

# TARGET DESIGN CONSIDERATIONS FOR LINAC-BASED ASTATINE-211 PRODUCTION

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## Abstract

Astatine-211 ( $^{211}\text{At}$ ) is a highly promising radionuclide for targeted alpha therapy (TAT), yet its clinical adoption is limited by production constraints.  $^{211}\text{At}$  is predominantly produced using cyclotrons, where beam currents rarely exceed a few hundred  $\mu\text{A}$ , thereby limiting achievable production yields. Linear accelerators (LINACs) offer an attractive alternative due to their potential for substantially higher beam currents, reduced irradiation times, and improved overall efficiency. To enable a reliable  $^{211}\text{At}$  supply, the Tera-Care Foundation is developing a target system specifically engineered to withstand the power levels of the planned LINAC, which will directly irradiate bismuth targets. The initial analyses focus on estimating thermal loads, energy deposition, and temperature profiles to determine safe operating limits and prevent material degradation. This work establishes the foundational design framework needed to implement a reliable, high-power  $^{211}\text{At}$  production system.

## INTRODUCTION

Targeted alpha therapy (TAT) has emerged as a promising approach for cancer treatment, supported by encouraging clinical results [1, 2]. It combines  $\alpha$ -emitting radionuclides with suitable targeting agents, such as antibodies or peptides, to deliver highly localized radiation over a range of only a few cell diameters. This localized dose deposition, resulting from the short path length and high linear energy transfer of the  $\alpha$ -particles, makes TAT particularly attractive for treating small and disseminated tumours while limiting damage to healthy tissues.

Among the  $\alpha$ -emitters considered for TAT, astatine-211 ( $^{211}\text{At}$ ) is of particular interest because of its favourable decay properties, including a 7.2-hour half-life and  $\alpha$ -particle emission suitable for therapeutic applications.  $^{211}\text{At}$  is commonly produced through the  $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$  reaction by irradiating natural bismuth targets with  $\alpha$ -particles. This route is typically implemented using cyclotrons; however, achievable yields are often constrained by the available beam currents, which commonly range from a few  $\mu\text{A}$  to a few hundred  $\mu\text{A}$  [3]. This limitation restricts the total activity produced per irradiation and remains a barrier to routine regional and large-scale clinical supply.

Linear accelerators (LINACs) offer a potential pathway toward increased  $^{211}\text{At}$  production capacity, as they can operate at substantially higher beam currents than conventional cyclotrons. Higher beam currents may reduce irradiation time and improve production efficiency, but they also

increase the deposited beam power in the target. Efficient heat removal and control of peak temperatures are therefore critical to maintaining target integrity and preventing material degradation during irradiation.

To address this challenge, the Tera-Care Foundation [4], a not-for-profit research organization based in Geneva, Switzerland, is developing a dedicated target system for high-power  $^{211}\text{At}$  production using a LINAC, such as the one recently designed at CERN [5]. This activity is part of the CHEFS (Clinical Helium Facility for Switzerland) project that Tera-Care is promoting, based on the technologies developed by the NIMMS activities, led by CERN [5], which includes a LINAC-based infrastructure for medical applications and therapeutic radionuclide production. Within this project, high-current  $\alpha$ -particle beams will directly irradiate bismuth targets, with the aim of improving the availability of  $^{211}\text{At}$  for TAT. The target system must therefore be designed to withstand elevated beam power densities while maintaining acceptable operating temperatures.

This paper presents the initial design analysis of the proposed high-power  $^{211}\text{At}$  production target. The study focuses on beam-induced energy deposition, thermal loading, and temperature profiles in the target assembly, providing a basis for defining safe operating conditions and guiding the future target design, cooling-system development, and experimental validation.

## $^{211}\text{AT}$ PRODUCTION TARGET SYSTEM CONCEPT

The production of  $^{211}\text{At}$  from natural bismuth is based on the  $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$  reaction. The  $\alpha$ -particle beam energy must be selected within a restricted energy window that favours  $^{211}\text{At}$  production while limiting the competing  $^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$  reaction, which produces  $^{210}\text{At}$  and subsequently the long-lived radiotoxic  $^{210}\text{Po}$ .

Production targets for  $^{211}\text{At}$  commonly consist of a thin metallic bismuth layer deposited on a thermally conductive backing material, which provides mechanical support and the main heat-removal path during irradiation. For high-current pulsed LINAC operation, the target must withstand elevated volumetric power densities while maintaining the bismuth below its melting point of approximately 546 K. The design must also limit thermal gradients and cyclic stresses that may cause deformation, fatigue, or degradation of the thermal contact between the bismuth layer and the backing material.

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In this work, the baseline target model consists of a 50  $\mu\text{m}$  bismuth layer deposited on an aluminium backing block. The incident beam is defined as a 29 MeV  $\alpha$ -particle beam with a Gaussian transverse profile of  $\sigma=5$  mm. Normal beam-incidence is used as the reference configuration, while the incidence angle is considered as a design parameter to increase the effective beam footprint and reduce local power density. This geometry is used to quantify the energy deposition distribution and provide the heat-source term required for the subsequent thermal assessment.

## THERMAL MODELLING

The thermal analysis was based on a two-step workflow combining particle-transport simulations and transient thermal calculations. Energy deposition from the incident  $\alpha$ -particle beam in the target assembly was first calculated using the Monte Carlo particle-transport code FLUKA [6,7]. The simulations provided the three-dimensional spatial distribution of the deposited energy in the bismuth target and aluminium backing defining the volumetric heat-source term required for the subsequent thermal assessment of the target.

The simulation geometry reproduced the baseline target model shown in Fig. 1, consisting of a thin bismuth layer deposited on an aluminium block and surrounded by vacuum. The reference geometry considered a bismuth layer of  $80 \times 60 \times 0.05$  mm<sup>3</sup> deposited on an aluminium block of  $100 \times 80 \times 5$  mm<sup>3</sup>. The incident beam was defined as a 29 MeV  $\alpha$ -particle beam with a Gaussian transverse profile representing the expected beam footprint.

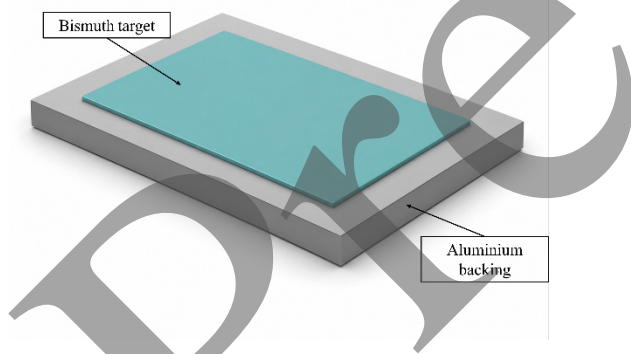


Figure 1: Schematic representation (not to scale) of the baseline target geometry used in the energy deposition calculations. The model consists of a bismuth layer (in cyan) deposited on an aluminium backing block.

For each configuration, the deposited energy was scored in the target region and exported for post-processing. Separate scoring regions were used for the bismuth layer and for the combined bismuth-aluminium target assembly, allowing the energy deposited in the production layer to be distinguished from the energy transported into the backing. The FLUKA results were normalized per incident  $\alpha$ -particle and converted to volumetric energy density. For the pulsed-beam analysis, the deposited energy maps were scaled to the LINAC pulse structure using a repetition frequency of 50 Hz, a pulse duration of 2 ms, and a duty factor

of 0.1. The deposited power per pulse was fixed at 10 kW, allowing the effect of the beam-incidence angle on the thermal-load distribution to be evaluated independently of changes in the total deposited power.

A transient thermal analysis was performed using computational fluid dynamics (CFD) for the normal-incidence beam configuration. The target assembly was modelled with ANSYS Fluent [8]. In this model, the FLUKA-derived volumetric power density distribution was imported as the heat source in a discretised target geometry. The bismuth layer and aluminium backing were meshed to resolve the thin production layer and the steep temperature gradients near the beam interaction region. This calculation was used to evaluate the transient temperature evolution and identify surface hotspots.

## RESULTS AND DISCUSSION

The FLUKA simulations were used to define the volumetric heat source applied in the thermal model. Fig. 2 shows the calculated energy deposition distribution in the plane perpendicular to the beam direction, corresponding to a surface view of the target for the normal-incidence configuration. These are the results for the reference, worst-case scenario, defined as a Gaussian beam perpendicular to the target surface. The distribution is centred on the beam axis and reflects the imposed Gaussian beam profile, with the highest deposited energy density located at the centre of the beam footprint. The deposited energy decreases radially away from the beam axis by several orders of magnitude, indicating a strongly localized volumetric heat source in the target. Although the total deposited power determines the overall heat load, the peak temperature is governed primarily by the local power density and the heat-transfer path through the bismuth-aluminium assembly.

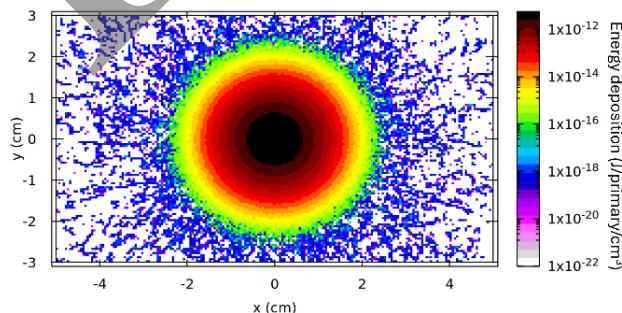


Figure 2: Energy deposition distribution map in the plane perpendicular to the beam direction for a normally incident 29 MeV  $\alpha$ -beam with a 5 mm  $\sigma$  Gaussian profile.

The calculated volumetric energy deposition maps were converted into deposited power and imported into the CFD model as the heat source for the baseline bismuth-aluminium assembly. The calculated surface temperature distribution is shown in Fig. 3. The highest temperatures are concentrated at the beam footprint, where the deposited power density is maximum. In this region, the calculated temperature exceeds the bismuth melting point, indicating the formation of a localized molten region under the assumed irradiation conditions. The steep radial decrease in

temperature away from the beam footprint confirms that the thermal response is dominated by the spatial localization of the deposited power.

The corresponding three-dimensional temperature field is shown in Fig. 4. It is possible to observe that the region exceeding the bismuth melting temperature remains localized near the beam-interaction zone, while heat spreads into the surrounding bismuth layer and aluminium backing. This distribution produces steep thermal gradients around the hotspot region, indicating that the thermal contact between the bismuth layer and backing material, together with the cooling configuration, will strongly influence the peak temperature and the extent of the overheated region.

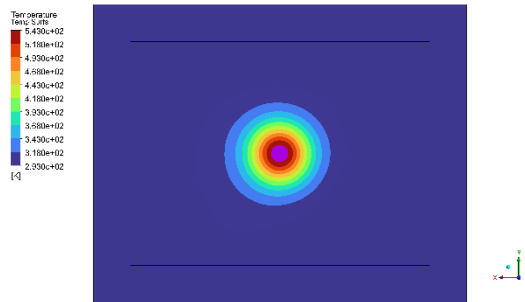


Figure 3: Calculated surface temperature distribution in the bismuth-aluminium target assembly for the normal-incidence beam configuration.

The transient evolution of the maximum temperature is shown in Fig. 5. The pulsed beam structure produces repeated heating and cooling cycles, with rapid temperature increase during each pulse followed by partial cooling between pulses. Nevertheless, the cooling interval is insufficient to restore the initial temperature before the next pulse, resulting in cumulative heating. For the baseline configuration, the calculated maximum temperature reaches the bismuth melting point after approximately 0.6 s and continues to increase thereafter.

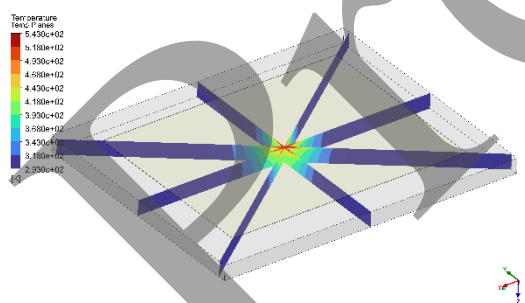


Figure 4: Three-dimensional temperature distribution in the bismuth-aluminium target assembly for the normal-incidence beam configuration.

Together, the temperature maps and transient evolution indicate that the present target configuration is thermally limited under the assumed operating conditions. The combination of localized energy deposition and cumulative pulsed heating leads to temperatures above the acceptable operating limit for bismuth. Further optimization is therefore required to reduce the peak power density and improve heat extraction from the irradiated region.

The next design phase foresees investigating beam-incidence optimization and active cooling strategies to reduce the peak target temperature, in addition to the more straightforward measure of shaping the transverse beam profile, e.g. to a waterbag-like distribution, and increasing its size. Applying a grazing beam angle is expected to increase the effective beam footprint and lower the local power density, while cooling-system developments will focus on improving heat extraction through the target system. These studies will be used to define the operating conditions that maintain the bismuth layer below critical temperature limits during high-power irradiation.

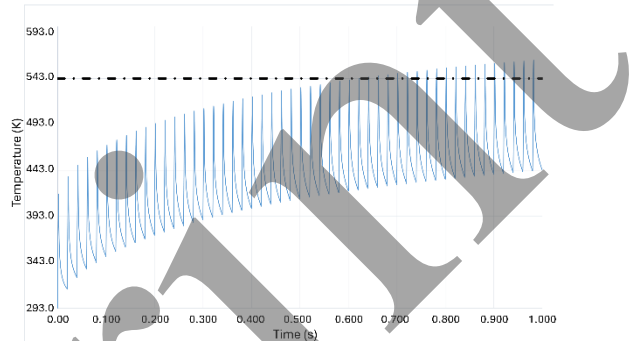


Figure 5: Transient evolution of the maximum temperature during pulsed irradiation for the normal-incidence configuration. The dashed line indicates the bismuth melting temperature.

## CONCLUSION

This work presents the initial thermal analysis of a high-power bismuth target for LINAC-based  $^{211}\text{At}$  production for the CHEFS project, promoted by the Tera-Care Foundation in Switzerland. Energy deposition and CFD simulations were used to assess the thermal response of the target under representative pulsed-beam conditions. The first simulations show that the studied baseline produces localized overheating at the beam footprint, with calculated target temperatures exceeding the melting threshold. These results indicate that the reference geometry is thermally limited and requires optimization. Ongoing work will focus on reducing the local power density through beam-incidence angle and beam-footprint optimization, together with the development of an active cooling system capable of maintaining the target below critical limits during high-power irradiation.

## REFERENCES

- [1] R. P. Coll, *et al.*, “Alpha particle–emitting radiopharmaceuticals as cancer therapy: biological basis, current status, and future outlook for therapeutics discovery”, *Mol. Imaging Biol.*, vol. 25, pp. 991–1019, 2023.  
[doi:10.1007/s11307-023-01857-y](https://doi.org/10.1007/s11307-023-01857-y)
- [2] M. Tosato, *et al.*, “Alpha atlas: mapping global production of  $\alpha$ -emitting radionuclides for targeted alpha therapy”, *Nucl. Med. Biol.*, vols. 142–143, pp. 108990, 2025.  
[doi:10.1016/j.nucmedbio.2024.108990](https://doi.org/10.1016/j.nucmedbio.2024.108990)
- [3] Y. Feng and M. R. Zalutsky, “Production, purification and availability of  $^{211}\text{At}$ : near term steps towards global access”, *Nucl. Med. Biol.*, vols. 100–101, pp. 12–23, 2021.  
[doi:10.1016/j.nucmedbio.2021.05.007](https://doi.org/10.1016/j.nucmedbio.2021.05.007)
- [4] Tera-Care Foundation, <https://tera-care.ch/>
- [5] M. Vretenar, A. Lombardi, and L. Nikitovic, “A helium ion linear accelerator optimised for astatine production”, *Instruments*, vol. 10, no. 2, pp. 25, 2026.  
[doi:10.3390/instruments10020025](https://doi.org/10.3390/instruments10020025)
- [6] C. Ahdida, *et al.*, “New capabilities of the FLUKA multi-purpose code”, *Front. Phys.*, vol. 9, pp. 788253, 2022.  
[doi:10.3389/fphy.2021.788253](https://doi.org/10.3389/fphy.2021.788253)
- [7] G. Battistoni, *et al.*, “Overview of the FLUKA code”, *Ann. Nucl. Energy*, vol. 82, pp. 10–18, 2015.  
[doi:10.1016/j.anucene.2014.11.007](https://doi.org/10.1016/j.anucene.2014.11.007)
- [8] ANSYS® Fluent, Release 2025 R2, ANSYS, Inc.