HEDGEHOG: a ridge filter design for FLASH proton therapy

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Introduction

Reports of tissue-sparing effects with ultra-high beam dose rates have led to growing interest in FLASH radiotherapy. Combining this with the useful proton dose distribution could greatly improve cancer treatment outcomes. However, bringing FLASH safely and effectively to the clinic requires an array of technical innovations and a lot more research. TRIUMF's Proton Therapy Research Centre (PTRC) is well suited to conduct this with its experienced and robust passive scattering setup, versatile cyclotron, and leading experts. While the adjustments to the PTRC beamline required for this are minimal, the current way of modulating proton energy – a modulator wheel – is not suitable for ultra-high dose rates due to its rotation speed being too slow for the treatment timescales. The aim of this research is to provide a quick and simple way to produce devices to instantaneously modulate proton beam energy.

What is a HEDGEHOG?

The Homogeneous Energy Distribution GEnerator for tHerapeutic prOton beam shapinG (HEDGEHOG) is a type of static ridge filter used for the modulation of proton beam energies. It is placed directly in the beamline and does not rotate which avoids the issues at high dose rates faced by spinning modulator wheels. Protons experience differing energy loss depending on the thickness of material they pass through. In traversing the "forest" of pins shown in figures 1 & 2, the proton beam will be made of particles of many energies evenly distributed in space. The sum of the dose distribution of each proton gives a Spread-out Bragg Peak (SOBP) which shows the total dose deposited along the beam axis.

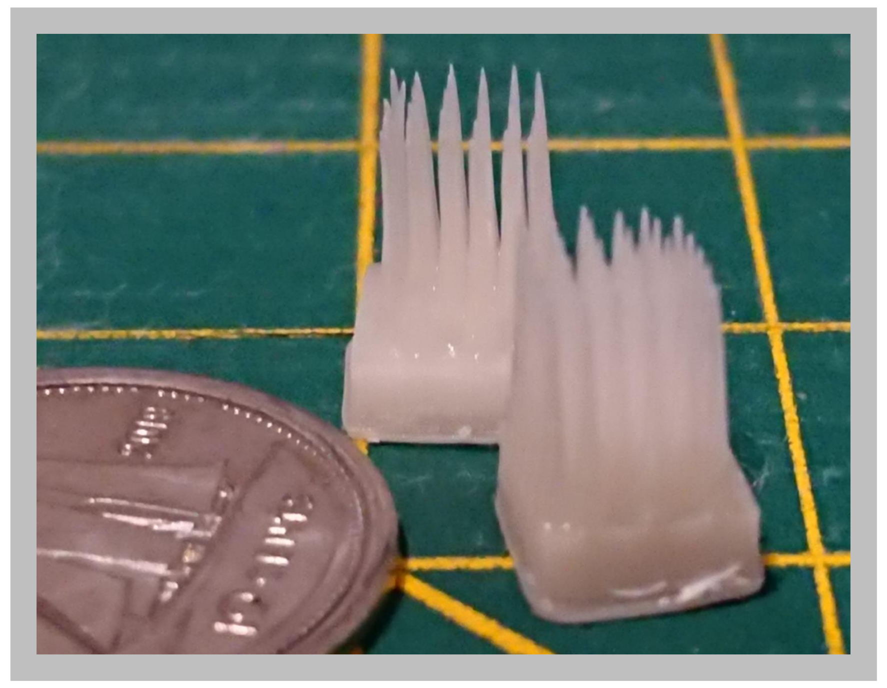

Figure 1: the first HEDGEHOG prototypes printed using a resin printer.

HEDGEHOG production

Making a HEDGEHOG consists of three stages:

- **Optimization.** An algorithm for making smooth modulator wheels developed at TRIUMF was adapted for designing HEDGEHOG pins.
- **Simulation.** The optimized design is constructed using Python and prepared for Monte Carlo simulation using the FLUKA particle transport code.
- **Printing.** The same HEDGEHOG geometry can be converted to STL file format and 3D printed. This allows high similarity between simulated and experimental geometries.

The optimization algorithm

The optimization algorithm is the most complex and customizable stage of HEDGEHOG production. Several FLUKA simulations with PMMA blocks of various thickness were performed to obtain depth-dose profiles, and these are interpolated to produce a continuous function for dose at any depth or PMMA thickness. The algorithm then finds the combination of simulated pristine BPs closest to the desired SOBP using an objective function of plateau uniformity and total entrance and exit doses. The output is a set of PMMA thicknesses and their relative weights which are used to define a pin shape for placement on a device.

In adapting the algorithm for use with the HEDGEHOG, several key changes were made, most significantly the optimization of the pristine BP weights rather than the modulator shape. While bringing benefits like precision and simplicity, this decision is likely responsible for the differences between the simulated and optimized SOBPs in figure 3 c) and is being reviewed.

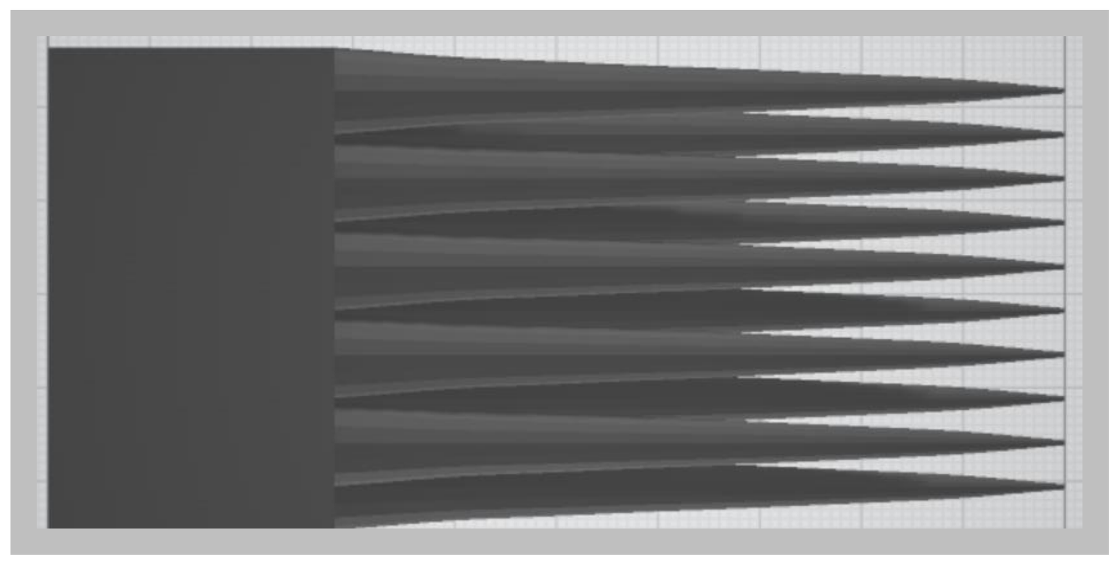

Figure 2: 3D model of a hedgehog designed for a 0.7cm SOBP at a depth of 4cm.

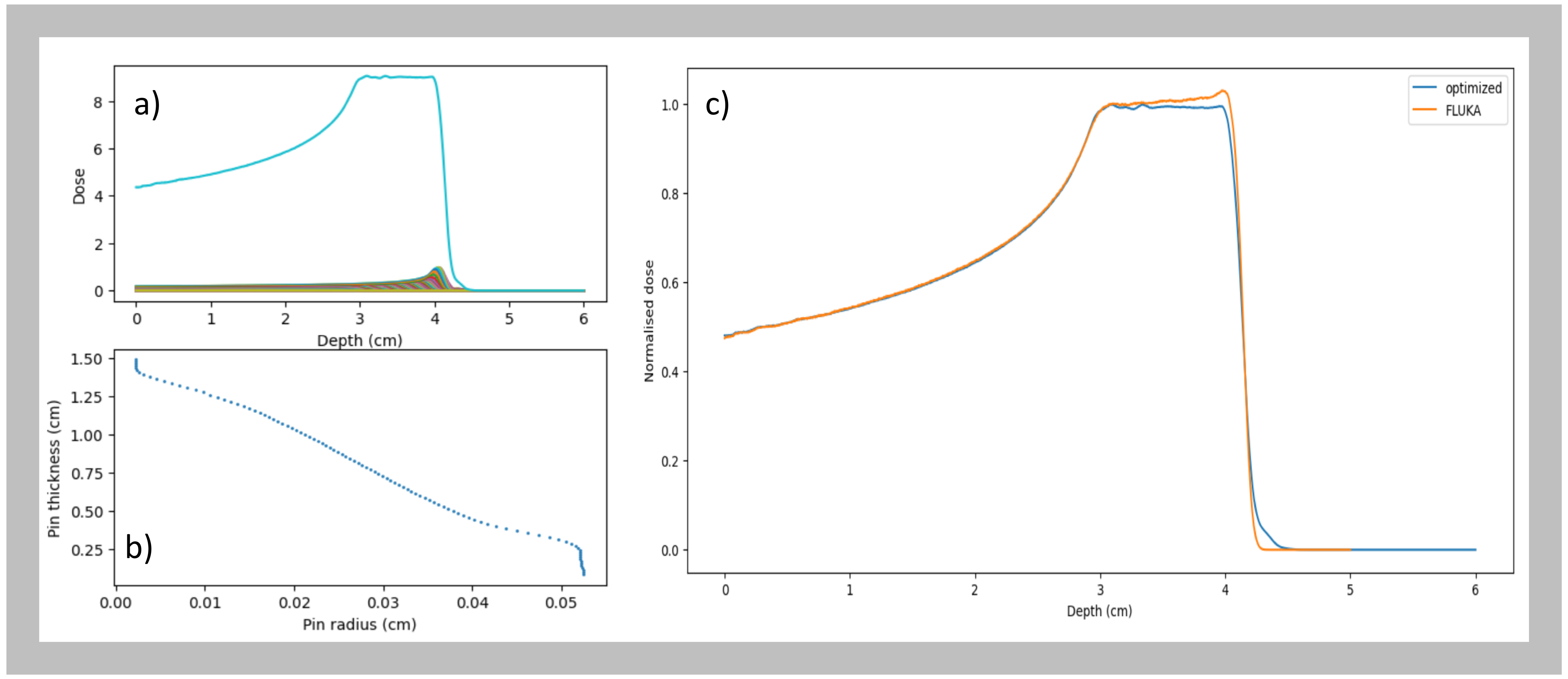

Figure 3: a) optimized SOBP and its constituent Bragg peaks, b) optimized HEDGEHOG pin contour from tip to base, c) optimized SOBP overlaid on SOBP generated from a Monte Carlo simulation of that HEDGEHOG.

Current progress

There has been significant progress towards the aims of this research, but some aspects of the design are yet to be incorporated and refined. All stages of HEDGEHOG production have now been created and tested to an extent with the first 3D prints successfully completed (figure 1). The process can implement desired beam parameters which stand up reasonably well to testing in simulations, and this can be done quickly with minimal effort required to design new HEDGEHOGs.

Future developments

However, there is much still to do. On top of the refinement of the optimization algorithm, the meshing of the design for 3D printing could be customized to better maintain similarity with the simulated geometry.

Also, a key feature of the HEDGEHOG design is that by varying the pin heights the peak dose region can be conformed to the proximal and distal edges of the target. This aspect is yet to be explored fully and could increase the reliability of beam shaping. Furthermore, the 3D printing method used strongly affects the final product through density and defects, and this has not yet been studied closely. Full beamline testing of printed HEDGEHOGs will be conducted in the coming months, informing the design process and allowing comparison with simulated data.

Summary

Modification of the TRIUMF PTRC beamline is needed to enable more complex FLASH experiments, and the HEDGEHOG appears to meet the requirements for this. A quick way to design and test HEDGEHOGs is in development with promising results, but significant refinement remains to be completed.

Discovery, accelerated