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A collimator design for using HPGe detectors in neutron beams

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Abstract: The use of detectors in neutron beams, particularly within Prompt Gamma Neutron Activation Analysis (PGNAA) facilities, is essential for accurate elemental analysis. However, operating these detectors in high-dose radiation fields presents significant challenges, primarily due to high background radiation rates. In this study, three distinct collimator designs were evaluated through Monte Carlo simulations, using the gamma spectrum from a fission reactor as the radiation source. The best-performing collimator was shown to optimize the performance of HPGe detectors, enhancing the accuracy of elemental detection under high-background conditions.

Keywords: Gamma Shielding, Monte Carlo, PGNAA, Collimator Design.

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Um design de colimador para uso em detectors de HPGe em feixes de nêutrons

Resumo: O uso de detectores em feixes de nêutrons, particularmente em instalações de Análise por Ativação com Nêutrons e Gamagrafia Prompt (PGNAA), é essencial para uma análise elementar precisa. No entanto, a operação desses detectores em campos de radiação de alta dose apresenta desafios significativos, principalmente devido às altas taxas de radiação de fundo. Neste estudo, três projetos distintos de colimadores foram avaliados por meio de simulações Monte Carlo, utilizando o espectro gama de um reator de fissão como fonte de radiação. O colimador com melhor desempenho demonstrou otimizar a performance dos detectores HPGe, aumentando a precisão da detecção elementar sob condições de alta radiação de fundo.

Palavras-chave: Blindagem gama, Monte Carlo, PGAA, Design de colimadores.

1. INTRODUCTION

Prompt Gamma Activation Analysis (PGNAA) is a powerful, non-destructive technique for the quantitative and qualitative analysis of elements within a sample [2]. Key advantages of PGNAA include that it does not require chemical preparation of the sample, measurements can be obtained within hours, and it can identify elements that are undetectable by conventional Neutron Activation Analysis (NAA) [6]. Consequently, PGNAA has been applied in diverse fields such as chemistry, archaeology, and geology [1, 4, 7, 12].

The IEA-R1 is a pool-type research reactor, moderated by light water, which currently operates at 3.5 MW. It is located at the Nuclear and Energy Research Institute (IPEN) on the campus of the University of São Paulo (USP). The reactor serves multiple purposes, including neutron activation analysis, radiopharmaceutical production, and materials science studies. One of its irradiation channels is used for neutron tomography and features a more thermalized neutron flux compared to other channels due to an installed bismuth filter. Taking into account the collimation and shielding, the thermal neutron flux at the sample position is approximately 8×10^6 n·cm^{-2}·s^{-1} [11].

These characteristics are appropriate for installing a PGNAA system by adapting the existing neutron tomography setup to operate as a hybrid system [13]. Such a system, termed PGAI-NT, is currently in use at the Budapest Research Reactor [3].

The advancement of high-purity germanium (HPGe) semiconductor detectors has significantly benefited nuclear applications, establishing neutron activation analysis as a truly multi-elemental technique. However, in PGNAA, detectors must be positioned near the neutron beam. At some facilities, maintaining the required beam intensity also generates a high flux of unfiltered gamma rays. This presents a significant challenge, as shielding must be implemented without compromising the detector's efficiency.

The main goal of this work is to evaluate the feasibility of installing a PGAI-NT system at the IEA-R1 reactor via Monte Carlo simulations. This process involves assessing different collimator plug and shielding designs for an HPGe detector. The design of this plug must accomplish two primary objectives: (1) collimate the prompt gammas generated by the sample, and (2) shield the detector from prompt fission gammas originating from the reactor core. For this study, three plug designs—namely Thor, Freya, and Loki—were tested using lead for gamma shielding. Lead is widely used as a radiation shield due to its high atomic number, which enhances gamma absorption [5].

The efficiency of the plugs was simulated using the MCNP6.1 Monte Carlo N-Particle transport code, developed by the Los Alamos National Laboratory [5]. The MCPLLB84 library was used for photon transport, and the fission gamma source was based on the characteristic prompt gamma-ray energy spectrum described in the literature [8, 10].

The results indicate the optimal plug design for shielding against fission gammas of various energies while effectively collimating gammas from a calibration source. These findings demonstrate the necessary adaptations to the Neutron Tomography (NT) channel for the installation of the first PGNAA setup in Brazil.

2. MATERIALS AND METHODS

The simulations were divided into two main phases: (1) an evaluation of the shielding models (Thor, Freya, and Loki) in reducing gamma rays from fission, and (2) an evaluation of the geometric efficiency of these models for collimating prompt gammas emitted by a sample.

To accomplish this, two distinct radiation sources were created for the MCNP simulations. The first was a source representing the prompt-gamma spectrum from the thermal fission of ^{235}U (for phase 1), and the second represented the decay spectrum of ^{60}Co (for phase 2). These simulations were designed to assess the shielding and collimation performance of the models. In the future, these simulation results will be normalized with experimental data to provide quantitative results for the system.

2.1. Gamma Source

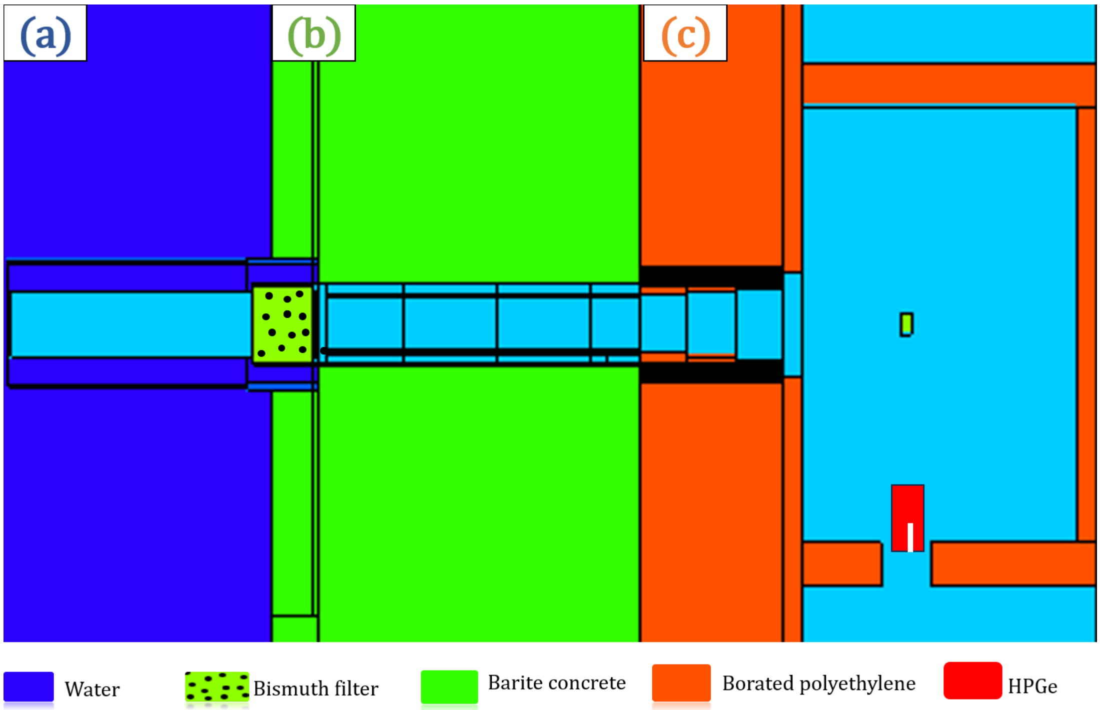
To assess the shielding efficiency of the plugs, the gamma-ray fission source was modeled using a simplified prompt-gamma spectrum from the thermal fission of ^{235}U [10]. To reduce computational time, an approximate spectrum consisting of eight energy groups ranging from 0 to 8 MeV was used. The source was implemented in the MCNP6.1 code using the SDEF card to define a virtual source, with the SI and SP cards specifying the energy distribution and probabilities

To test the collimation efficiency of the plugs, a cylindrical source with a 7 cm diameter was simulated. This source emitted gamma rays at discrete energies of 1.3325 MeV and 1.1732 MeV, mimicking a ^{60}Co calibration source. The goal of this test was to evaluate the geometric efficiency of the collimator arrangement. The simulation calculated the number of gamma rays from the source that reached the detector and deposited energy, thereby creating a signal.

2.2. Neutron Tomography Channel

Figure 1 illustrates the model of the NT channel, which is divided into three main sections for the gamma transport simulation: (a) the virtual source and the IEA-R1 reactor pool; (b) the beam collimation system and the bismuth filter; and (c) the diaphragm, which is responsible for beam divergence, and the sample holder of the NT facility.

Figure 1: Scheme of the horizontal view of the NT facility at IEA-R1 reactor (a) source, (b) beam guide and (c) sample holder.



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2.3. PGAA Plug Design

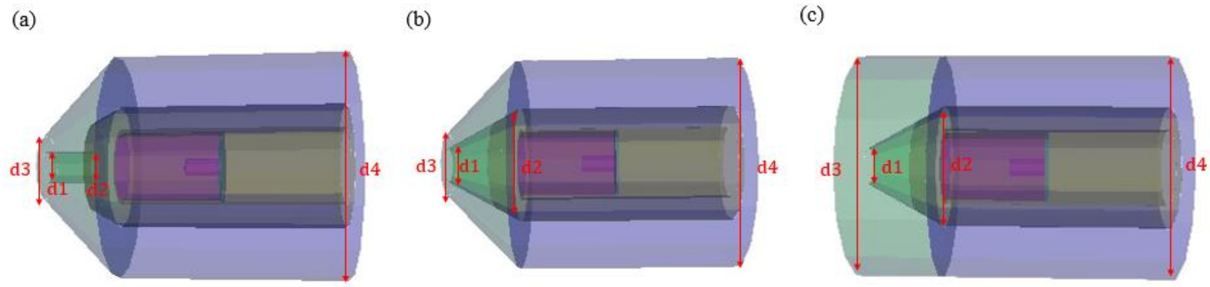
The collimator models were inspired by the design used at the Budapest Research Reactor [3]. However, geometric and material alterations were necessary to ensure compatibility with the NT facility at the IEA-R1 reactor. Detailed specifications for each collimator model are provided in Table 1. Figure 2 shows a visual representation of these plugs, with the internal red cylinder representing the HPGe gamma detector.

As depicted in Figure 3, all three plugs consist of an outer lead casing for gamma radiation shielding and an inner polyethylene layer to prevent direct contact between the HPGe crystal and the lead. The geometric parameters for this design, labeled in Figure 2, are listed in Table 1. These parameters were chosen to evaluate the optimal shielding and collimation of gamma rays from the sample, thereby maximizing detection efficiency.

Table1 : Simulation parameters of the PGAA plugs and HPGe detector

Components	Parameters
Thor	d_1= 3.00 cm, d_2= 3.00 cm d_3 = 6.00 cm, d_4= 20.00 cm Lead thickness = 4.50 cm, polyethilene thickness = 2.00 cm
Freya	d_1= 3.00 cm, d_2= 11.00 cm d_3 = 6.00 cm, d_4= 20.00 cm Lead thickness = 4.50 cm, polyethilene thickness = 2.00 cm
Loki	d_1= 3.00 cm, d_2= 11.00 cm d_3 = 20.00 cm, d_4= 20.00 cm Lead thickness = 4.50 cm, polyethilene thickness = 2.00 cm
HPGe	d= 6.30 cm, h = 8.97 cm $d_{cold\ finger}$= 1.60 cm, $h_{cold\ finger}$= 3.47 cm Window = Aluminium

Figure 2: 3D scheme of the three models of plug for PGAA called (a) Thor, (b) Freya and (c) Loki.



Source: Own author.

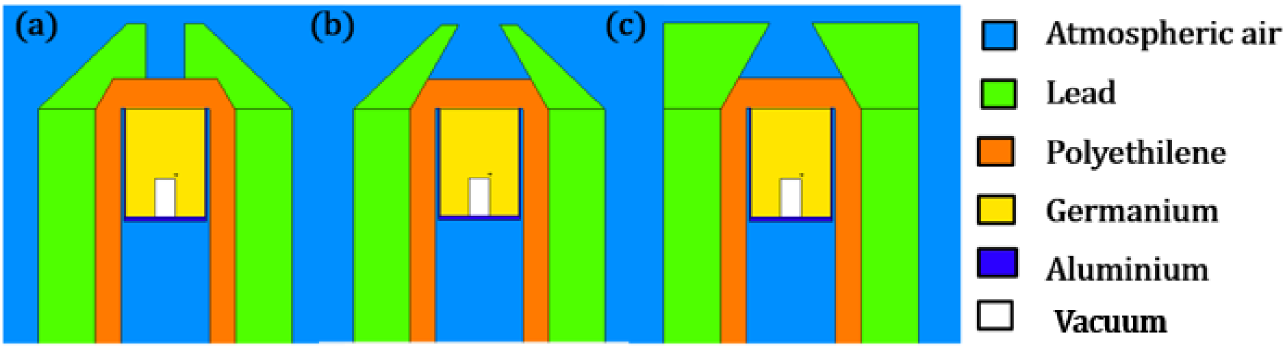
2.4. Collimation efficiency

The collimation efficiency was evaluated using a simulated ^{60}Co source placed 29 cm from the HPGe detector. The energy spectrum was generated using the F8 pulse-height tally, which records the energy deposited by photons in the detector's active volume to create a pulse-height distribution. The performance of the Thor, Freya, and Loki plug models was then compared by analyzing the area of the photopeaks in the resulting spectra. A larger photopeak area signifies a higher geometric efficiency for collimation.

2.5. Shielding Efficiency

To evaluate shielding efficiency, the gamma fission source was used in the simulations. The gamma flux in the area surrounding the detector was calculated with an F4 mesh tally. Within the detector volume itself, two tallies were employed: an F6 tally to determine the energy deposition (heating), and a standard F4 tally to calculate the gamma flux.

Figure 3: MCNP models of the three plugs design (a) Freya, (b) Loki and (c) Thor.



3. RESULTS AND DISCUSSIONS

The three plug designs were evaluated using the simulated ^{60}Co source, placed 29 cm from the detector. Collimation efficiency was determined by comparing the area of the 1.3325 MeV photopeak for each design. Figure 4 displays the spectra showing this photopeak for the three configurations. The optimal design was the one that produced the largest peak area, indicating superior collimation efficiency.

Figure 4: MCNP simulation spectra at 1.3225 peak energy of the cobalt source in a distance of 29 cm to the HPGe detector using a pulse Tally F8.

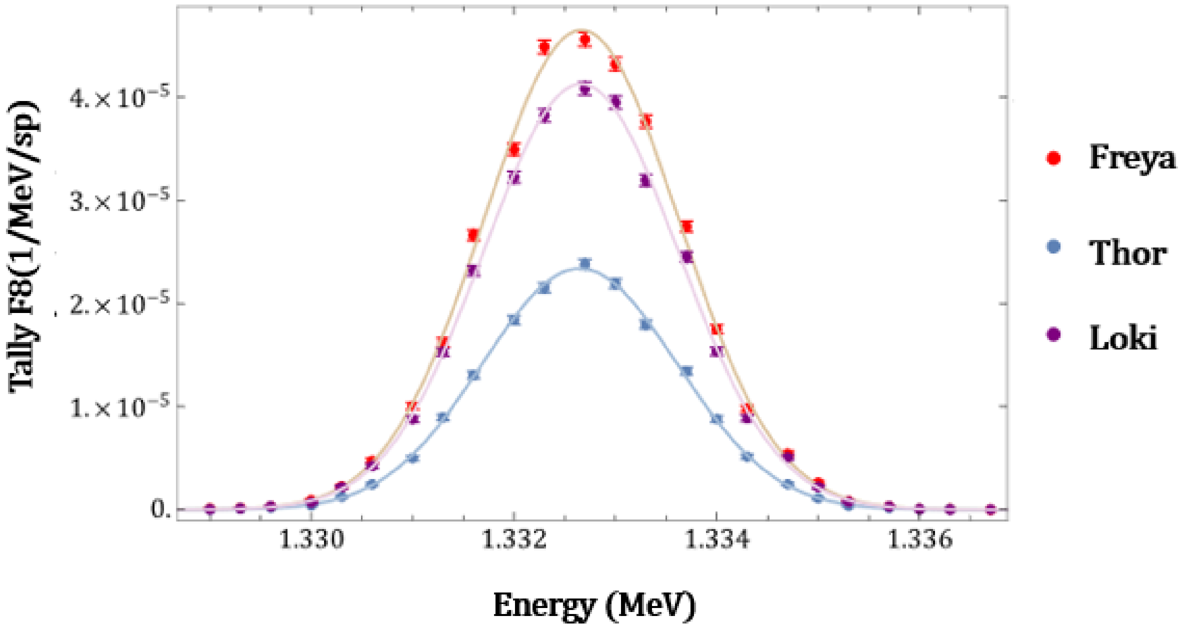


Figure 4 demonstrates that the Freya design exhibits the highest collimation efficiency. This is because its conical internal geometry directs more gamma rays toward the detector crystal. In contrast, the Thor design has a cylindrical collimator, which restricts the number of gamma rays that can interact with the crystal, resulting in lower efficiency. The Loki design, which also has a conical shape, shows better performance than Thor but is less efficient than Freya.

Figure 5: Simulated gamma flux per source particle (n/cm²·sp) for different configurations: (a) bare HPGe detector, (b) Thor, (c) Freya, and (d) Loki.

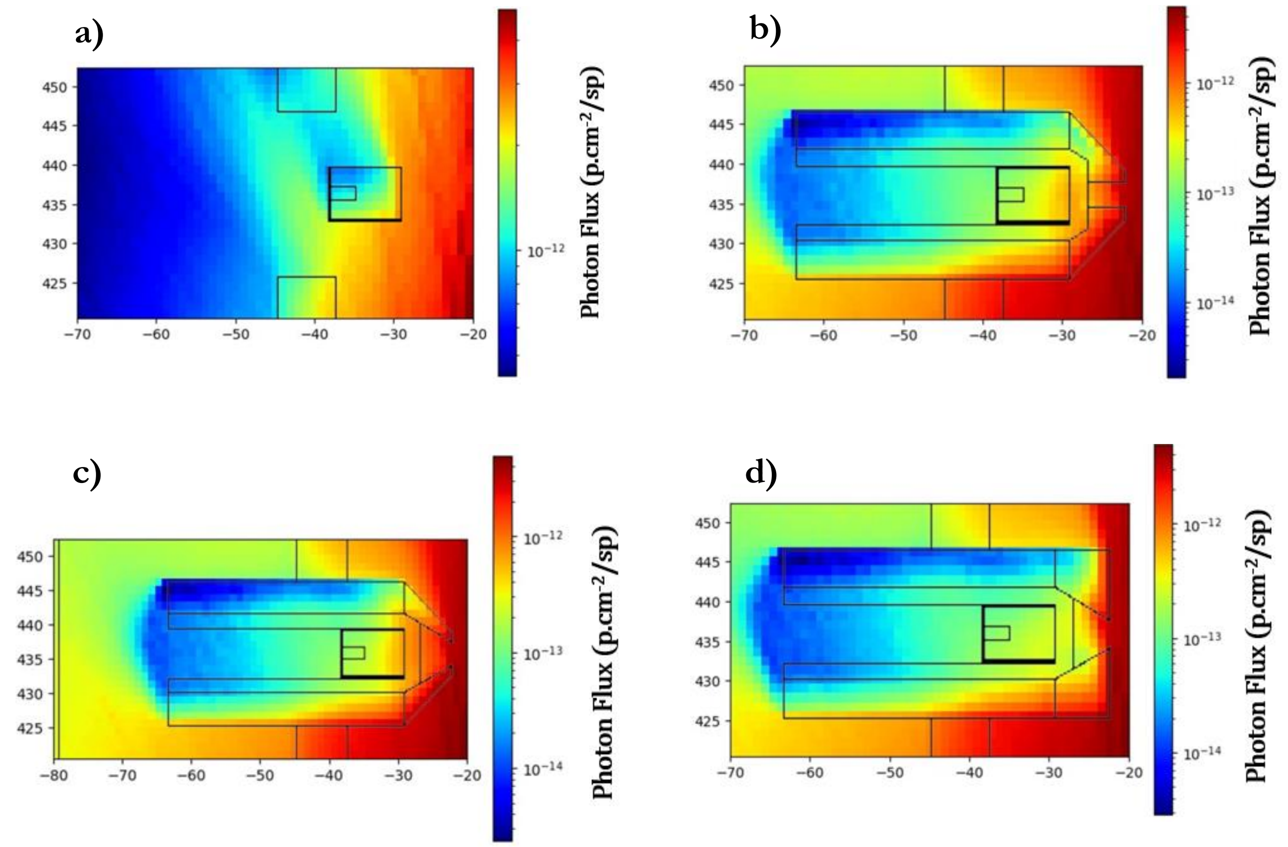


Figure 5 compares the shielding performance of the Thor, Freya, and Loki plugs against gamma radiation from the fission source. The figure also shows the baseline exposure for an HPGe detector without any plug, highlighting the overall effectiveness of the shielding designs.

Figure 6 shows the energy spectrum of gamma rays scattered toward the detector for the three shielding models and for a bare detector. The results demonstrate a significant reduction in gamma-ray flux when any of the shielding models are used. Among the designs, Loki shows the best performance in reducing the gamma flux, particularly in the 0.7 to 4 MeV energy range.

Figure 6: MCNP gamma flux in the detector volume by energy bins using Thor, Freya and Loki plug design.

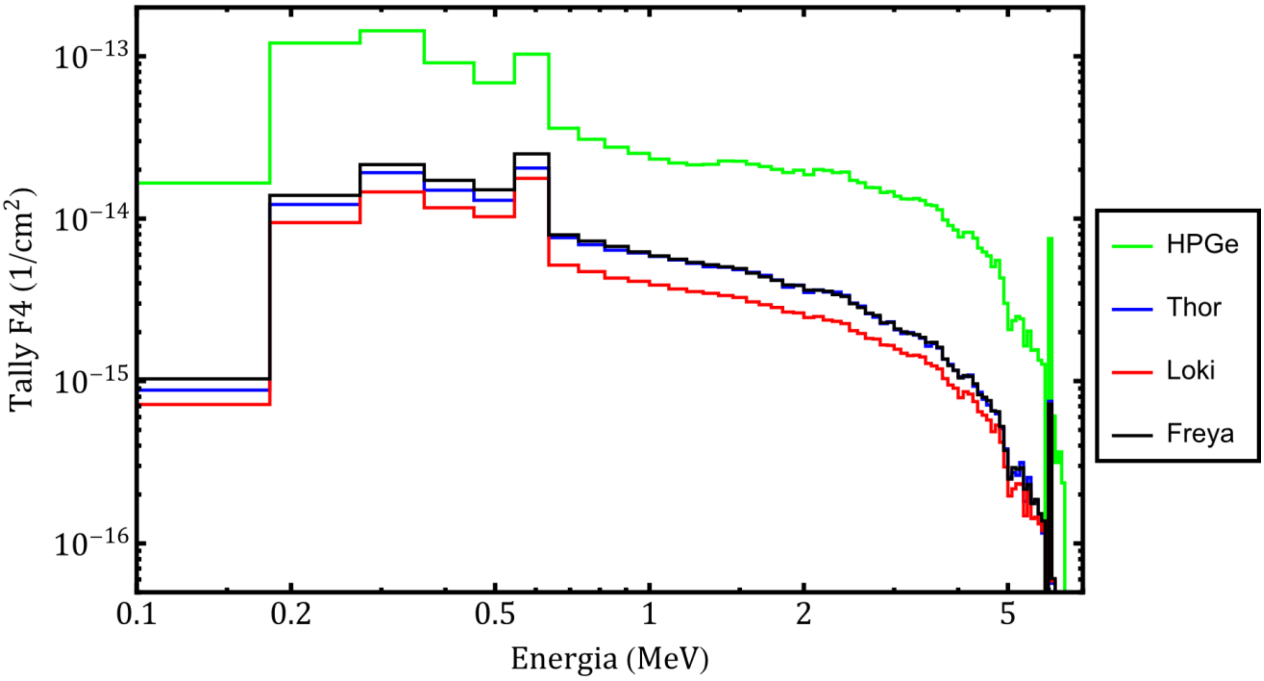


Table 2 presents the simulated energy deposition results in the HPGe detector, calculated using the F6 tally. These results demonstrate that the Loki plug reduces the dose rate by approximately one order of magnitude compared to a detector without shielding. When comparing the three designs, Loki is clearly the most effective at shielding gamma radiation. The Freya and Thor plugs show similar, but higher, dose rates. This data confirms the superior shielding performance of the Loki design.

Since the goal of this work is to determine the best collimator design to build, the only scenario that could be validated experimentally was the one without any collimator. This configuration was reproduced using a physical ^{60}Co source. By comparing the experimental and simulated results for this uncollimated case, it was possible to normalize the simulations and accurately estimate the expected dose rates for the Thor, Freya, and Loki designs.

Table 2 : Values of the MCNP gamma dose induced by gamma of the thermal fission in the detector volume with the relative error of the simulation.

Component	Tally F6 Dose (MeV/g)	Error (%)
Thor	6.77×10^{-15}	3.11
Freya	6.96×10^{-15}	3.06
Loki	4.72×10^{-15}	3.29
HPGe	4.30×10^{-14}	2.67

4. CONCLUSIONS

The simulations conducted in this study provide a clear path for installing Brazil's first PGNAA system in the NT channel of the IEA-R1 reactor. The results show that while the Freya design offers the highest collimation efficiency, the Loki design provides superior gamma radiation shielding.

Given that effective shielding is critical for reducing background noise in a high-flux environment, the Loki design is the most suitable choice for the collimator plug. Its excellent shielding capabilities make it the optimal configuration for adapting the NT facility into a hybrid PGNAA-NT system.

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CONFLICT OF INTEREST

Nothing to declare.

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