JULY 19–22 2026 VANCOUVER, BC
JOINT AAPM | COMP MEETING

Monte Carlo-Based Feasibility Study of Large-Area 2D Micromegas Detector for Real-Time Beam Monitoring in Boron Neutron Capture Therapy

Tianhe Lu[1], Zirui Ye[1], Yuxing Wang[1], Meitong Wei[1], Xie George Xu[1]
School of Nuclear Science and Technology, University of Science and Technology of China[1], Hefei 230026, China

ABSTRACT

Boron neutron capture therapy (BNCT) currently lacks an effective method for real-time neutron beam monitoring during treatment.

This study evaluates the feasibility of a large-area two-dimensional Micromegas detector for in-beam BNCT quality assurance using a Geant4-based virtual clinical trial framework. A clinically representative neutron source, beam shaping assembly, Micromegas detector, and patient phantom were modeled to assess detector radiation damage, material activation, and activation-induced dose.

The annual Micromesh displacement damage remained below 1×10^{-7} dpa, while the PCB absorbed dose did not exceed 20.25 Gy. Prompt and delayed gamma emissions were characterized, with ^{56}Mn identified as a major delayed-gamma contributor. The estimated staff dose was approximately 10^{-7} mGy per operation and was reduced to 1.24×10^{-9} mGy through material and structural optimization.

These results support the safety, durability, and clinical feasibility of Micromegas-based real-time BNCT beam monitoring.

CONTACT

[name]: Tianhe Lu
[organization]: School of Nuclear Science and Technology, University of Science and Technology of China
[email]: maslth@mail.ustc.edu.cn
[phone]: +86 18315578159

INTRODUCTION

BNCT requires stable and spatially uniform neutron beams to ensure accurate dose delivery, yet current activation-based QA methods are performed offline and cannot provide real-time two-dimensional beam information.
Micromegas detectors offer large active area, high counting-rate capability, and millimeter-scale spatial resolution, making them promising candidates for in-beam neutron monitoring.
In this work, a Geant4-based virtual clinical trial framework was established to evaluate radiation damage, neutron activation, and clinical feasibility of a large-area 2D Micromegas detector.

METHODS AND MATERIALS

Simulation geometry and clinical use scenario

A Geant4-based virtual clinical trial framework was established to simulate realistic BNCT treatment conditions and evaluate detector performance.

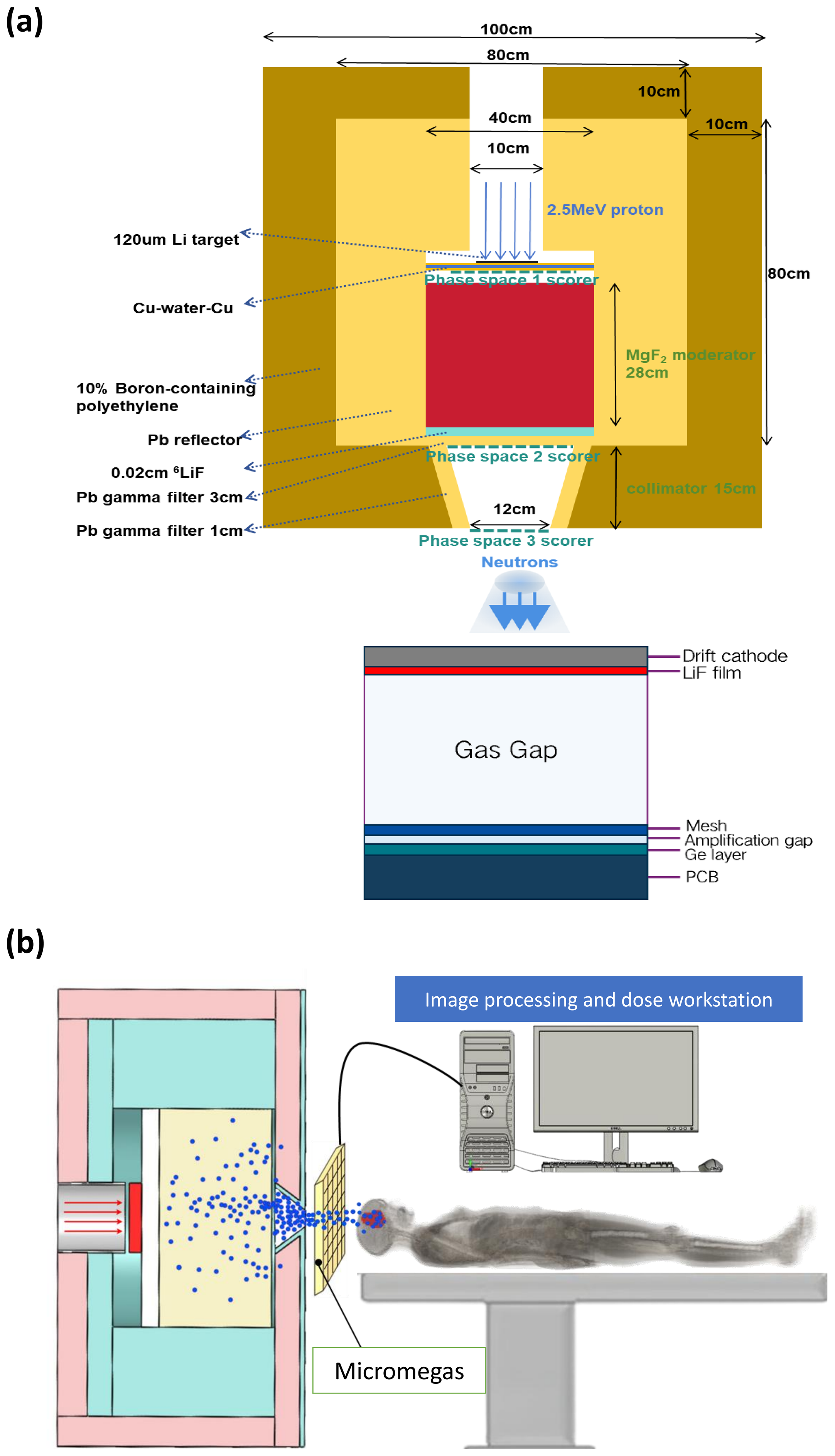

Figure1: Monte Carlo-based virtual clinical trial framework. (a) Geant4 model of BNCT neutron source, BSA, and Micromegas detector geometry. (b) Clinical deployment scenario for in-beam monitoring and radiation safety evaluation.

RESULTS

The Micromegas detector was evaluated under clinically relevant BNCT conditions in terms of beam perturbation, gamma-ray production, neutron activation, radiation damage, and activation-induced staff dose.

Prompt and Delayed Gamma-Ray Characteristics

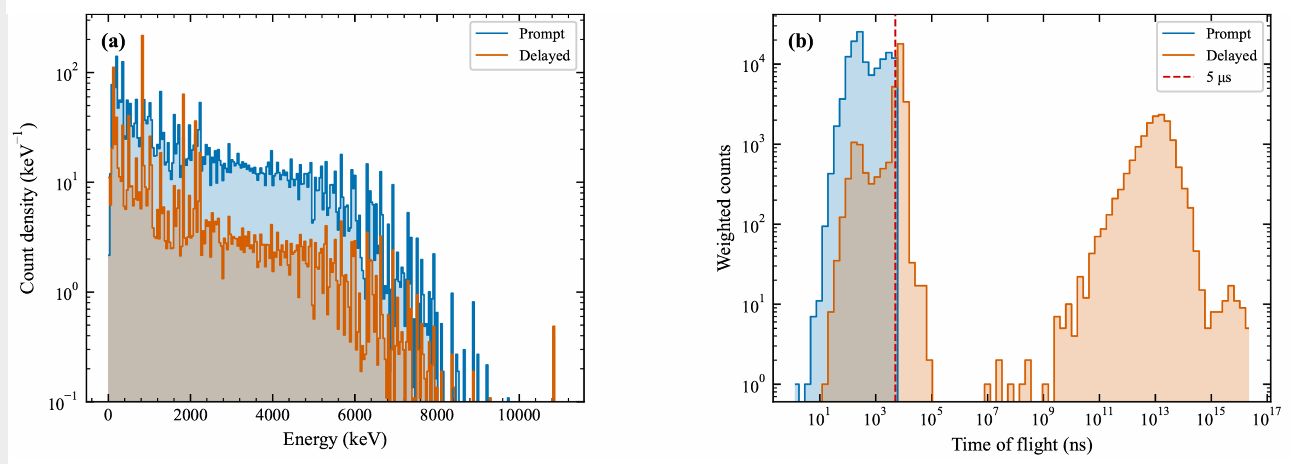

Figure2: Energy spectra (a) and time-of-flight distributions (b) of prompt and delayed gamma rays generated by neutron irradiation. A 5 μs time gate was used to separate the two components.

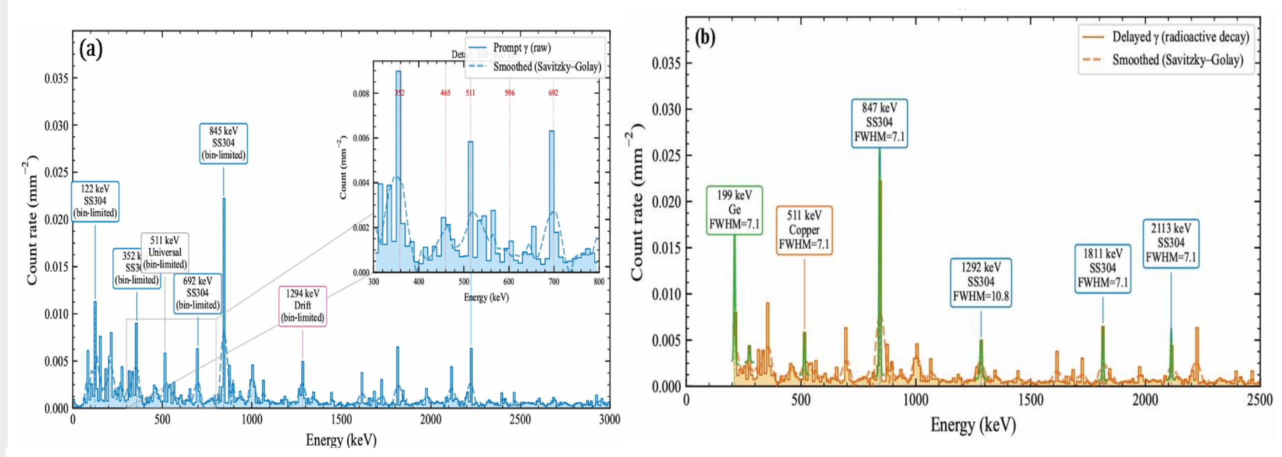

Figure3: Characteristic energy peaks of prompt (a) and delayed (b) gamma rays generated by neutron interactions and radioactive decay in detector materials. The dominant peaks are mainly associated with SS304 and copper components.

Radiation damage assessment

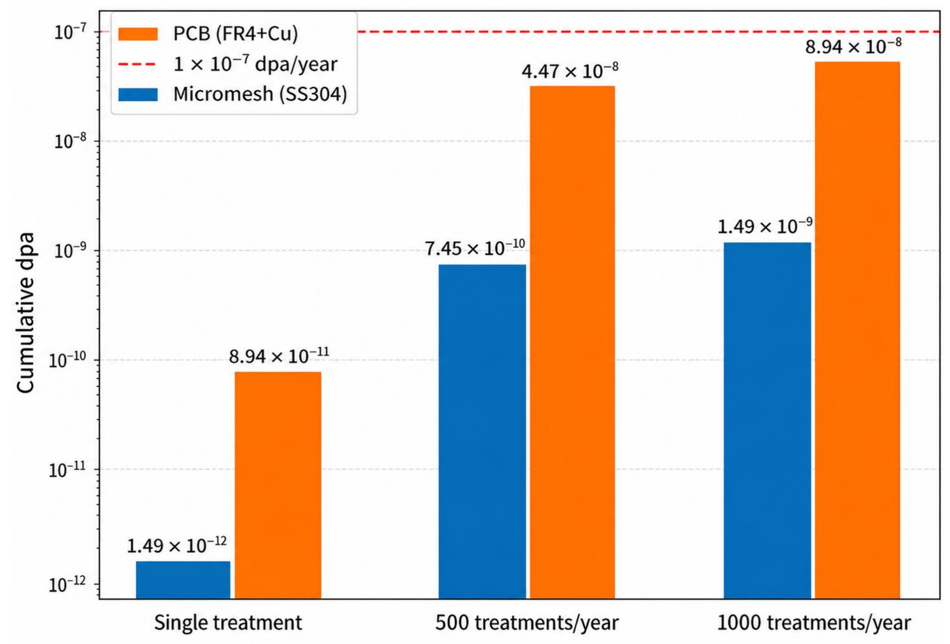

Figure4: Cumulative displacement damage under single-treatment and annual operating scenarios. At 1000 treatments/year, the calculated dpa values were 1.49×10^{-9} for the SS304 Micromesh and 8.94×10^{-8} for the PCB model.

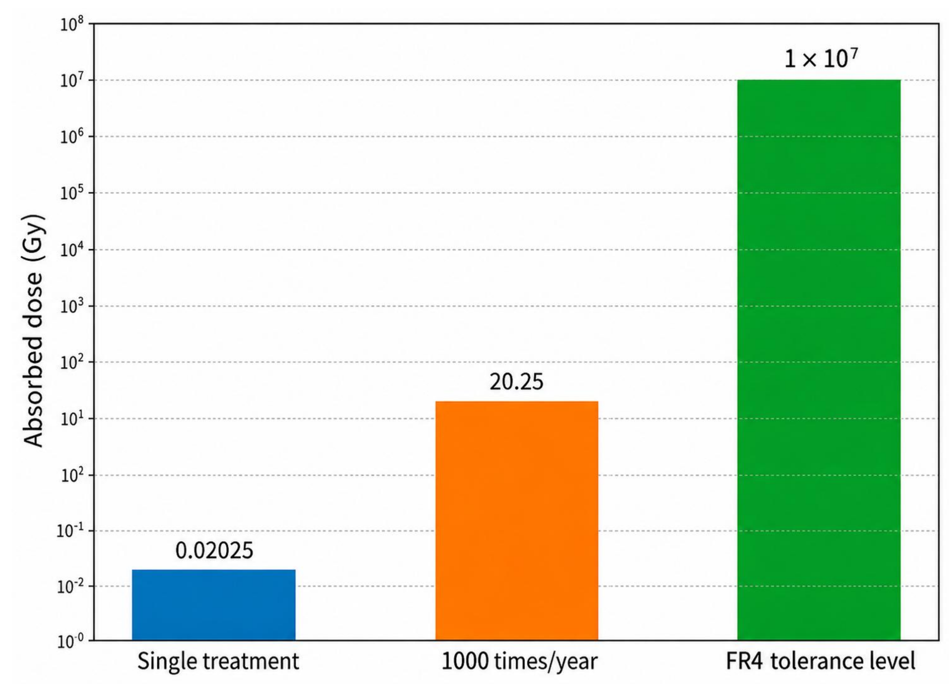

Figure5: Absorbed dose in the PCB for a single treatment and an annual workload of 1000 treatments. The annual dose of 20.25 Gy remained far below the 1×10^7 Gy FR4 tolerance level.

Simulate clinical scenarios

45-min treatment irradiation → 3-min waiting period before entering the treatment room → Staff remain in the treatment room for 2.5 min

Staff position: Approximately 2 m from the detector, with anterior–posterior (AP) irradiation

Neutron activation

Neutron activation mainly originates from SS304, copper, and metallic support components of the detector.

Major Reaction	Half-life	Detector Component
$^{55}Mn(n,\gamma)^{56}Mn$	$2.579\ h$	SS304 Micromesh
$^{63}Cu(n,\gamma)^{64}Cu$	$12.7\ h$	PCB copper layer
$^{65}Cu(n,\gamma)^{66}Cu$	$5.12\ min$	PCB copper layer
$^{40}Ar(n,\gamma)^{41}Ar$	$1.83\ h$	Detector gas (Ar)
$^{74}Ge(n,\gamma)^{75}Ge$	$82.8\ min$	Ge resistive layer

Table1: Major neutron activation reactions in the detector materials

Activation-induced dose was independently estimated using a water phantom, an ICRU sphere phantom, and ICRP 116 fluence-to-effective-dose conversion coefficients.

Evaluation Method	Total Dose (mGy)	Effective Dose (mSv)
Water Phantom Dosimetry	1.511×10^{-7}	—
ICRU Sphere Phantom Dosimetry	1.702×10^{-7}	—
Effective Dose Evaluation Based on ICRP116 Conversion Coefficients	—	1.92×10^{-7}

Table2: Activation-induced dose to personnel following a single BNCT treatment, evaluated using three independent dosimetric methods.

DISCUSSION

- Neutron activation is dominated by SS304 structural components located in the direct neutron field.
- Material substitution and structural optimization provide an effective approach to reducing activation-induced dose.
- Replacing the aluminum backplate with a carbon-fiber support further suppresses secondary activation while maintaining mechanical stability.
- The optimized detector design reduced the predicted post-treatment dose by nearly two orders of magnitude, demonstrating improved radiation safety for clinical operation.

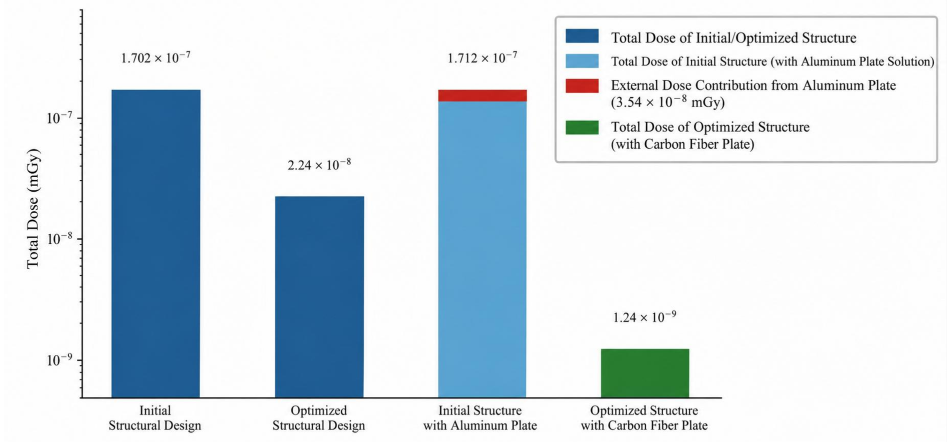

Figure6: Reduction of activation-induced dose through detector structural optimization and material replacement.

CONCLUSIONS

- Annual Micromesh damage remained below 1×10^{-7} dpa, while the PCB received only 20.25 Gy, indicating excellent radiation durability.
- Structural optimization reduced the activation-induced staff dose to 1.24×10^{-9} mGy per treatment.
- These results support the feasibility of large-area Micromegas detectors for real-time BNCT beam monitoring.

REFERENCES

[1] **Fang Z J**, **Zhang Z Y**, **Shi B**, *et al.* A large area, high counting rate micromegas-based neutron detector for BNCT [J]. *Nuclear Instruments and Methods in Physics Research A*, 2023, **1053**: 168361. DOI: 10.1016/j.nima.2023.168361

[2] **Jiang W, Cao P, Wu Y M**, et al. FPGA-based position reconstruction method for neutron beam flux spatial distribution measurement in BNCT [J]. Nuclear Science and Techniques, 2024, 35(3): 56. DOI: 10.1007/s41365-024-01417-1
…