Magnetically Focused Proton Irradiation of Small Volume Radiosurgery Targets Using a Triplet of Quadrupole Magnets

Patrick Q. McGee[1], Grant A. McAuley[1] , James M. Slater[1], Jerry D. Slater[1,2], Andrew J. Wroe[1,2]

[1]Loma Linda University School of Medicine, Loma Linda, CA
[2]Department of Radiation Medicine, Loma Linda University Medical Center, Loma Linda, CA

Introduction

Proton therapy is an advantageous choice for the irradiation of tumors in proximity of critical structures due to rapid dose fall off and high dose deposition at target compared to dose at the surface of the patient (ie, peak-to-entrance dose ratio (P/E)). However, with target fields below 1.0 cm, as often encountered in proton radiosurgery, multiple Coulomb scattering (MCS) broadens proton beams leading to a diminished P/E ratio and reduced dose delivery efficiency (DDE) (Fig 1).

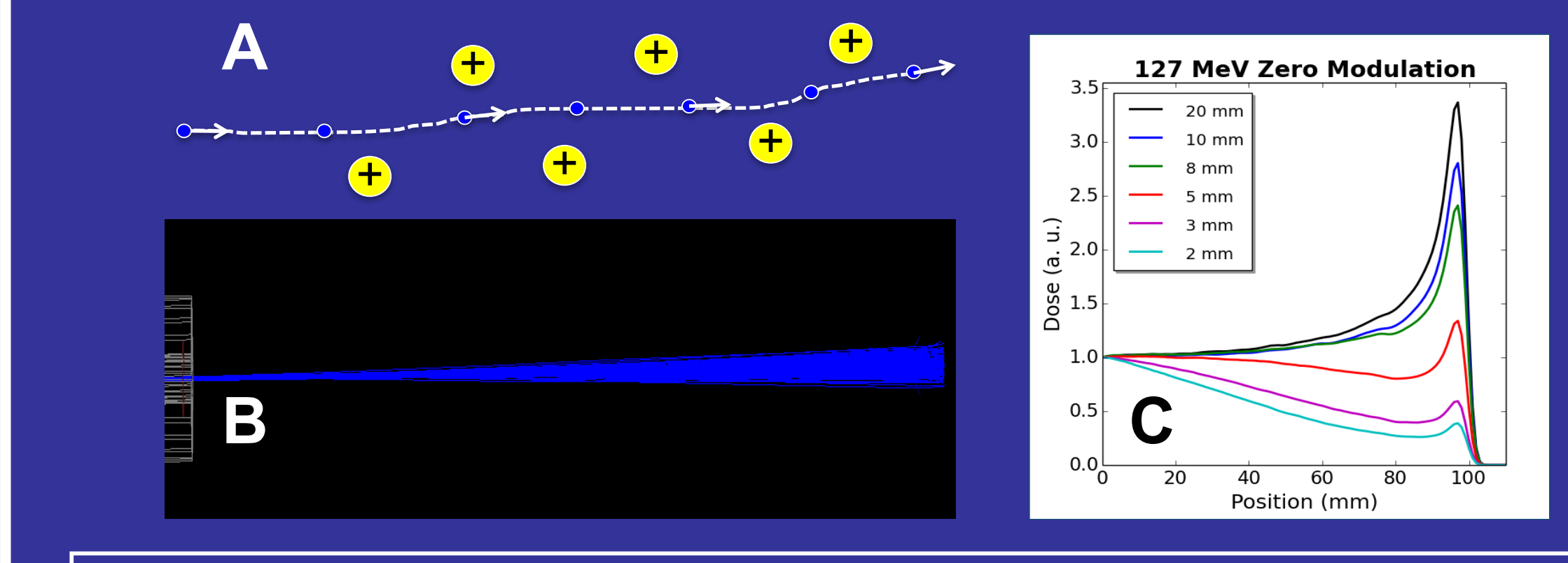


Fig 1: (A) Multiple interactions of protons with atomic nuclei lead to (B) beam broadening and (C) Bragg peak degradation that increases as beam diameter decreases.

Research in our laboratory suggests magnetic focusing of protons before tissue entrance counteracts MCS, leading to reduced P/E and decreased treatment times.

Purpose

To investigate the potential clinical advantages of proton magnetic focusing with a triplet of quadrupole magnets

Hypothesis

Magnetic focusing of protons will counteract MCS experienced during beam travel, increasing P/E ratio and delivering more protons to the target per unit time

Clinical Significance

Magnetic focusing could reduce radiation damage to normal tissue and deliver enhanced dose to the target in less time compared to unfocussed collimated beams (the current standard of practice in radiosurgery). The potential benefits to the patient are reduced treatment times, less target motion during treatment, and reduced dose to surrounding normal tissue. Such improvements would be immediately applicable to clinical proton radiosurgery practice (Fig 2).

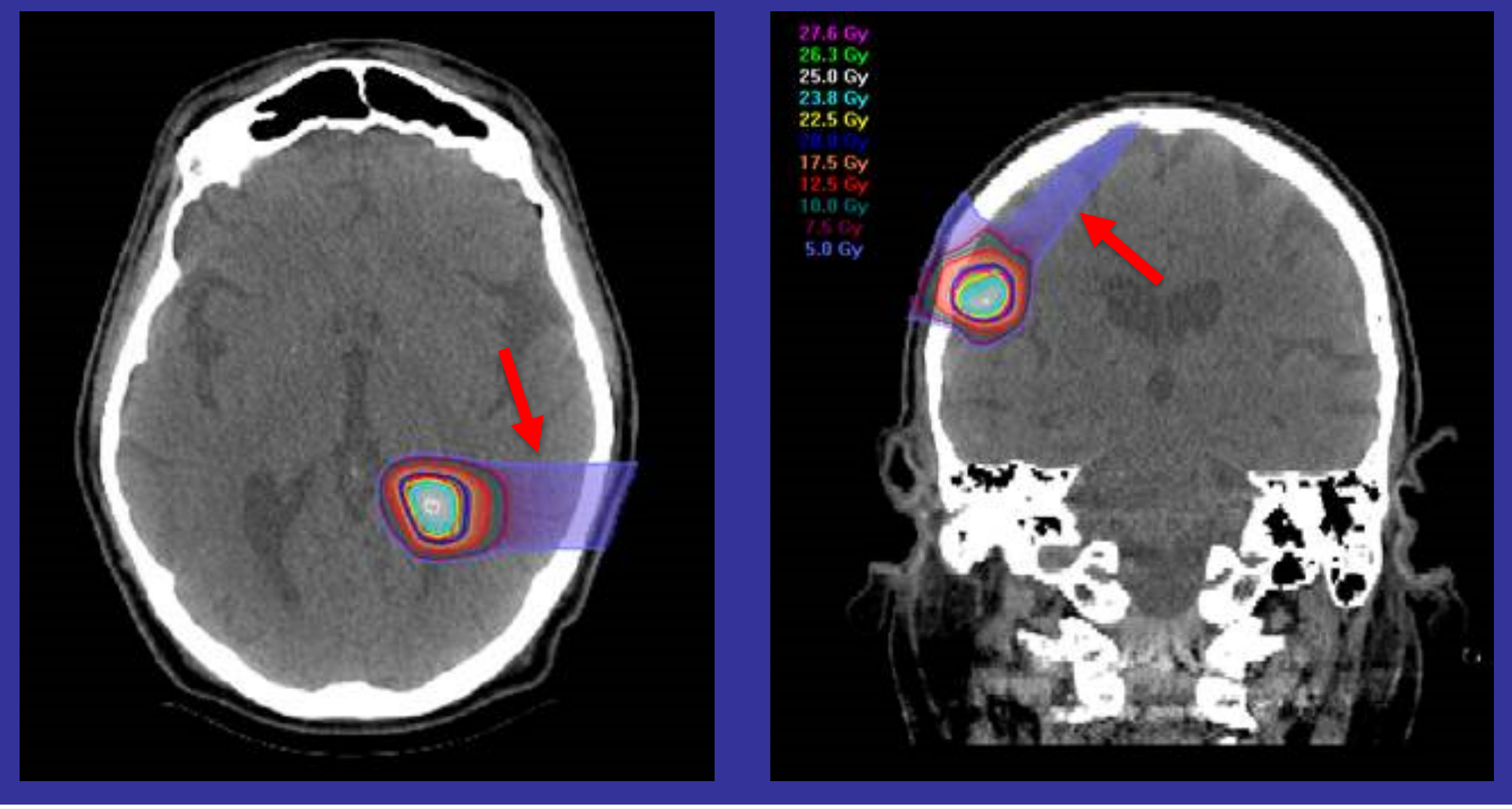


Fig 2: Intracranial brain tumors irradiated by proton radiosurgery (arrows show entrance dose delivered to non-target tissue).

Methods

Monte Carlo (MC) simulations of 127 MeV protons were performed using a model of the Gantry 1 clinical beam line at James M Slater MD Proton Treatment and Research Center (Fig 3). Dose deposited by proton beams transported through a triplet of quadrupole magnets (MF3) was compared to that of beams without magnetic focusing (UNF). Three triplet sets of magnets were used, each with a different magnetic field gradient (150, 200 & 250 T/m). Initial beam diameters were 5, 6, 8, 12, 15, 18, and 20 mm for MF3 and UNF beams.

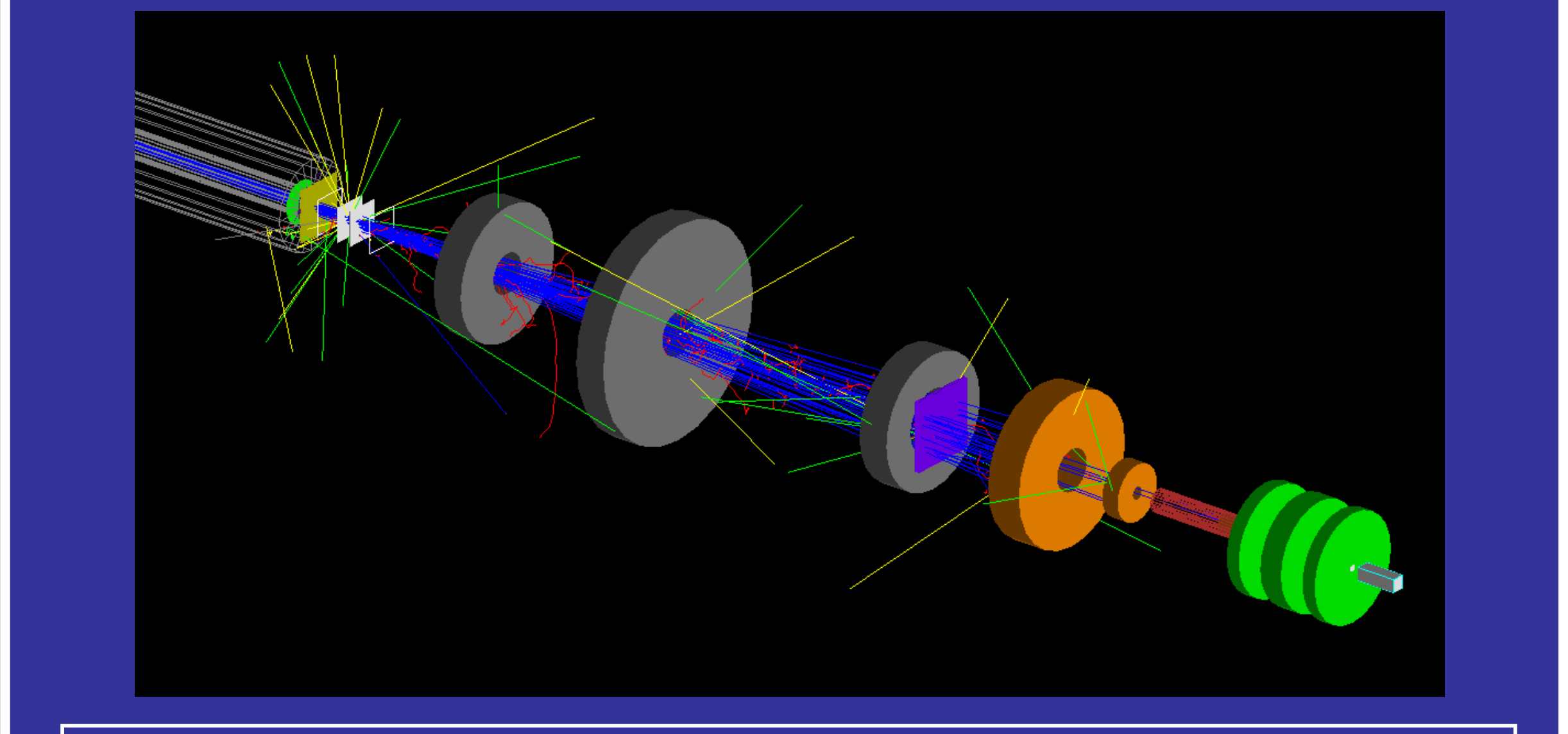


Fig 3: Monte Carlo Simulations were performed of 127 MeV protons (blue) focused by three quadrupole focusing magnets (green) using the Geant4 C++ toolkit.

Experiments analogous to the MC simulations were performed using 127 MeV protons with collimator diameters equal to those used in the simulations (Fig 4). Magnets consisted of 24 segments of Sm_2Co_{17} permanent magnetic material adhered into cylinders (150, 200 & 250 T/m field gradients). MF3 dose distributions were measured with a PTW PR60020 proton diode and EBT3 film and were size matched at target depth and compared with UNF beams.

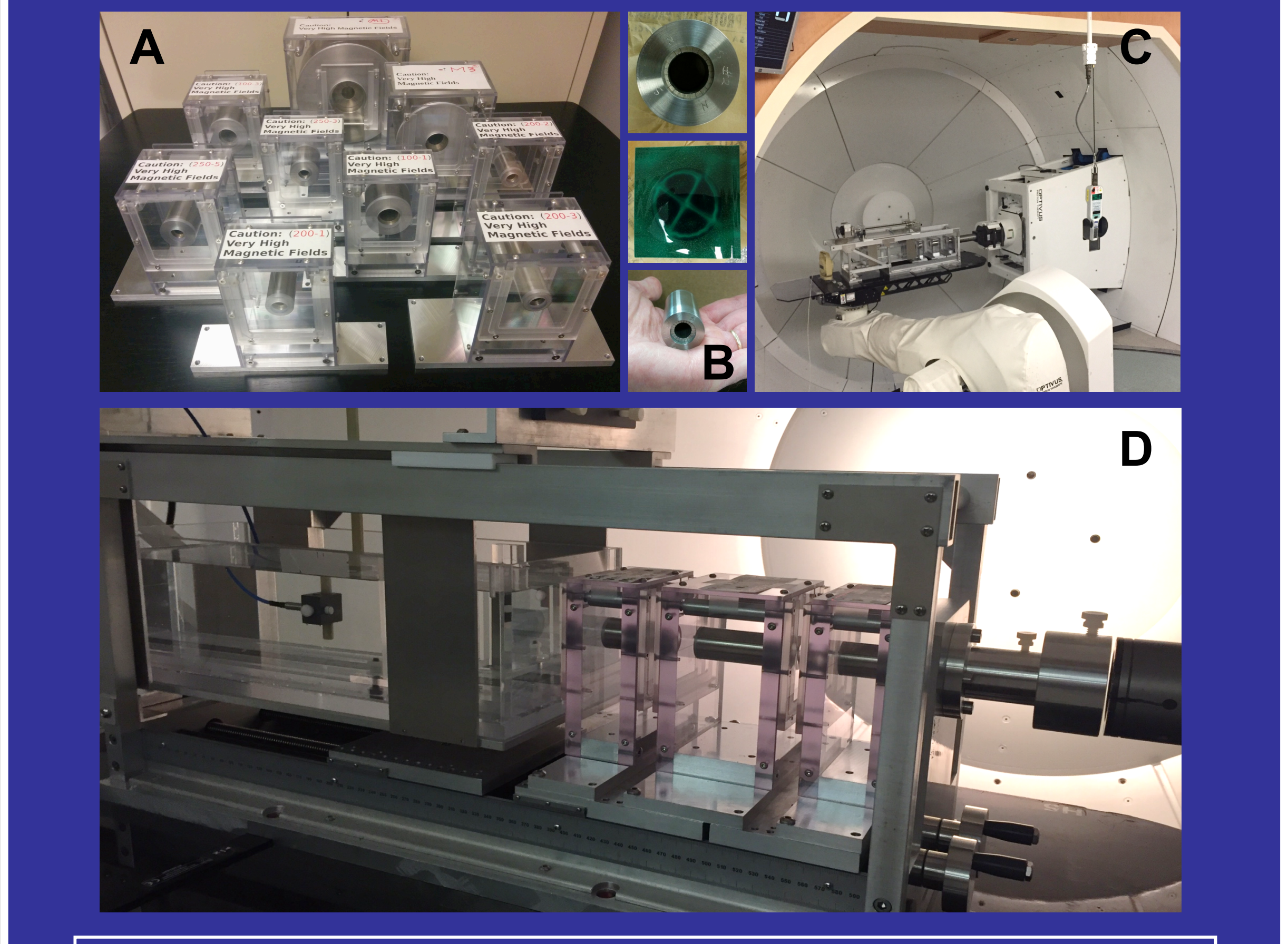
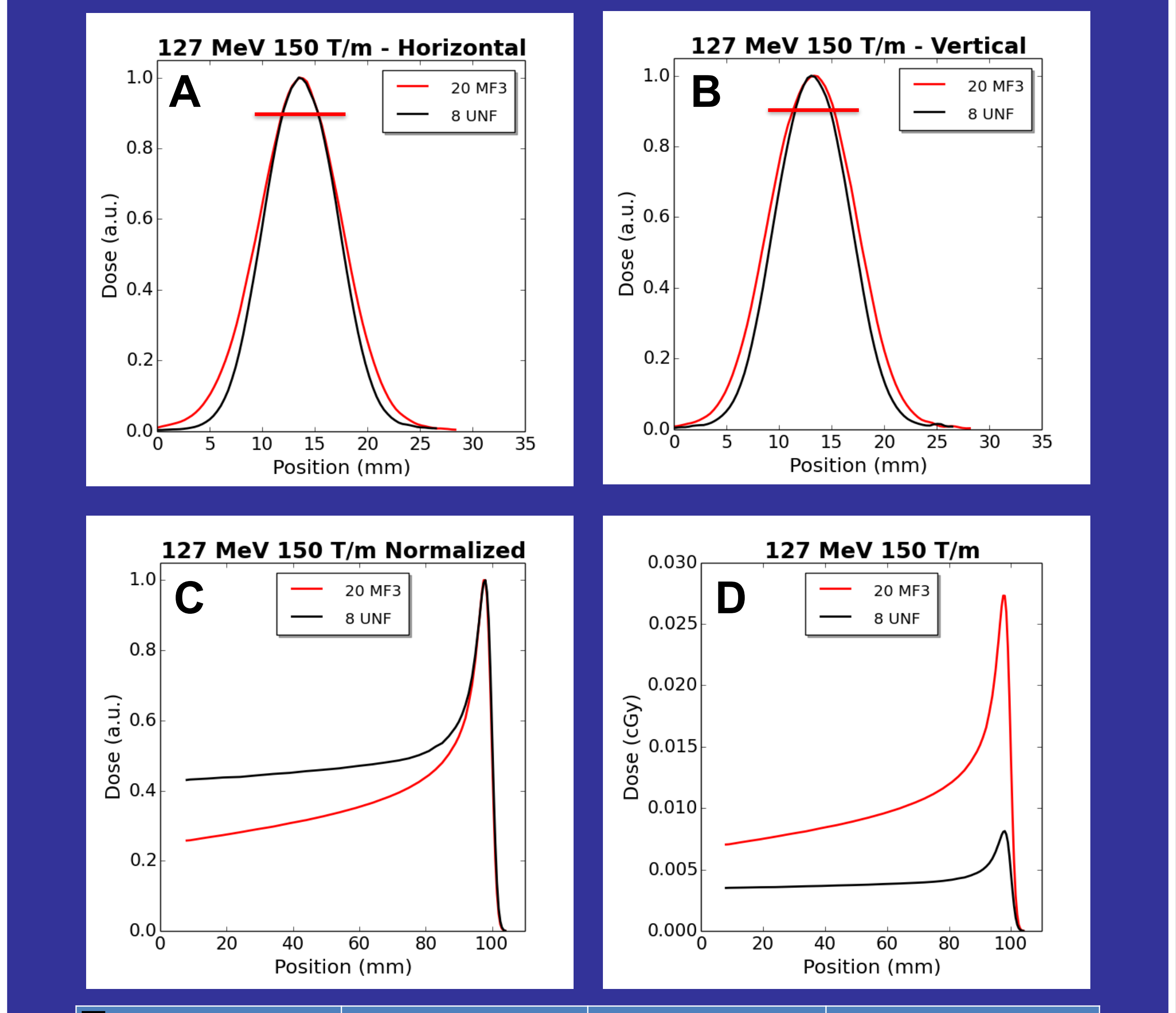


Fig 4: Focusing Experiments - (A ,B) Quadrupole focusing magnetic assemblies. (C, D) Experimental setup showing a triplet set of focusing magnets upstream from a water tank.

Results

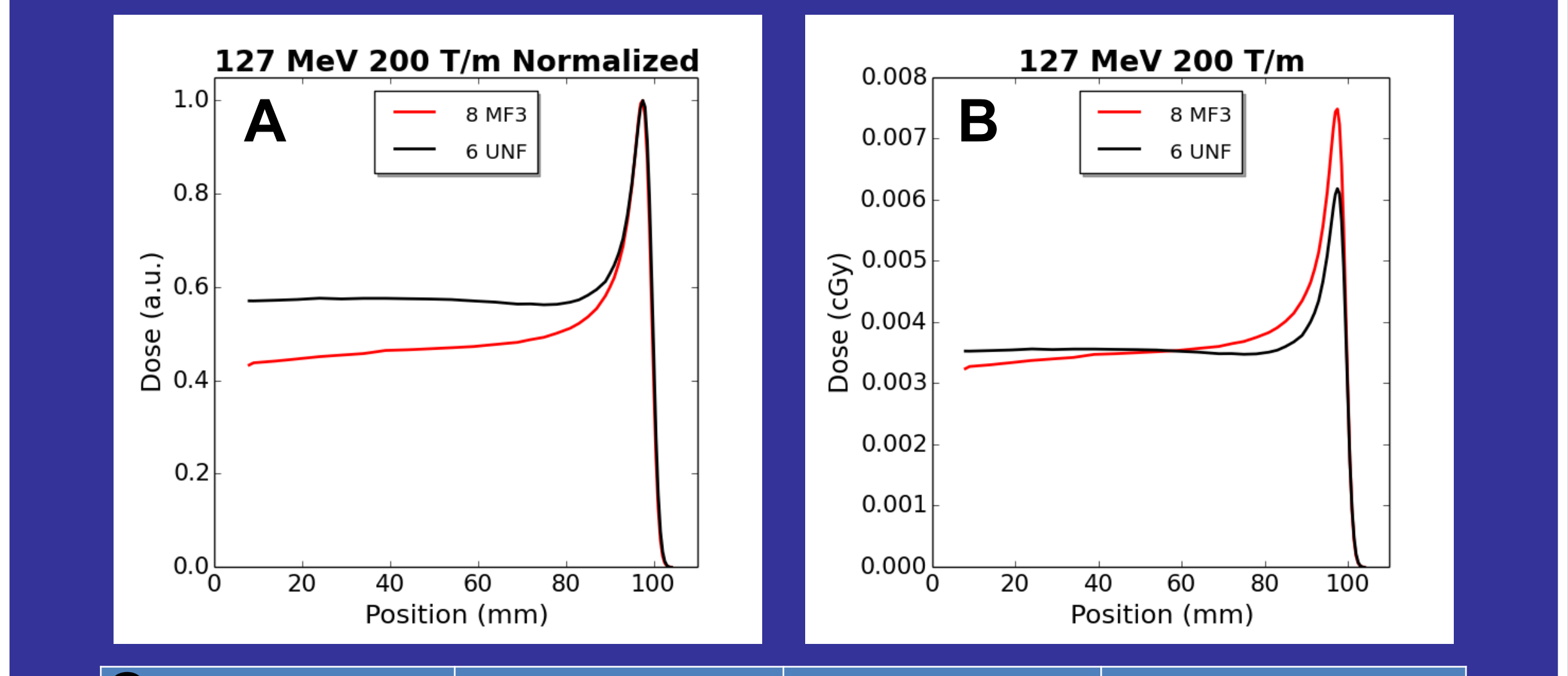
Preliminary experimental results showed 20 mm MF3 beams compared in size to 8 mm UNF beams using 150 T/m magnets (3.3 mm diameter at target, red bar in Fig 5A & B). However, the P/E ratios were 67% larger and DDE was 3.4x greater for the MF3 beams (Fig 5C - E).



E MF3 vs. 8 mm UNF	B Gradient (T/m)	P/E Gain	Efficiency Gain
20 mm MF3	150	67.0%	3.4x

Fig 5: MF3 vs. UNF Beams – (A-E) 20 mm MF3 beams using 150 T/m magnets compared with 8 mm UNF beams. Table E compares P/E ratios and beam delivery efficiency. Red bar designates target dose level.

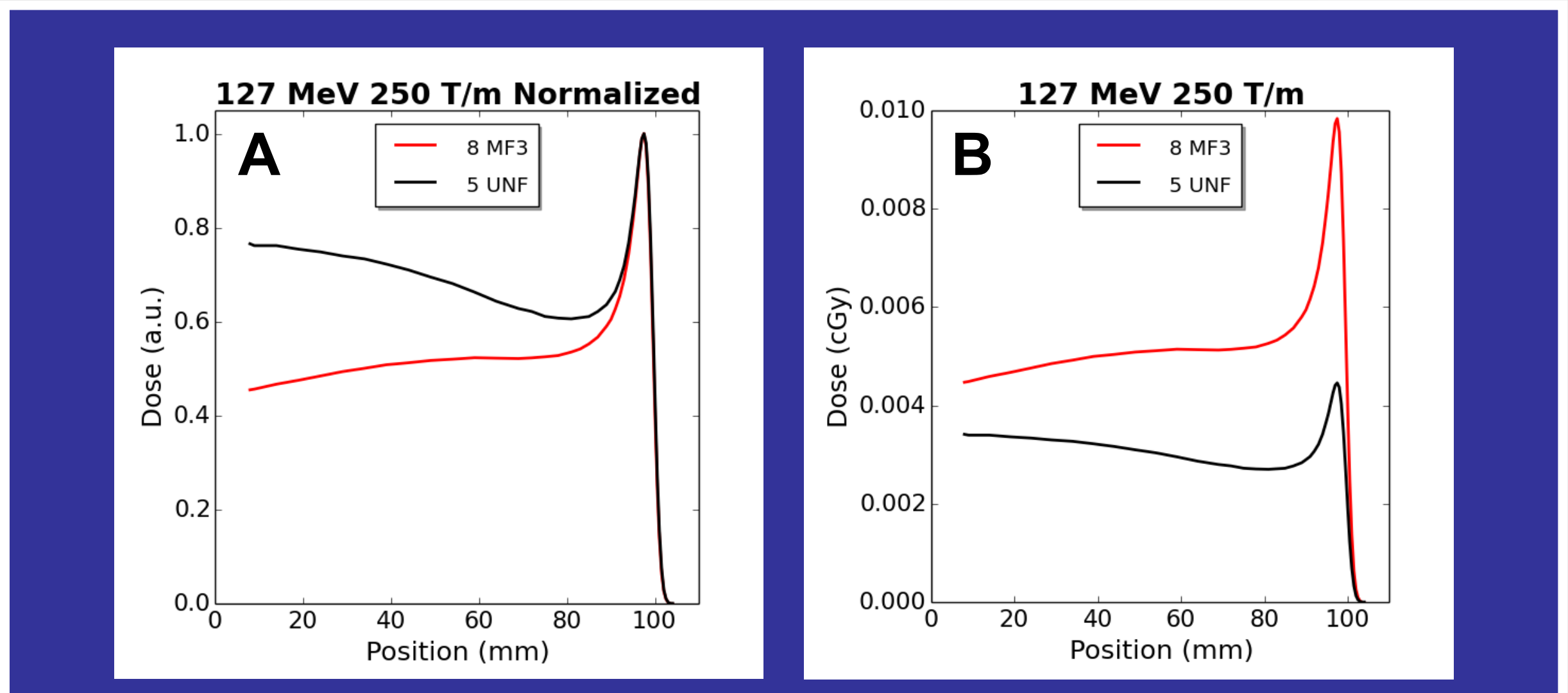
Focusing smaller diameter beams yielded similar results. 8 mm MF3 beams matched 6 mm UNF beams (2.7 mm target) using 200 T/m magnets with P/E dose improvements of 23.7% and 1.2x gains in DDE (Fig 6).



C MF3 vs. 6 mm UNF	B Gradient (T/m)	P/E Gain	Efficiency Gain
8 mm MF3	200	23.7%	1.2x

Fig 6: MF3 vs. UNF Beams – (A - C) 8 mm MF3 beams using 200 T/m magnets compared with 6 mm UNF beams. Table C compares P/E ratios and beam delivery efficiency.

Finally, 8 mm MF3 beams that were focused with a stronger magnet (250 T/m) matched 5 mm UNF beams (2.5 mm target) and showed P/E dose improvements of 66.7% and 2.2x gains in DDE (Fig 7).



C MF3 vs. 5 mm UNF	B Gradient (T/m)	P/E Gain	Efficiency Gain
8 mm MF3	250	67.7%	2.2x

Fig 7: MF3 vs. UNF Beams – (A - C) 8 mm MF3 beams using 250 T/m magnets compared with 5 mm UNF beams. Table C compares P/E ratios and beam delivery efficiency.

Conclusions

- Consistent with our hypothesis, magnetic focusing of proton beams showed improved P/E ratios and DDE compared to unfocused beams
- Magnetic focusing has the potential to improve peak to entrance dose ratio up to ~ 67%
- Magnetic focusing has the potential to improve efficiency in dose delivery up to ~ 3.4x
- Clinically, magnetic focusing would benefit the patient by reducing dose to normal tissue, lessening target motion, and decreasing treatment times
- These focusing magnets are available commercially, inexpensive, do not require power or cryogenic cooling, and easily incorporated into common existing hardware

Future Work

Future work includes the development of a prototype radiosurgery treatment cone that incorporates a triplet of focusing magnets (Fig 8).

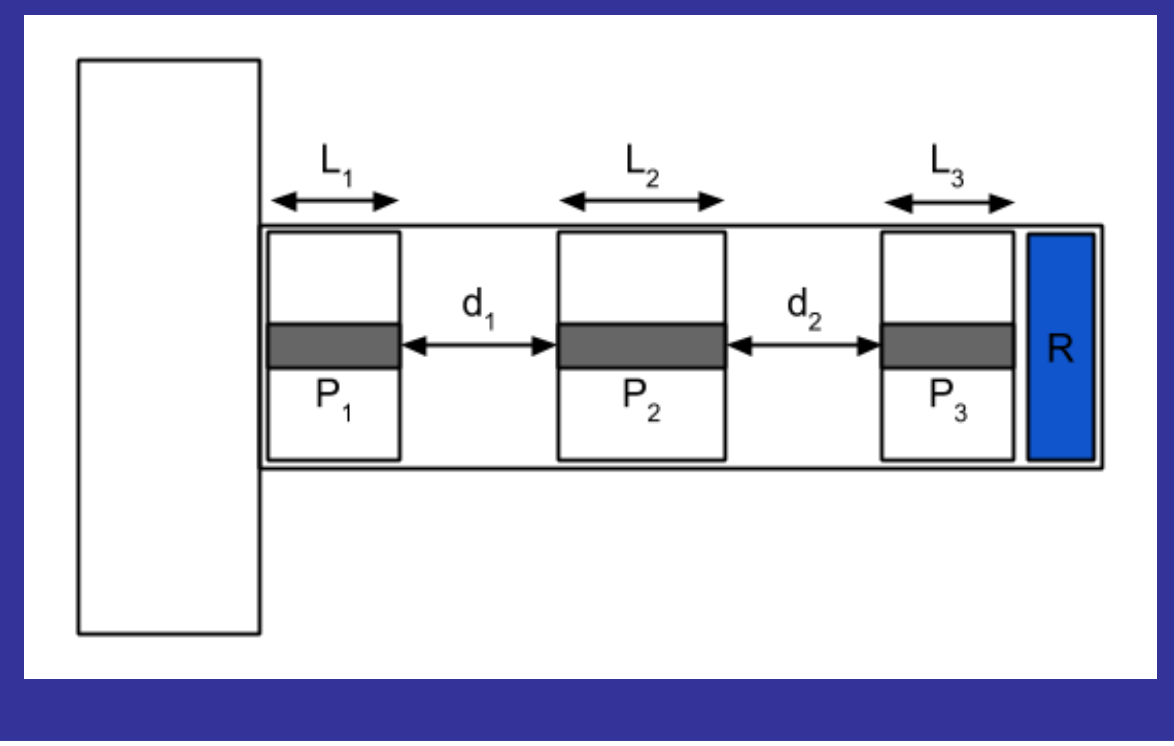


Fig 8: Future Prototype Treatment Cone – Schematic of proposed cone using three focusing magnets with focusing powers of P_1, P_2 and P_3 and range shifter (R)

Acknowledgements

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Contact: Grant McAuley gmcauley@llu.edu