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Design of An Adaptable Permanent-Magnet Quadrupole Triplet for Refocusing of Energy Degraded Proton Beams for Small Animal Irradiation

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Purpose: Energy degradation and refocusing of clinical proton beams to energies and dimensions relevant for small animal irradiation.

Methods: Geant4 Monte Carlo simulations were carried out to degrade a 75 MeV clinical proton beam by graphite to 20-60 MeV. A lattice based on permanent-magnet quadrupoles (PMQs) was designed using the beam-optics code elegant, to refocus the resulting large emittance beams to iso-center. The drift lengths and collimator openings were further optimized for the same range of energies while maintaining a small spot at iso-center, fulfilling additional design constraints. The PMQs were modeled in Radia and CST to define design parameters and tolerance levels.

Results: A triplet of PMQs was optimized for focusing 20-60 MeV proton beams at the iso-center, ~70 cm downstream the degrader. Two collimator assemblies, with two pairs of rectangular collimators each, dynamically defined the accepted emittance upstream the magnets. The strong magnetic field gradient of ~350 T/m required for the magnets was found feasible using Hallbach-type quadrupoles modeled using 16 NdFeB segments.By dynamically adjusting the collimators, spot sizes smaller than 1 mm FWHM were achieved for an energy spread up to 4 % with transmissions below 1 %. Compared to a collimator-only passive beam delivery, neutron fluence at the iso-center below 10 % was observed, along with improved entrance-to-peak and plateau-to-peak ratios of the simulated laterally-integrated dose distributions in a water phantom.

Conclusion: A permanent-magnet quadrupole triplet with high field gradients can be used to refocus energy degraded clinical proton beams for preclinical studies. Spot sizes below 1 mm FWHM can be achieved for degraded beams with energy spreads <4 % by beam shaping with collimators upstream the magnets. PMQ beamline results in reduced neutron fluence and improved laterally-integrated dose distributions.

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