Using non-linear beam optics to shape the lateral penumbra of a proton beam: Proof of concept

Anne I. S. Holm[1], Stine S. Korreman[1,2], Søren P. Møller[3], and Jørgen B. B. Petersen[1]
[1]Aarhus University Hospital, Department of Medical Physics, Aarhus, Denmark
[2]Aarhus University Hospital, Danish Center for Particle Therapy, Aarhus, Denmark
[3]Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark

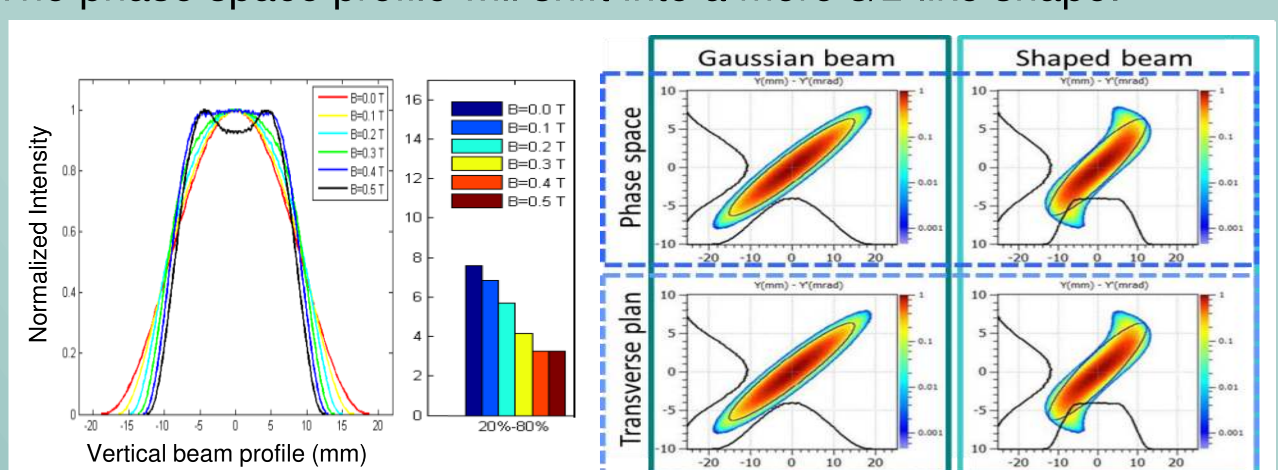
BACKGROUND AND INTRODUCTION:

A major benefit of particle therapy compared to conventional X-ray therapy is the low dose deposited after the Bragg peak. If a tumor is located near critical organs at risk (OAR), beam angles towards the tumor which stop just before the OAR may seem to be an advantage. This however is not used clinically, due to range uncertainty and the unknown RBE in the distal edge. Thus, the lateral beam penumbra is the primary tool in reducing the dose to the organs at risk.

The lateral beam distribution is determined by the delivery technique used. Modern proton therapy centers employ pencil-beam scanning. In pencil beam shaping small proton beamlets are magnetically scanned over the target volume in a spot-by-spot fashion one energy layer at a time. For each individual spot the position and the intensity can be varied, resulting in optimal target coverage and maximal OAR sparing. One major advantage of pencil beam shaping over passive scattering is that no patient specific apertures or compensators are needed, which greatly improves the workflow.
For pencil beam shaping the lateral fall-off outside the target is dictated by the pencil beam, which can be inferior to the one obtained for a collimated passively scattered beam.

Many studies have suggested the use of MLCs or dynamic collimation systems in order to reduce the lateral penumbra. Collimation may be used to reduce the lateral beam penumbra, but may also increase the ambient neutron flux. Here, we present an alternative solution; we show that non-linear beam components can be used to shape the beam without introducing high Z components, like Wolfram, in the beamline.

For a standard Gaussian beam both the transverse profile and the profile in phase space is Gaussian. By introducing non-linear components, i.e. octupoles, in the beamline, the transverse profile will shift, and for octupole the shift is into a more box-like distribution. The phase space profile will shift into a more s/z-like shape.



MATERIALS AND METHODS:

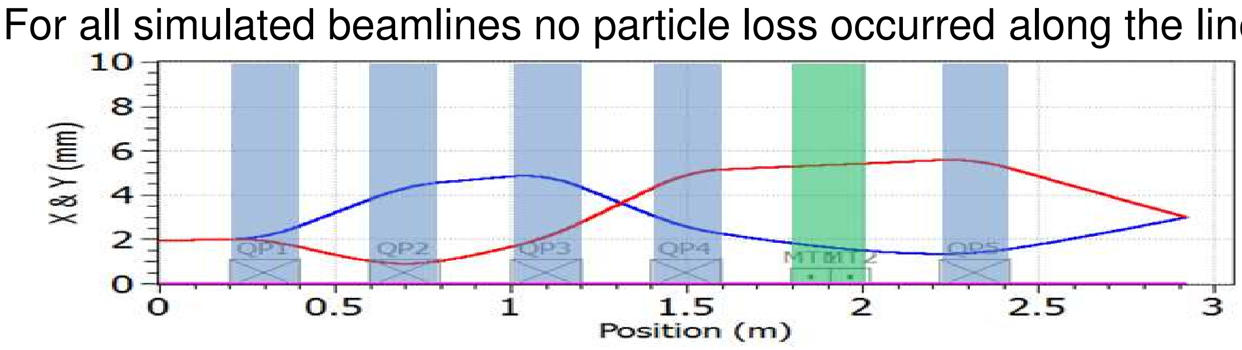
- A generic proton beamline with five quadrupoles and one octupole was simulated using TraceWin for beam envelope computations and Monte Carlo simulations of the lateral beam distribution (1.000.000 protons).
- All beam line input parameters, e.g. current, energy and beam spot sizes, were comparable to those of clinical delivery systems.
- The beamline was optimized to obtain maximal sharpening of the lateral vertical penumbra.
- The lateral fall-off is estimated by the 20%-80% distribution width.

CONCLUSIONS:

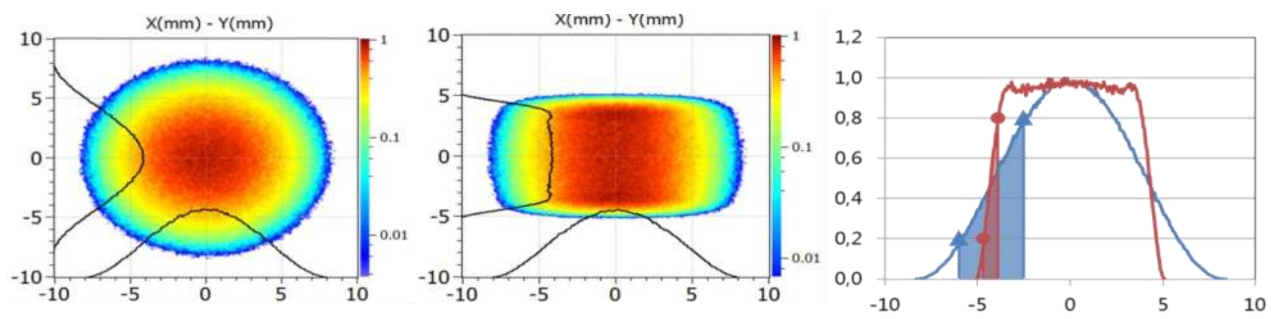
- **The transversal spot distribution may be changed from Gaussian-like to box-like by introducing an octupole.**
- **The lateral beam penumbra is reduced by at least 66% for a 70 MeV beam and by at least 77% for a 250 MeV beam.**
- **The lateral beam penumbra can be significantly reduced without the use of any collimation**

RESULTS:

As an example the horizontal and vertical root-mean-square (rms) beam envelopes for 250 MeV and a spot size of 3 mm are shown. For all simulated beamlines no particle loss occurred along the line.



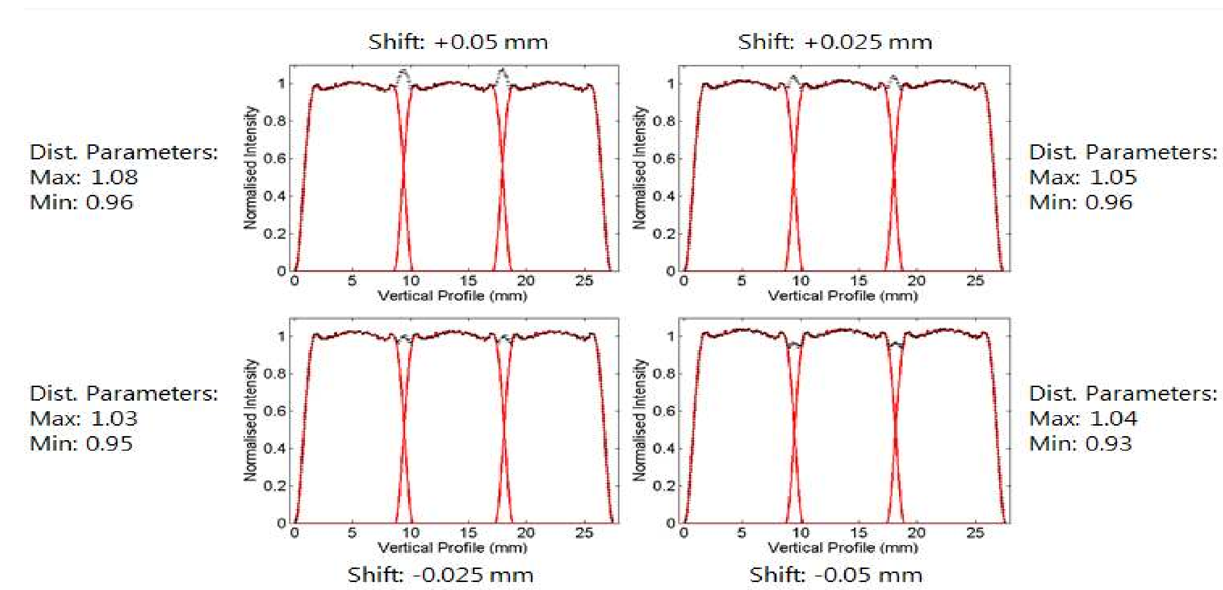
The vertical beam profile has a Gaussian-like distribution when the octupole is switched off, but, when the octupole is switched on, the beam output will have a box-like distribution. Below, the two beam distributions for a 250 MeV beam with a final spot size of 3 mm, and a comparison of the vertical beam profiles are shown.



Lateral fall-off for two energies as well as three spot sizes for each energy as a function of octupole modality are summarized below.

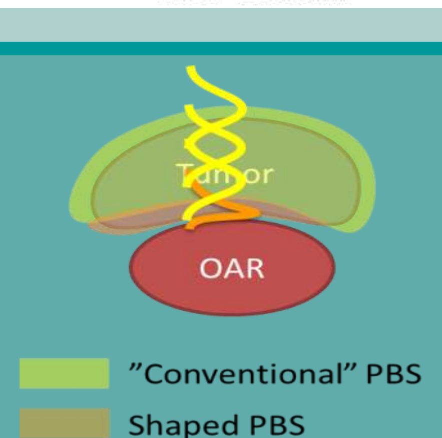
		20%-80% Penumbra (mm)		Reduction (%)
		Gaussian beam	Box-like beam	
70 MeV	σ_{spot} = 4.5 mm	5.0	1.7	66
	σ_{spot} = 6.0 mm	6.7	1.5	78
	σ_{spot} = 7.5 mm	9.5	1.5	84
250 MeV	σ_{spot} = 3.0 mm	3.5	0.8	77
	σ_{spot} = 4.5 mm	5.1	0.8	84
	σ_{spot} = 6.0 mm	6.6	0.8	88

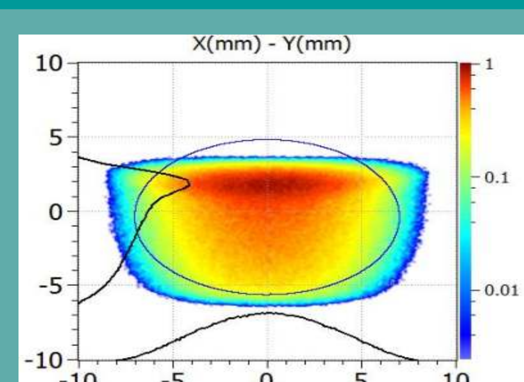
To simulate the robustness of the overlay between adjacent spots, the vertical beam projections have been added with different shifts between spots. With shifts up to 0.5 mm in either direction, i.e. placing the spots closer together or further apart, the beam distribution remains fairly constant.



DISCUSSION:

Non-linear components, with higher orders than eight, may shape the beam into many different profiles. One could imagine generating a beam with a high intensity in one side of the beam and low in the other (see figure to the right for an example). So, if most of a tumor is covered by "conventional" spot scanning, the part just adjacent to the OAR is covered by a shaped spot distribution, which towards the tumor has a fall-off and towards the OAR has a very high gradient and high intensity. Used in this fashion one may only need a horizontal beam and shaping in one direction.





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