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A Novel Energy Modulator Design Concept for FLASH Proton Therapy

A Simple and Cost-Effective Energy Modulator with Improved Structural Robustness

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Abstract: *Introduction:* Energy modulators (EM) have gained increasing attention due to their relevance in FLASH proton therapy. Current EM designs are fragile, necessitating thin ridges and limited sizes. Production requires advanced and costly 3D printers, as basic filament printers are inadequate, leading to expensive outsourcing. We propose an innovative EM design to address these limitations.
Methods: The novel design consists of boxes stacked one on top of the other. Each box is created with two distinct infill ratios: one for the inner cube and one for the larger cube surrounding it. The size of the inner and outer cubes is optimized along with the infill ratio. This structure is repeated periodically for box-like targets or varied to achieve the desired dose distribution. We design, slice, and print the EM using a Bambu Lab-X1C filament printer and polylactic acid filament. The simulation was performed using a GPU-based Monte Carlo simulation (FRED), where the EM was modeled as a combination of cubes with variable heights, with the infill ratio mapped to the material height. The simulation design was validated through depth-dose curve measurements using PSI Gantry 2.
Results: EM for box-like targets of 35mm depth were designed and manufactured by varying the infill ratio between 30% and 100%. We chose cubic infill for isotropic periodicity, ensuring that impinging particles encounter uniform material distribution. Manufacturing constraints require 100% (concentric) infill in areas smaller than 1.5mm^2. The simulations were validated by depth dose curve measurements with shape and distal range agreement to within detector uncertainties (<1mm).
Conclusion: We realized a 3D-printed EM that is easier to produce and more resistant to physical damage than current alternatives. This design demonstrates the potential for a cost-effective, easily manufacturable, and scalable EM.

Keywords: FLASH radiotherapy, Proton therapy, Energy modulator, filament 3D printer

1 Introduction

Recent advances in radiotherapy have investigated strategies to enhance therapeutic potential by reducing toxicity and enabling dose escalation, exploiting the so-called FLASH effect, which occurs with irradiation at ultra-high dose rate (UHDR, exceeding 40 Gy/s) [1, 2]. To achieve UHDR with proton therapy, the delivery time must be substantially reduced. For instance, in pencil beam scanning [3], a narrow beam is scanned in three dimensions to cover the target volume. To deliver a conformal dose, the target is "painted" energy by energy layer by scanning Bragg peaks (spots) laterally across the target at each layer, deposited dose at predefined positions before

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moving to the next energy layer. The delivery time depends on beam intensity and energy/position changes, with energy switching being a major constraint due to the need to adjust the dipole magnet fields to match the energy changes. For UHDR, using a single energy level minimizes treatment time, but energy modulators (EM) [4] are then essential to shaping the dose distribution while maintaining fast delivery. Energy modulators (EM) can be realized as 3D-printed pyramid-like filter structures that modulate incoming protons' energy distribution by varying material thickness along the beam path [5], allowing for precise dose shaping to match tumor geometry. The pyramids usually have a small base of 4-5mm [6, 7] and a submillimeter apex, leading to the development of thin and, therefore, fragile ridges [8]. Additionally, manufacturing these EMs requires high-precision 3D printing, leading to expensive and complex production, often requiring outsourcing. To overcome these limitations, we present a novel EM design that features a simple box design with variable 3D printing infill ratios. This study explores the possibilities of this new design, analyzes the feasibility of 3D printing with variable infills, and evaluates the ability of MC simulations to effectively and accurately replicate its behavior.

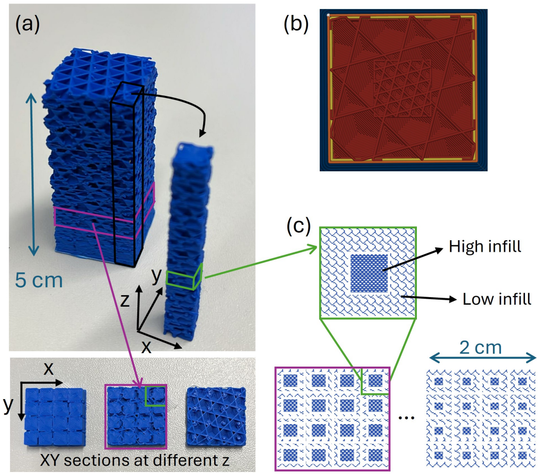

Fig. 1: Concept of the new design for a simple case using only two infill ratios for the inner cube and one for the outer cube surrounding it for all layers. (a) 3D printed EM. For demonstration purposes, one single vertical module and variable layers have been printed separately. (b) A screenshot of the Bambu Studio slicer shows how the high and low infill regions align for one module. (c) Schematic representing the printed layers.

2 Methods

2.1 EM design

The new EM features a modular design consisting of boxes stacked one on top of the other, each measuring 5x5x5mm. Each box consists of two volumes with square bases, one inside the other, featuring two distinct infill ratios, see Fig.1(c): one for the inner and one for the outer volume surrounding it. The size of the cubes is optimized along with the infill ratio. This structure is then repeated periodically for box-like targets or varied to achieve the desired dose distribution in the target. A simple EM design with two infill ratios is shown in Fig. 1.

2.2 3D Printing Processs

We designed the EM using the Bambu Studio slicer [9]. We used two volumes with a square base to generate the two different infill ratios within a particular volume. A lower infill was used for the outer volume, and the inner volume with a higher infill was placed inside the first. The outermost part of the object, the so-called walls, was removed to reduce high infill areas that would affect the dose distribution. The ratio between the two infills was chosen to align the outer and inner infills' printing paths; see Fig. 1(b). We printed the EM with polylactic acid (PLA) filament using a Bambu Lab-X1C filament printer with a 0.4mm nozzle. We utilized a concentric pattern for 100% infill while opting for cubic infill for the other ratios. This cubic infill features an overlapping path in each layer, resulting in cubes positioned with one corner facing downward. The benefit of this design lies in its isotropic periodicity, which guarantees a homogeneous distribution of material for impinging protons.

2.3 Measurement and Simulations

To validate the EM design, measurements were performed in a clinical proton therapy room at PSI (Gantry 2). We measured the depth dose curve of the proton beam using a multilayer ionization chamber (MLIC). The sample was placed close to the chamber's entrance window. Additionally, we measured the beam's transverse distribution after the EM with a charge-coupled device (CCD) camera, positioning the EM on the measuring plane. We simulated the proton response in FRED (v3.70): a GPU-accelerated fast Monte Carlo code [10], previously validated with TOPAS MC [11, 12]. FRED allows for the import of voxelwise geometries, facilitating the incorporation of the EMs in the simulations. The EM was represented as a combination of cubes with variable heights, mapping the infill ratio to material height. The depth dose curve was scored in water, and the measured data points were converted into water-equivalent thickness to allow for comparison. The different infill ratios need to be tested for the attenuation of the proton beam to ensure that the simulations and optimization processes consider the various material properties. We measured the proton beam's depth dose curve after passing through 20mm 3D-printed boxes with varying infill ratios (from 10% to 100%). We simulated the depth dose curve for proton beams going through PLA boxes of varying heights (from 20mm to 2.5mm)

3 Results

3.1 3D printing constraints

We found that the achievable and printable 3D printing infill ratio depends on the nozzle size and the box dimension. With the 0.4mm nozzle used, we could reach a minimum infill of 25% for a cube of $5x5x5mm^3$. In Table 1, we report the minimum printable infill for the given base size.

Tab. 1: Minimum infill percentage for different base sizes (height 5mm).

Base [mm×mm]	Min infill
5 x 5	25%
4.5 x 4.5	25%
4 x 4	30%
3.5 x 3.5	40%
3 x 3	40%
2.5 x 2.5	50%
2 x 2	70%
1.5 x 1.5	100%
1 x 1	100%
0.5 x 0.5	100%

3.2 Measurement and Simulations

We found a linear relationship between the measured depth dose curve of the proton beam after it passed through different materials and the simulated depth dose curve for proton beams that traveled through PLA boxes of varying heights, as shown in Fig. 2. A box measuring 20mm with a 50% infill ratio corresponds to 10mm of material.

Our simple 30%-100% design successfully enlarged the Bragg peak shape to 35mm for energies between 120 - 220MeV, increasing the beam size after the EM by no more than 2% at the entrance. Fig. 3 (a) illustrates a comparison between the measured and simulated depth dose curve, indicating shape and distal range agreement within detector uncertainties (<1mm). Fig. 3(b) pictures that we could achieve the desired dose distribution independently of the beam position.

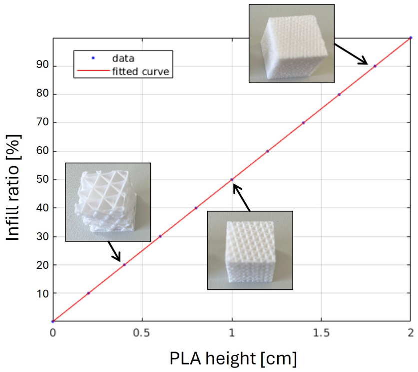

Fig. 2: Relation between infill ratio and PLA height. The 3D printed boxes with 20%, 50%, and 90% infill ratios are also illustrated.

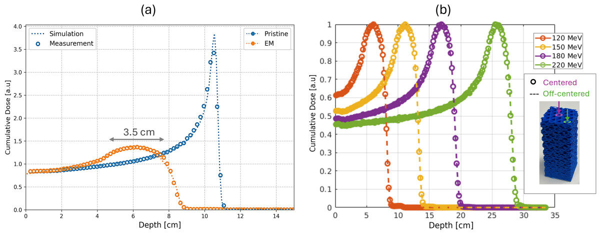

Fig. 3: (a) Depth dose curve measured and simulated for a proton energy of 120 MeV. Additionally, the pristine Bragg peak is included for comparison. (b) Depth dose curve measured for different energies for the proton beam impinging in the center (dotted line) and in a corner (dashed line) of the EM.

4 Discussion

Our novel design can effectively substitute the classical ridge shape, improving the object's robustness and handling. We tested the feasibility of this approach from the point of view of the 3D printing process, showing that we can print objects with variable infill without affecting the homogeneity of the dose distribution. We found constraints in the printability of such an object, particularly on the minimum printable infill for small structure sizes below 1.5mm. We could also use simple filament printers without relying on external companies with advanced and costly 3D printers. We could successfully reproduce the simulated proton beam behavior with MC simulations. The use of FRED, a GPU-accelerated fast Monte Carlo code, allows for fast evaluation of the results, a fundamental step toward fast optimization of the EM design. The development of EM is a key element for the clinical translation of FLASH radiotherapy. UHDR requires beam delivery within milliseconds, which is not possible with the techniques currently used to change the energy in proton therapy [4, 13]. EMs produce a homogeneous dose distribution conformed to the distal and proximal edge of the target by using one single energy, thereby greatly reducing the irradiation time. However, previously designed EMs are made of tiny ridges and are very fragile, difficult to handle, and sensitive to alignment precision and material properties [14]. These factors can considerably influence the efficacy and safety of treatment delivery. Our feasibility study shows that we can effectively modulate the beam energy by changing the infill ratio of a robust and compact box-shaped EM. Our compact structure facilitates positioning and alignment procedures. Moreover, it can be easily optimized using fast MC simulations and produced with a commercial filament printer, overcoming the challenges of current EM designs. Future steps will include designing complex, conformal EM with integrated compensation and modulation and exploring methods to automate 3D printing for efficient production.

5 Conclusion

We have experimentally validated a novel EM design of enhanced mechanical robustness compared to conventional filters. This design demonstrates the potential for cost-effective, easy-to-manufacture, and scalable EM while facilitating the clinical translation of FLASH radiotherapy.

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