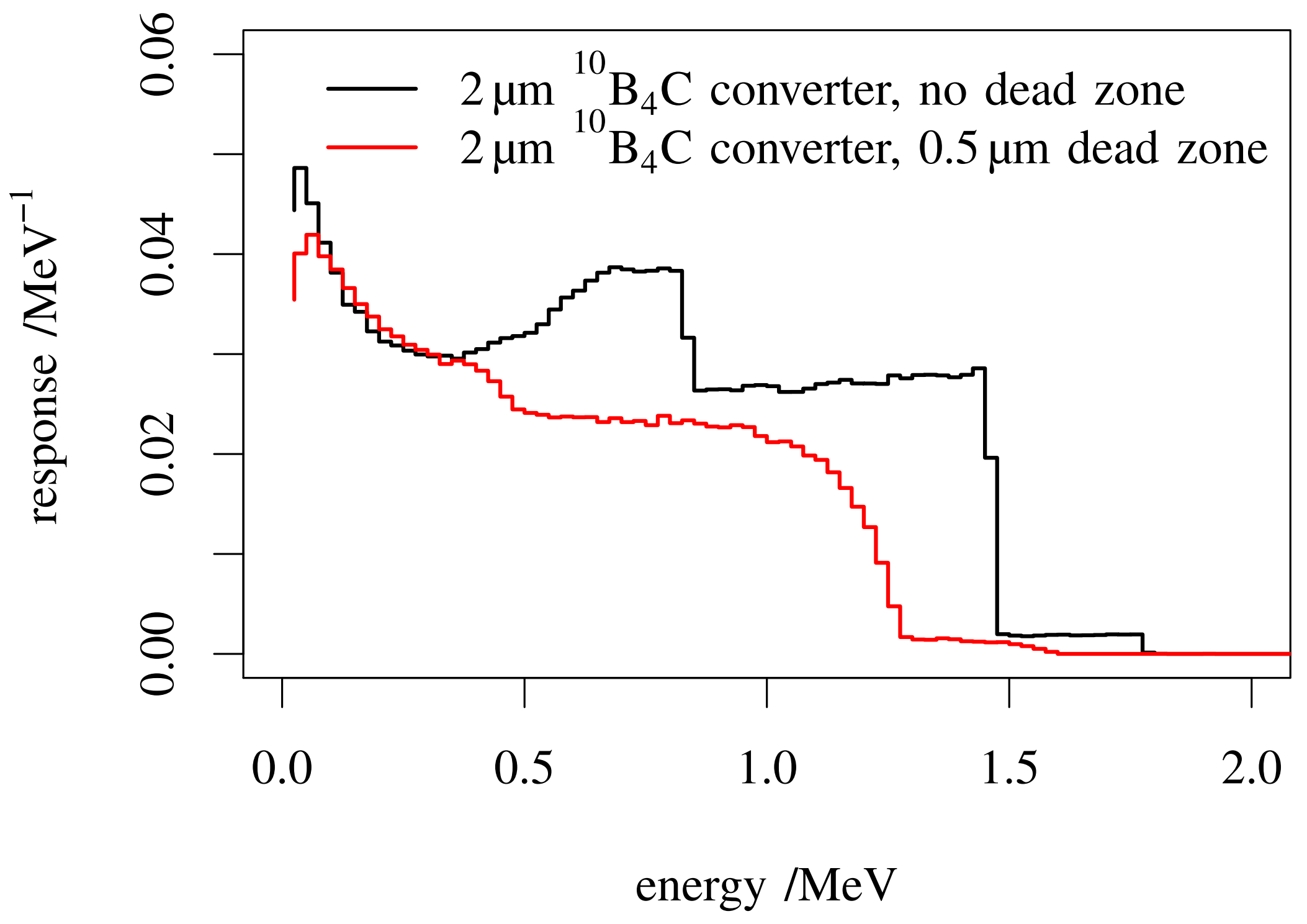
- Gd was excluded as the energies of its reaction products are below the lower limit of detection.
- Converter layers of ^{6}LiF, ^{10}B and $^{10}B_4C$ were investigated by Monte Carlo simulation using MCNP 6.2.
- ^{10}B was preferred to ^{6}Li for availability and efficiency, especially in thinner detectors.
- $^{10}B_4C$ is ∼80% as effective as ^{10}B and is available to us. $^{10}B_4C$ is our preferred converter material.



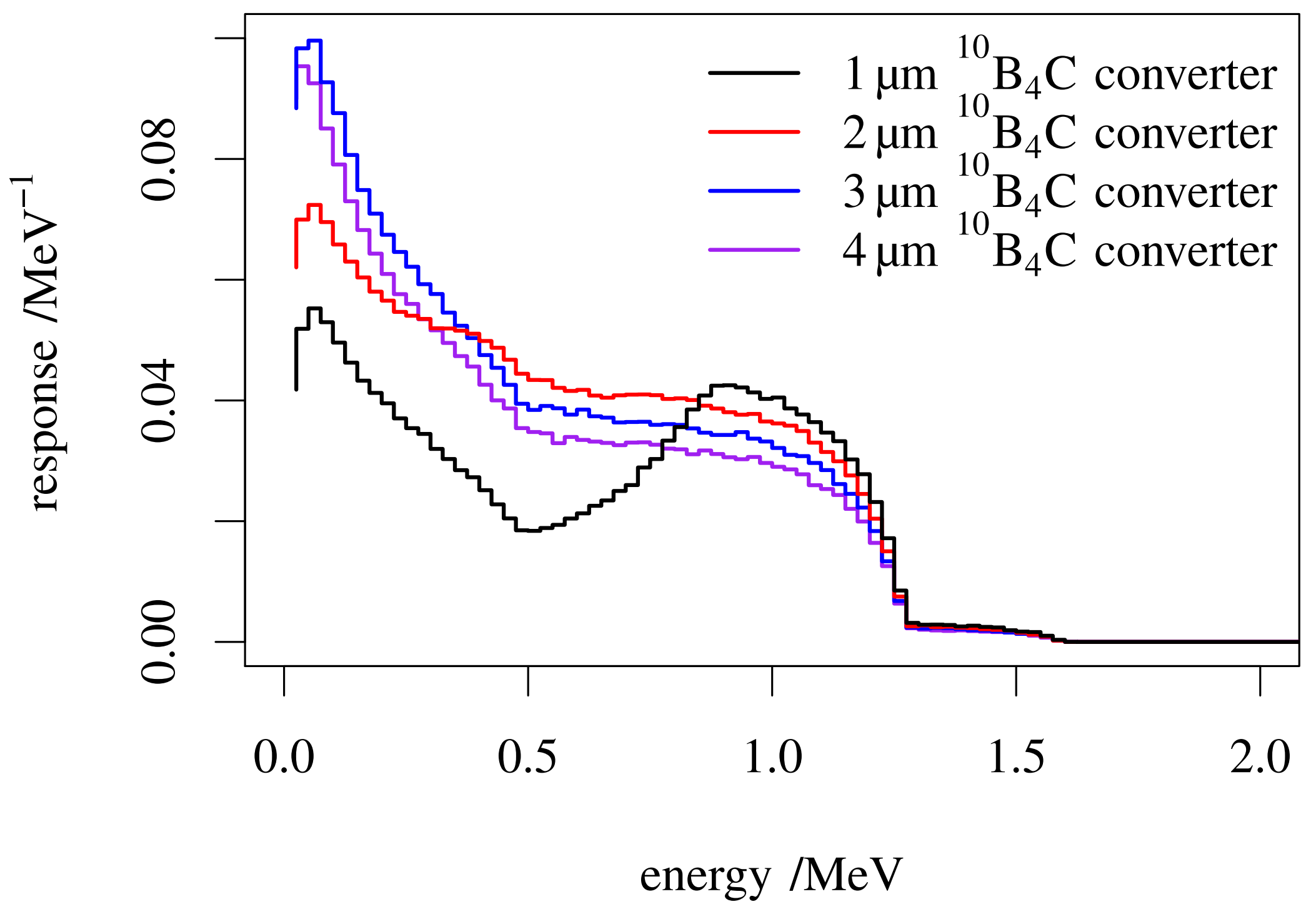
Detector geometry

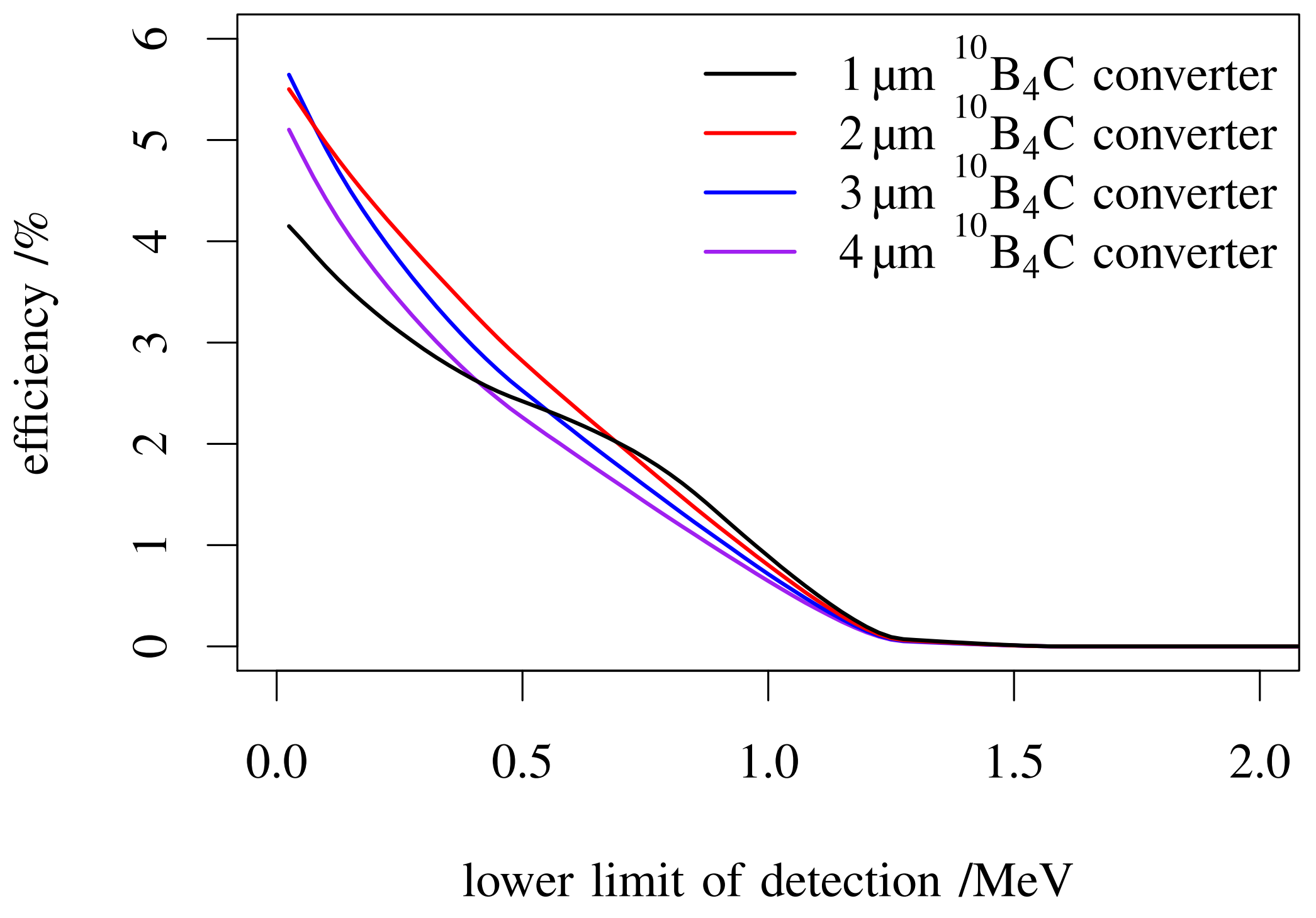
All $^{10}B(n,\alpha)^7Li$ reaction products have range <5 μm in SiC. Energy deposition in the active region is unaffected by active region depth in this case. The thicknesses of both converter and contact layers do affect response. We consider converter layer thickness t_c in the range from 1 μm to 4 μm, contact layer (dead zone) thickness t_d in the range up to 0.5 μm.

A 0.5 μm p^+ contact layer (dead zone) stops almost all the lithium ions and reduces detection efficiency by about half.

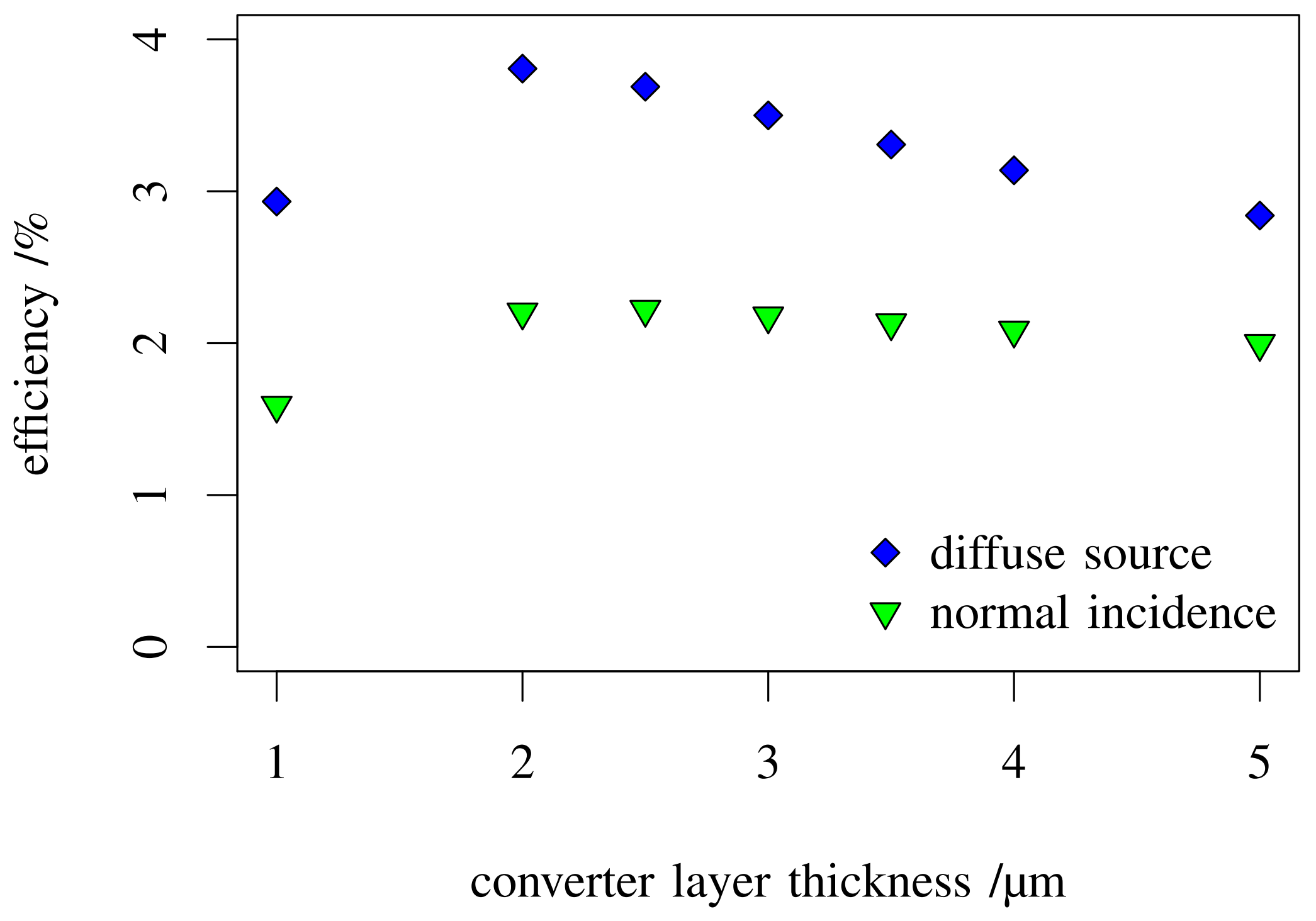


A 2 μm $^{10}B_4C$ converter layer maximizes detection efficiency over a wide range of detection thresholds in a detector with 0.5 μm p^+ contact layer.



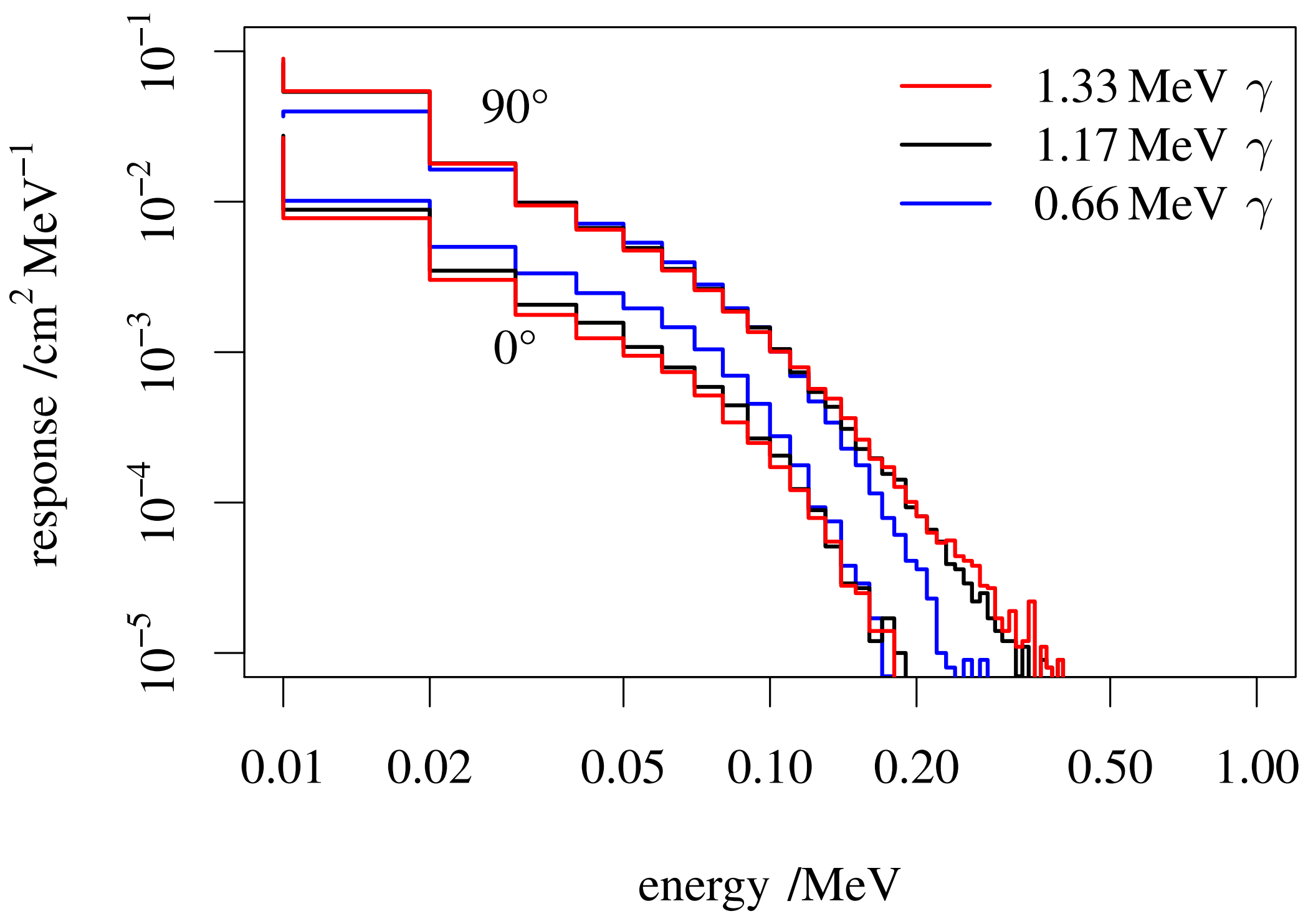


Normal incidence is the worst case for neutron detection efficiency, as neutrons have the shortest path through the converter. Response to a diffuse (Lambertian) source is about twice as strong.



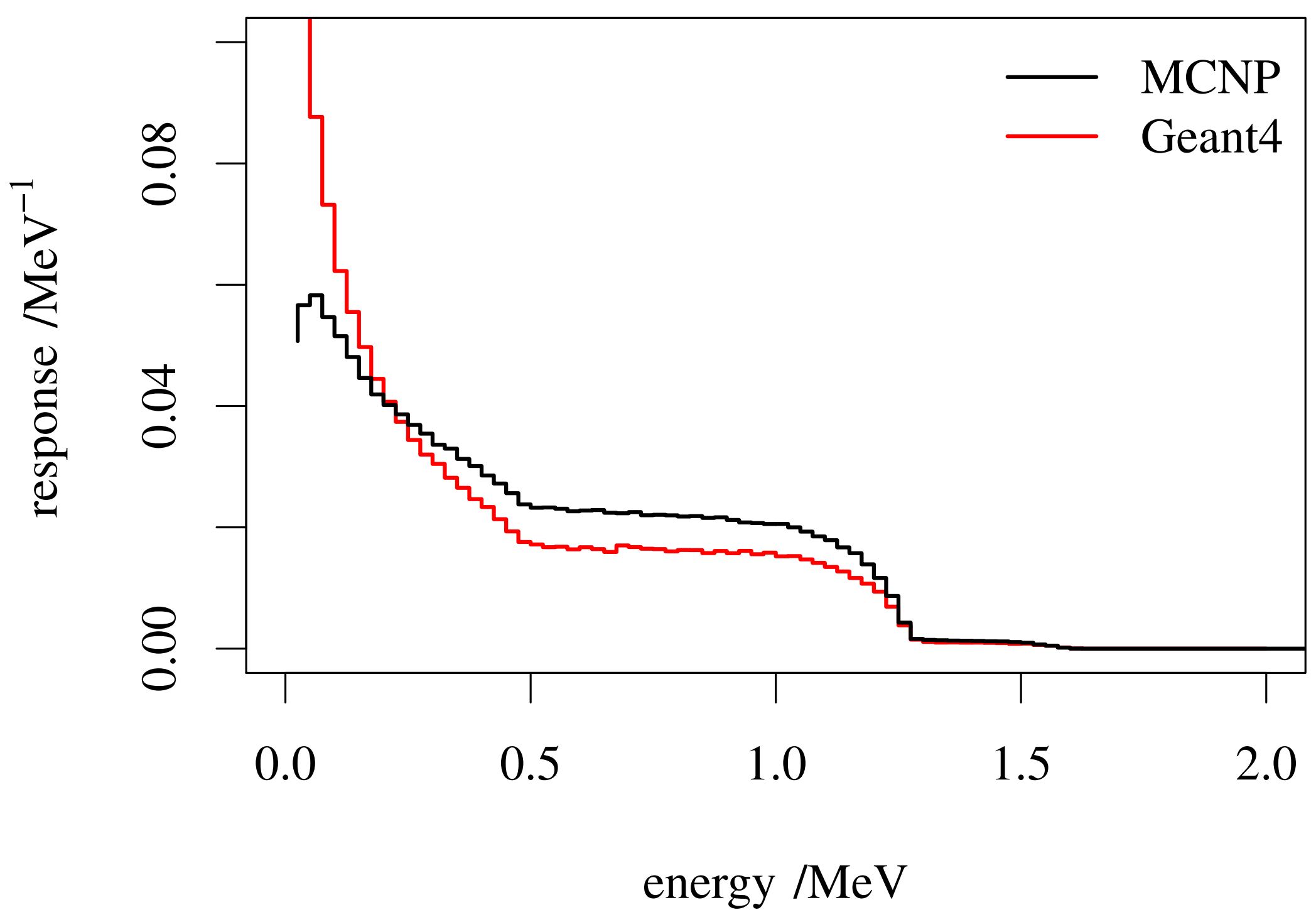
Gamma response

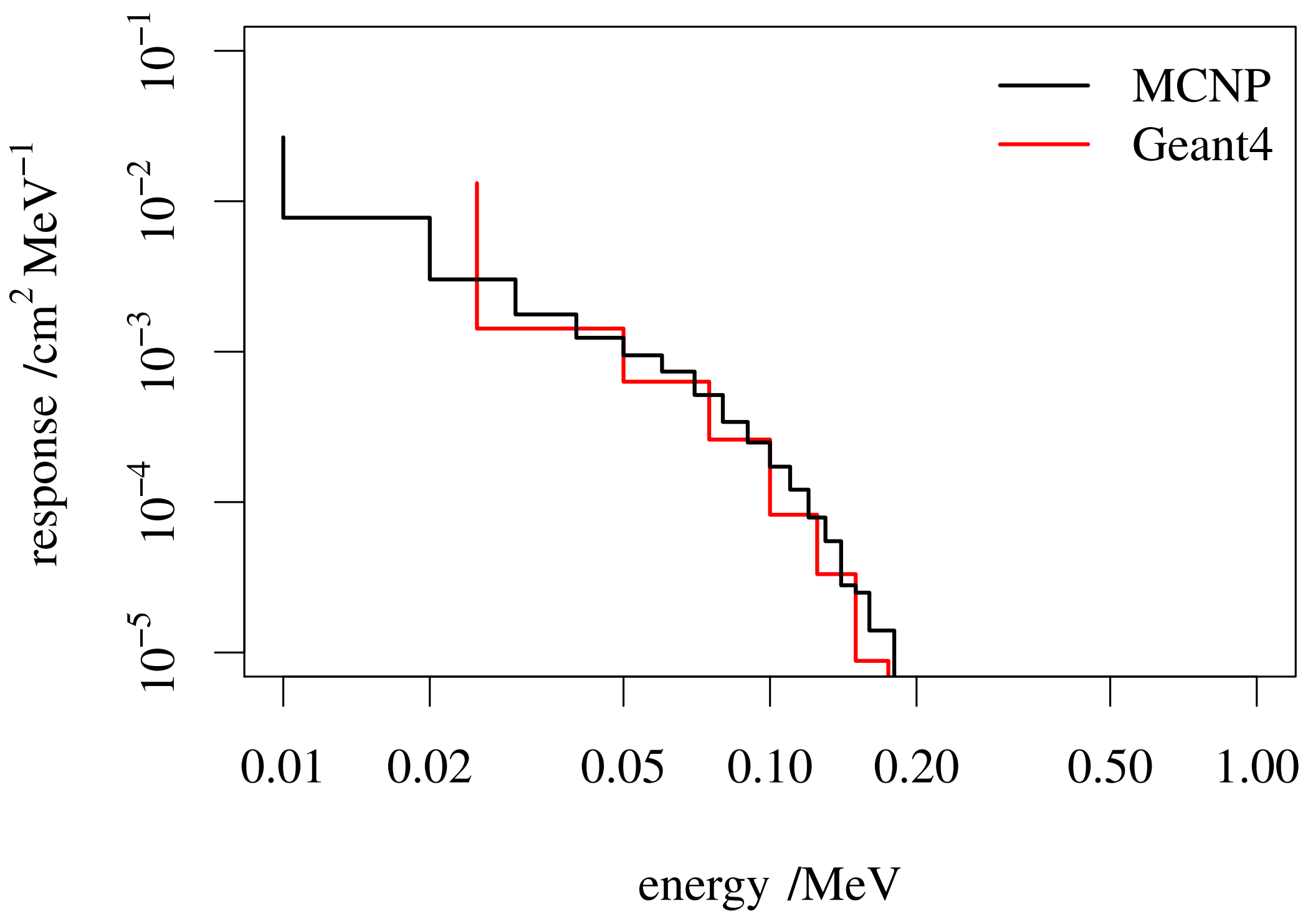
Few gamma interactions lead to pulses above likely detection thresholds. However, high gamma background is expected to lead to substantial photocurrent and reduced noise margin.



MCNP/Geant4 comparison

MCNP 6.2 and Geant4 10.05.01 simulations agree qualitatively. High-precision neutron physics and step limiting were used in the Geant4 simulations to ensure comparability. Neutron detection efficiency as calculated using Geant4 is about 25% less than that calculated using MCNP. Gamma responses agree closely.





Summary

Decommissioning the Fukushima Daiichi nuclear power plant has identified a requirement for a thin neutron detector system with good gamma rejection. MCNP simulations show that a silicon carbide PN diode with a ^{10}B-enriched boron carbide converter layer can achieve an intrinsic efficiency for thermal neutron detection approaching 4%, assuming a detection threshold compatible with thermal noise from a large-area detector with capacitance ∼1 nF, with strong gamma rejection.

At the time of presentation, a prototype $^{10}B_4C$:SiC detector is in fabrication.

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