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Combining Scanning Spot Weight Optimization With Ridge Filter Design For Single-energy Proton Pencil Beam

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Objective

To develop an optimization procedure of spot weight and ridge filter (RF) dimension for single-energy proton pencil beam and apply it to a water phantom with a square-shape target in the center (prescription dose 50 Gy).

INTRODUCTION

Few energies are available for FLASH pencil beam in clinics. At the same time switching energy during irradiation increases treatment time and may reduce flash effect. To irradiate the entire volume with a single-energy FLASH proton pencil beam, it requires a proper spot scanning map to cover the lateral extension and a ridge filter to spread out the Bragg peak for longitudinal coverage.

We developed a procedure to optimize beam scanning spot weight and ridge filter dimension for single energy proton pencil beam. It was based on a fast Monte Carlo dose engine (FDC) and our in-house developed optimizer based on the L-BFGS algorithm.

The first two steps of this 3-step procedure are important. We creatively generated a dummy IMPT plan, in which different energy layers in a standard IMPT plan are simulated by the same energy but including different thickness of PMMA in the beam path. We modified our dose engine to make particles go through different thickness of PMMA when it gets to different layers in the dummy IMPT plan. Another special thing for this dummy plan is that all layers are with the same spot map. After spot weights were obtained from the dummy IMPT optimization, the spot weights can be converted to RF because the spot weight is proportional to the ladder area in the ridge filter. The summary of the spot weights at the same spot across different layers are the weight for a real IMPT plan with a single layer.

The optimization procedure was proved to be efficient in a water phantom and is promising for real patient application.

METHODS AND MATERIALS

This optimization process included three steps.

(1) A dummy IMPT plan was created by replacing different energy layers in a real IMPT plan with single energy but inserting different numbers of equal-thickness PMMA slabs in the beam path. Every layer in this plan has the same spot map and the spot distance was determined by the beam width used. Doses for all beamlets was calculated with a fast Monte Carlo dose engine (FDC) and fed to the L-BFGS algorithm for spot weight optimization.

(2) The optimized spot weights were converted to RF dimensions using its relation to the ladder area in the ridge filter. The summary of the spot weights at the same spot across different layers were assigned to a real IMPT plan with a single-energy layer.

(3) The single-energy layer IMPT plan was reoptimized with the ridge filter in the beam path.

Table 1. DVH indices and HI.

Indices	D98	D95	D5	D2	HI
Value (Gy)	46.6	47.8	52.6	53.3	1.1
Value (%)	93.2	95.6	105.2	106.6	

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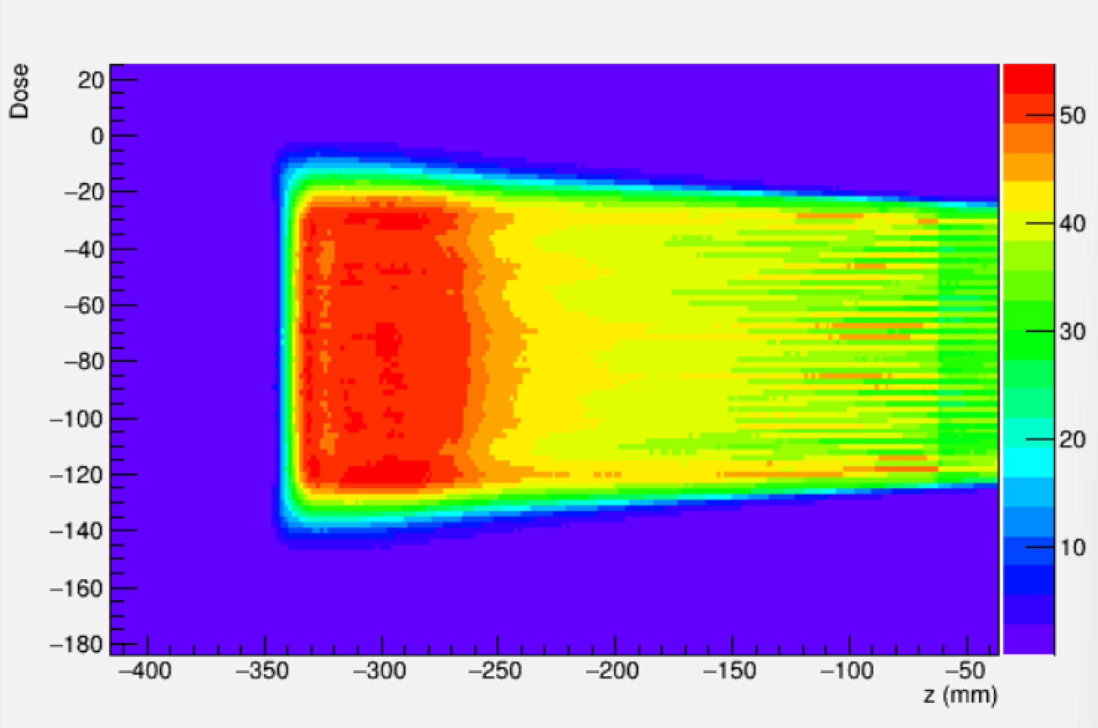
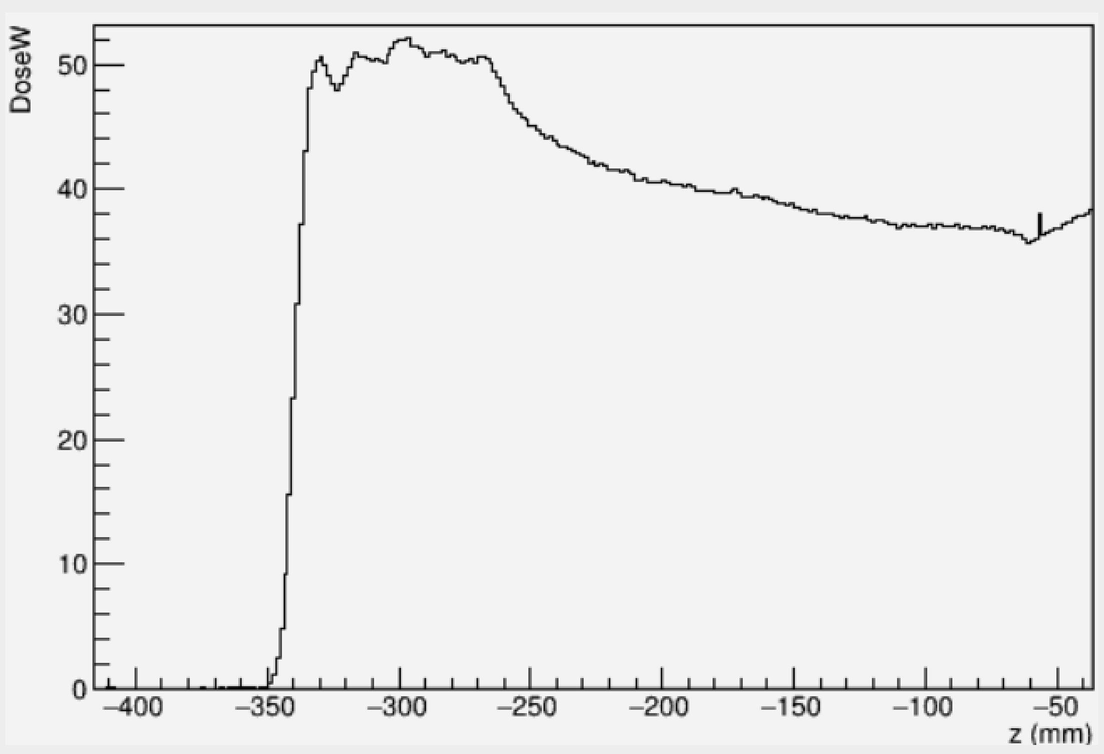
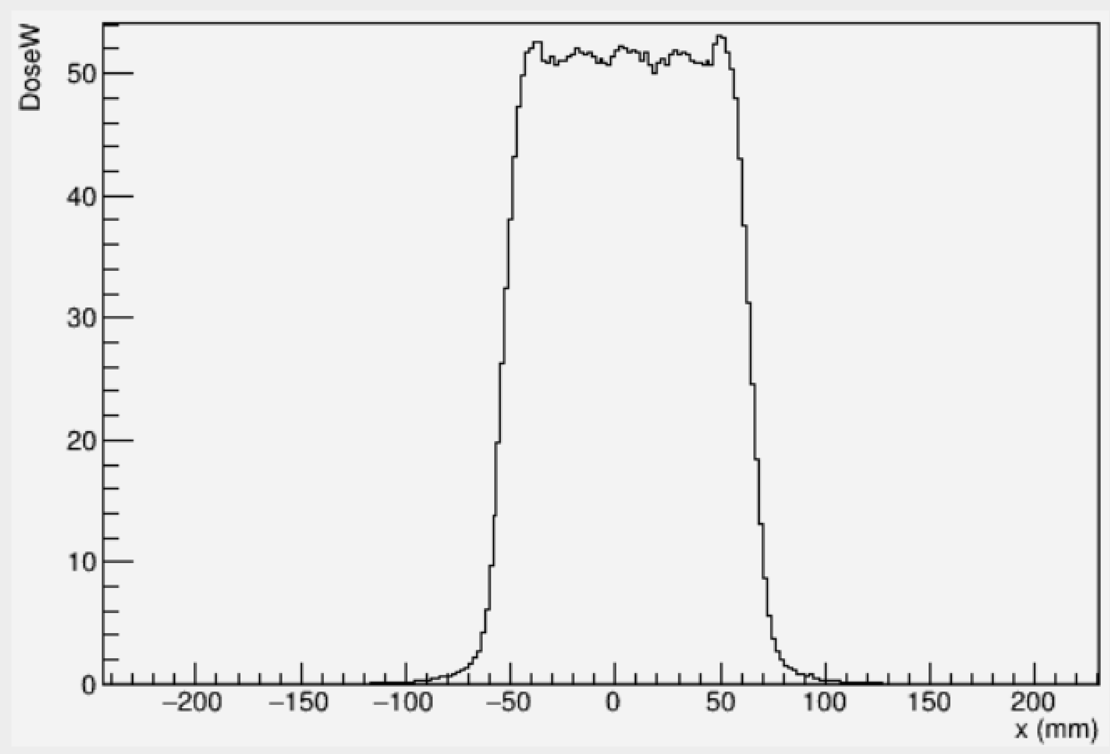
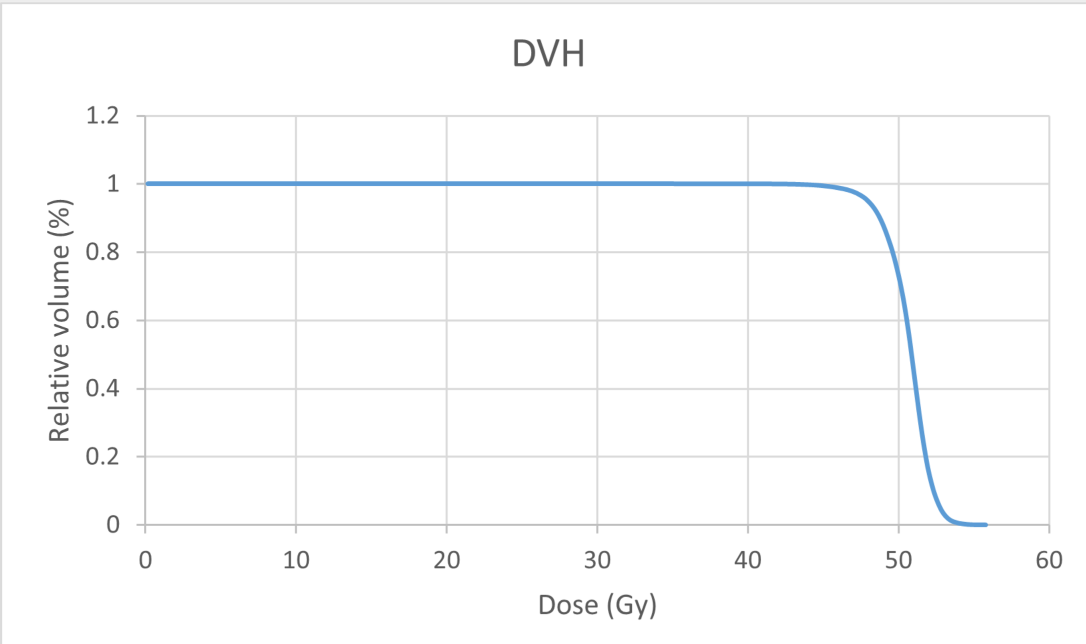
RESULTS

For the water phantom, the single layer plan used 208.3 MeV beam with a spot distance of 5 mm. The ridge filter was composed of 484 pyramids, and each pyramid had a base size of 3.974×3.974 mm², a total thickness of 66 mm and 22 ladders. The DVH indices for the target are 46.6 Gy (93.2%) for D98, 47.8 Gy (95.6%) for D95, 52.6 Gy (105.2 %) for D5, 53.3 Gy (106.6%) for D2. The Homogeneity Index is 1.1.









DISCUSSION

We developed an optimizer for Ridge Filter and other beam shaping components for passive scattering FLASH proton beams in 2022 [1]. In this project, we expanded the Ridge Filter optimization strategy to scanning FLASH proton beam.

Compared to the passive scatter beam, scanning beam is much narrower. So many spots instead of single one are required to cover the entire lateral dimension of a target. Optimizing spot weights with the Ridge Filter can uniformly cover the target without a collimator or compensator used for passive scattering beam.

Saving dose distribution of each beamlet for optimization becomes impractical with the same method used for passive scatter beam due to the substantially increased number of spots. To overcome this challenge, we created a dummy IMPT plan in which different energy layer was replaced by inserting different thickness of PMMA with the same energy. We modified FDC to make particles go through different number of PMMA slabs when it reads plan and perform dose calculation.

Spot weights from the optimized dummy plan can be converted to Ridge Filter dimension and real spot weights for a single layer IMRT plan. With the single layer IMRT plan and optimized Ridge Filter, we re-run the optimization to improve the dose distribution.

Compared with the passive scatter beam, less beam shaping components are required because spot position and weights can be varied to help the dose distribution. For the same reason, the optimized scanning beam shows better conformity in lateral direction.

The conformity in the longitudinal direction is not as good as the optimized passive scattering beam due to the approximation in converting spot weights of the dummy plan to Ridge Filter dimension: weight is proportional to ladder area in the ridge filter. This approximation is more accurate for the passive scatter beam.

But in general, the optimized plan has high quality from the HI and different DVH indices.

CONCLUSIONS

This procedure works for the water phantom according to the acceptable plan parameters. This procedure is promising for real patient application with flash beam.

REFERENCES

1. Wang Q, Titt U, MohanR, et al. Optimization of FLASH proton beamsusing a track-repeating algorithm. Med Phys.2022;49:6684–6698