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Optimization of the Geometry in a Nuclear Battery that Uses a Beta Emitter as Ionization Source

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1. Introduction

A nuclear battery converts the energy released in a nuclear decay directly into electrical energy. This class of device offers a long life cycle, high energy density, high durability and low maintenance cost [1]. The present study focuses on the geometry of a nuclear battery that uses a sealed beta emitter of Sr-90 [2] to ionize a liquid gallium medium, which acts as the energy transducer. Gallium was chosen mainly for its low melting point (around 29.76 °C), which allows it to operate as a liquid conductive medium under mild heating while remaining compatible with the zirconium and platinum electrodes of the cell. Among the factors that determine the performance of a nuclear battery are the power density and the energy conversion efficiency [3]; both quantities are evaluated here to justify the successive changes made to the geometry. The goal is to minimize the volume of the device without losing the concentrated dose delivered by the Sr-90 source, thereby maximizing the energy density of the battery.

2. Methodology

The battery and its Sr-90 beta source (activity of 200 mCi) were modelled with TOPAS (Tool for Particle Simulation) [4], an open-source toolkit built on the Geant4 code for the simulation of radiation transport in matter. A Monte Carlo simulation was used to compute the dose deposited in the liquid gallium, which made it possible to visualize the geometry of the dose. Two features of the deposited dose were studied: its shape and the distance over which it is deposited, since together they define the constraints on the size and shape of the battery. The simulation provided the efficiency of the geometry in absorbing the beta particles, obtained by comparing the number of particles absorbed by the gallium with the total number of particles emitted by the source, as defined in Eq. 1, where the numerator is the number of beta particles absorbed by the gallium and the denominator is the total number emitted by the source. It also provided the energy density and the deposited charge in each prototype.

$$\eta = \frac{N_{\text{abs}}}{N_{\text{emit}}} \tag{1}$$

The Monte Carlo simulation with 10^7 histories produced the dose deposited in the gallium as a function of depth, shown in Fig. 1. The dose falls off very steeply with distance: almost all of it is delivered within the first few tenths of a millimetre, and beyond roughly 0.5 mm the contribution becomes negligible. This behaviour reflects the fact that the radiation, predominantly beta particles from the Sr-90 source [2], is deposited superficially in the gallium.

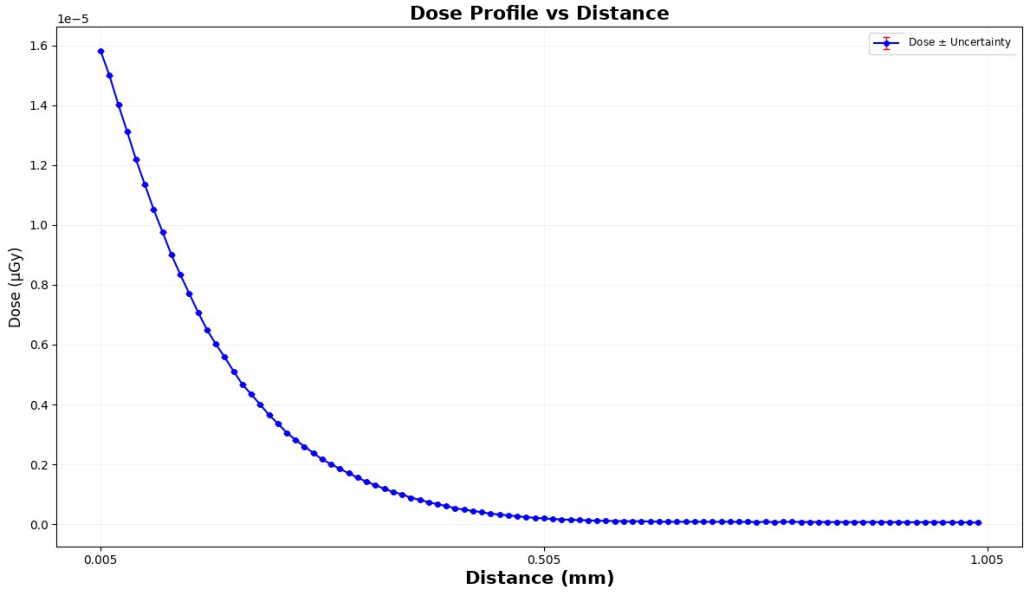


Figure 1: Dose deposited in the liquid gallium as a function of the distance from the Sr-90 source, obtained from the TOPAS Monte Carlo simulation.

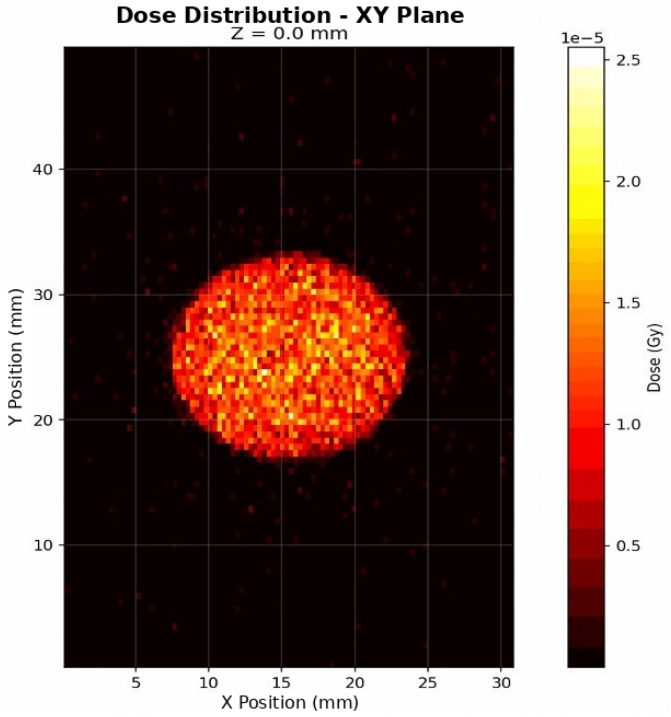


Figure 2: Dose 2D shape in the liquid gallium as a function of the distance from the Sr-90 source, obtained from the TOPAS Monte Carlo simulation.

The shape of the deposited dose and the geometry constraints derived from it guided the design of successive prototypes. Table I summarizes the four prototypes built during the optimization process, each printed in PLA or PETG and tested in the 30–80 °C range to confirm that they tolerate the operating temperature and contain the liquid gallium without significant leakage.

Table I: Summary of the four prototypes developed during the geometry optimization of the battery.

Prototype	Materials	Cell electrode gap	Main characteristic
1	Rubber stopper inside a beaker	Not controlled	First concept; separates the zirconium and platinum electrodes
2	PVC and PLA with spacer pieces	Adjustable (down to about 1 mm)	Isolates the effect of the electrode spacing on the measured voltage
3	PLA (discontinued)	Not controlled	Electrodes laid flat to enlarge the gallium surface; relied on silicone bonding
4	PLA/PETG cap with drawer mounts	Up to about 1 mm	Flattened gallium matched to the dose profile; electrodes held mechanically, without adhesive

Table II: Comparison of the relevant data from the simulation for each prototype.

Prototype	η	Energy density (MeV/cm^3)	Deposited charge (e$^-$)	Normalized geometric mean
1	20.76 %	3045.03	170080	0.603
2	7.82 %	9460.42	63302	0.457
3	11.02 %	9850.02	239390	0.810
4	7.48 %	6427.60	160683	0.540

3. Results and Discussion

The dose deposited in the gallium was found to have a circular cross section, in agreement with the cylindrical shape of the Sr-90 source, because the gallium sheet was placed on the same axis as the cylinder. As shown in Fig. 1, the dose is deposited within roughly 0.5 mm of depth; beyond this threshold the volume of gallium would grow without a relevant increase in dose, which would lower the energy density of the battery. In practice 0.5 mm proved too thin to reproduce with liquid gallium over the fixed area of the sheet, so a thickness of about 1 mm was adopted as a more achievable value. The circular dose footprint (Fig. 2) is about 15 mm in diameter, which sets the minimum width of the rectangular gallium sheet; since up to three sources can be aligned, the other side of the rectangle must be at least 45 mm so that the battery does not lose a relevant fraction of the dose. Four prototypes were built to adjust these dimensions and the thermal behaviour (Table I): the final prototype flattens the gallium to match the dose profile and holds the electrodes with mechanical drawer-style mounts, removing the need for silicone and allowing a higher energy density than the earlier, thicker designs, as summarized in Table II. Across the tested range (30–80 °C) the PLA and PETG containers kept the liquid gallium confined without significant leakage.

4. Conclusions

For each iteration of the prototype it was possible to minimize the wasted volume, maximizing the energy and power density of the battery while ensuring that it can operate with liquid gallium without significant leakage and the associated loss of material. The dose profile obtained with TOPAS [4] shows that a thin gallium layer, on the order of 1 mm and matched to the circular footprint of the Sr-90 source, is enough to capture essentially all of the deposited dose. Future work will refine the estimate of the beta-absorption

efficiency, characterize the ionic mobility of the liquid gallium and test the optimized geometry under full operating conditions.

Acknowledgments

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