

Design and implementation of a robust and cost-effective double-scattering system at a horizontal proton beamline

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Originally published:

November 2016

Journal of Instrumentation 11(2016), T11001

DOI: <https://doi.org/10.1088/1748-0221/11/11/T11001>

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A robust and cost-effective proton double-scattering system for experimental purposes

Ein robustes und kostengünstiges Doppelstreusystem für Protonenexperimente

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Abstract

Purpose: With an increasing number of proton therapy facilities coming into operation, also the interest for research at proton beams increases. Though many centers provide beam at an experimental room, some of these rooms do not feature a device for radiation field shaping, a so called nozzle. Therefore, a robust, mobile, and cost-effective double-scattering system for horizontal proton beamlines has been designed and implemented.

Materials and methods: The nozzle is based on the double scattering technique. Two lead scatterers, an aluminum ridge-filter and two brass collimators were optimized in a simulation study to form a laterally homogeneous 10 cm × 10 cm field with a spread-out Bragg-peak (SOBP). The parts were mainly manufactured using 3D printing techniques and the system was set up at the experimental beamline of the University Proton Therapy Dresden (UPTD). Measurements of the radiation field were carried out using a water phantom.

Results: High levels of dose homogeneity were found in lateral (dose variation $\Delta D < \pm 2\%$) as well as in beam direction ($\Delta D < \pm 3\%$ in the SOBP). The system has already been used for radiobiology and physical experiments.

Conclusion: The presented setup allows for creating clinically realistic extended radiation fields at fixed horizontal proton beamlines and is ready to use for internal and external users. The excellent performance combined with the simplistic design let it appear as a valuable option for proton therapy centers intending to foster their experimental portfolio.

Zusammenfassung

Ziel: Mit einer steigenden Zahl sich in Betrieb befindlicher Protonentherapieanlagen steigt auch das Interesse an Forschung mit Protonenstrahlen. Zwar besitzen viele Zentren einen Experimentierraum mit Protonenstrahl, jedoch gibt es einige davon, die ohne eine Vorrichtung zur Strahlformierung – eine sogenannte Nozzle – ausgestattet sind. Daher wurde ein robustes, mobiles und kostengünstiges Doppelstreusystem für horizontale Protonenstrahlführungen konzipiert und implementiert.

Material und Methoden: Die Nozzle basiert auf der Doppelstreutechnik. Zwei Streuer aus Blei, ein Ridge-Filter aus Aluminium und zwei Kollimatoren aus Messing wurden zunächst in einer Simulationsstudie

optimiert, um lateral homogene $10\text{ cm} \times 10\text{ cm}$ Felder mit einem in Strahlrichtung ausgedehnten Bragg-Peak (SOBP) zu formen. Das System wurde an der experimentellen Strahlführung der Universitäts Protonen Therapie Dresden (UPTD) aufgestellt. Die Teile wurden hauptsächlich mittels der 3D-Druck-Technik hergestellt. Messungen des Strahlenfeldes wurden unter Nutzung eines Wasserphantoms durchgeführt.

Ergebnisse: Das System erreicht ein durch Messungen bestätigtes hohes Maß an Dosishomogenität sowohl in lateraler (Dosisvariation $\Delta D < \pm 2\%$) als auch in Strahlrichtung ($\Delta D < \pm 3\%$ im SOBP). Das System wurde bereits für strahlenbiologische und physikalische Experimente verwendet.

Schlussfolgerung: Der präsentierte Aufbau ermöglicht klinisch realistische ausgedehnte Strahlenfelder an horizontalen Protonenstrahlführungen und ist für interne und externe Anwender verfügbar. Die exzellente Leistungsfähigkeit kombiniert mit dem einfachen Design lassen diese Lösung als wertvolle Option für Protonentherapiezentren erscheinen, die beabsichtigen ihr experimentelles Portfolio zu stärken.

Keywords:

radiation field formation, radiobiology, ion beam therapy, proton therapy
Strahlungfeldformierung, Strahlenbiologie, Ionenstrahltherapie, Protonentherapie

1. Introduction

Particle therapy has the potential to improve radiotherapy due to its higher spatial dose conformity and biological effectiveness compared to photon irradiation. At the same time, full utilization of these advantages requires advanced capabilities regarding high-precision delivery and monitoring of dose and a profound understanding of the variability of the relative biological effectiveness (RBE) for different beam qualities and cells [1, 2]. Accordingly, considerable effort is put on research to enhance particle therapy.

While at particle therapy centers patient treatment is usually prioritized, several centers also provide an experimental or quality assurance (QA) room with a beamline available for particle therapy experiments. However, for some of these rooms field formation capabilities are insufficient to meet requirements for clinically relevant experiments. For example, the large experimental room at the University Proton Therapy Dresden (UPTD) has been set up with a fixed horizontal beam line without the capability to create laterally extended radiation fields. To perform experimental proton radiobiology campaigns, a device to form treatment fields comparable to clinical conditions had to be installed meeting several specifications. First, mounting and demounting of the device at the beam line before and after a dedicated experiment has to be fast and reproducible. Accordingly, mobility, compactness, and robustness are essential. Second, design and production should be time- and cost-effective and realized in a way that makes it also convenient for other centers to (re-)build a comparable device when necessary.

In this work, we present the design and setup of a dedicated mobile proton double scattering beam shaping device as is now available for experiments at the UPTD for internal and external users. Additionally, we show its measured performance to demonstrate the ability to form proton fields relevant for radiobiology and physics experiments.

2. Materials and Methods

2.1. Design of scattering nozzle

A formalism by Takada [3] for a dual-ring double scattering method for proton beam spreading was used as starting point to determine optimal design parameters for the double scattering nozzle. The following specifications served as input for the nozzle design:

1. lateral dose homogeneity in an area of $10\text{ cm} \times 10\text{ cm}$,

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- 28 2. spread-out Bragg-peak (SOBP) width of about 3 cm,
- 29 3. low neutron load in the target volume, and
- 30 4. possibility to shape lateral dose contours,
- 31 5. maximal total length of the nozzle setup of 150 cm (restricted by available space at the beamline),
- 32 6. simplicity of design (especially no moving parts).

33 To achieve the aforementioned objectives (in particular item 6) it was decided to radically reduce the
 34 parameter space by using only a single primary energy $E_p = 150$ MeV. The dimensions of all nozzle compo-
 35 nents were calculated by means of a dedicated software written in Python based on the parameters obtained
 36 with the Takada formalism. Specifically, the software translates the required scattering angles and proton
 37 stopping into material extensions by using Highland’s formula [4] and stopping power tables [5], respectively.

38 Figure 1 (upper row) shows a scheme of the setup. The beam enters the first scatterer (SC_1), which
 39 consists of a single lead foil to widen the lateral proton distribution. The second scatterer (SC_2) is a dual
 40 ring scatterer which is built from a lead foil covering the full beam radius and a thicker central (with
 41 smaller diameter) lead foil. SC_2 flattens the lateral fluence distribution, which is no longer Gaussian when
 42 leaving SC_2 . To compensate for the different energy loss in the inner and outer part of SC_2 caused by the
 43 different thicknesses of the foils, a compensator made from polymethyl methacrylate (PMMA) is applied.
 44 To obtain an SOBP with a homogeneous dose region, a one dimensional ridge-filter is placed downstream.
 45 Its properties were calculated using the approach by Bortfeld and Schlegel [6] and formulas by Jette and
 46 Chen [7]. To cut the radiation field laterally, two collimators are applied. While a single collimator would be
 47 sufficient to stop protons with an energy lower than 150 MeV, the primary function of the first collimator is
 48 to considerably reduce the neutron contamination in the target volume as shown in figure 1. The fabrication
 49 of the nozzle elements is described in detail in section 2.3.

50 2.2. Monte Carlo Simulation

51 A Monte Carlo simulation of the nozzle has been setup using SHIELD-HIT12A [8, 9] to achieve three
 52 goals: a) optimization and fine tuning of beam shaping elements, b) *in silico* verification of nozzle design,
 53 and c) simulation of radiation field as basis for a beam model.

54 Two different scorer arrangements were used covering either the whole setup or only the target volume
 55 distal to the second collimator. The former had a relatively coarse spatial resolution of $10 \times 10 \times 10$ mm³
 56 and the latter a high resolution of $2 \times 2 \times 1$ mm³ (1 mm in beam direction). The quantities dose, particle
 57 fluence, and linear energy transfer (LET) were scored for the total radiation field as well as differential for
 58 specific particle species. To estimate the proton efficiency (ratio of protons entering the first scatterer and
 59 the target region) proton numbers were counted by plane scorers.

60 2.3. Fabrication of nozzle elements

61 All elements of the nozzle are mounted on a 95 mm rail system by Thorlabs¹ to ensure lateral alignment.
 62 All holders are adjustable in height. Commercially available mounting accessories were combined with
 63 customized holders for all nozzle elements. The latter holders were made of plastic using the 3D-printing
 64 technique to ensure a fast, cost-effective and custom-fit production of these parts. Plastic components also
 65 have the advantage of relatively fast decaying activity created during irradiation.

66 Scattering foils were made of high purity (99.95%) lead delivered by Goodfellow². For the dual-ring
 67 second scatterer, the necessary energy compensator for the outer ring was made of PMMA (density $\rho =$
 68 1.19 g cm⁻³). The collimators were machined at the proton therapy workshop in exactly the same way as
 69 the apertures for patient treatment in double scattering mode. The material is brass type Cu58Zn39Pb3
 70 with a density $\rho = 8.5$ g cm⁻³.

71 The most complex part is the ridge filter, figure 2(a). It consists of 24 ridges each having a width of
 72 5 mm and a maximal height of 13.73 mm. A single ridge is divided in 50 steps, figure 2(b), each having an

¹Thorlabs Inc, Newton, New Jersey, USA

²Goodfellow GmbH, Bad Nauheim, Germany

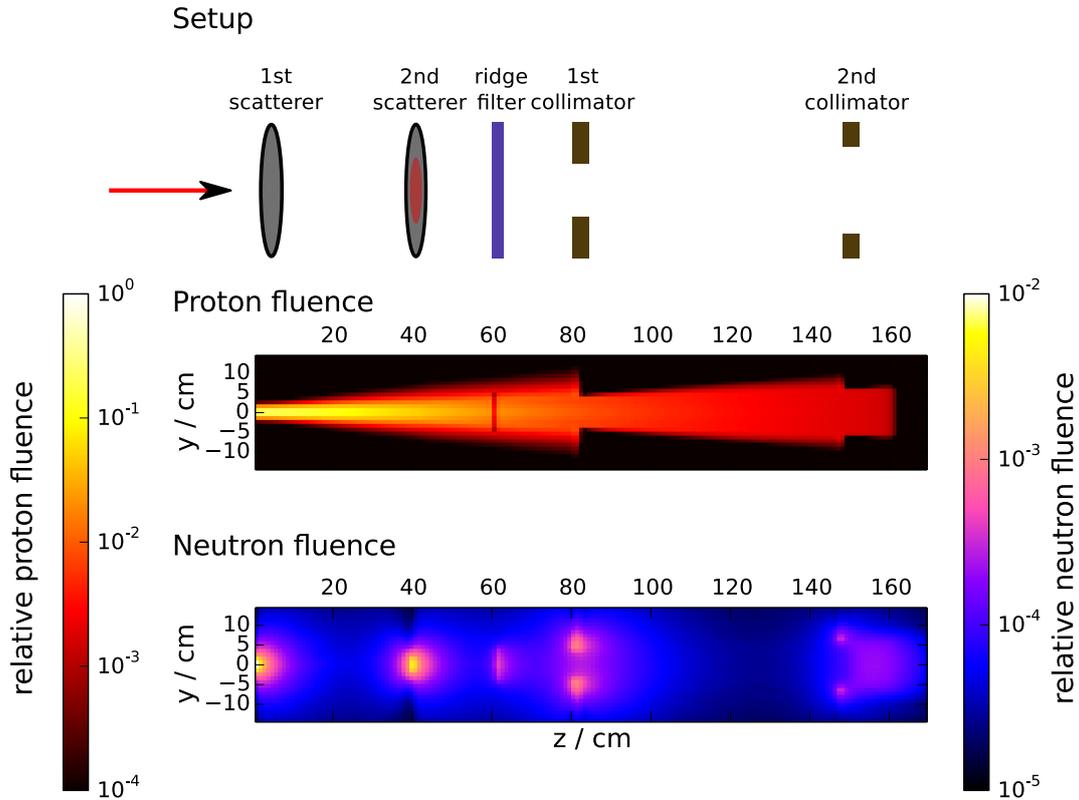


Figure 1: Schematic setup of the double scattering system along with simulated proton and neutron fluences in a central plane along the beam direction (z axis). The quantities are normalized to the number of incident protons. The effect of scatterers, collimators and the ridge-filter is, on the one hand, the shaping of the proton beam and, on the other hand, the creation of secondary radiation.

73 optimized step width proportional to the weight of the resulting Bragg-peak in the SOBP. The ridge-filter
 74 was manufactured of aluminum ($\rho = 2.7 \text{ g cm}^{-3}$) using the 3D-printing technique selective Laser sintering
 75 by techno-plastic³.

76 2.4. Measurement and analysis of dose distribution

77 The beamline at the experimental room of UPTD provides a proton beam with an energy $70 \leq E_p \leq$
 78 230 MeV . The lateral beam width is approximately $\sigma = 6 \text{ mm}$ at the beam exit window. The maximal
 79 available beam current depends on the selected energy and is largest at high energies with a maximum of
 80 30 nA [10]. A detailed analysis of the beam properties can be found in [11].

81 Relative and absolute dose measurements were carried out in a water phantom (type BluePhantom⁴)
 82 guided by the TRS 398 protocol [12] using PTW⁵ advanced Markus (type 34045) and Semiflex (type 31010)
 83 ionization chambers, respectively, to analyze the achievable dose homogeneity in the target region. Due the
 84 mechanics of the phantom the ionization chambers could not directly be positioned at the inner phantom
 85 wall and an absolute depth position had to be determined. Therefore, a spacer of known thickness was
 86 placed between the phantom wall and the chamber during phantom setup. The water equivalent depth of
 87 this chamber position was determined as the sum of the water equivalent thickness (WET) of the phantom

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⁴iba Dosimetry GmbH, Bahnhofstrasse 5, 90592 Schwarzenbruck, Germany

⁵PTW-Freiburg, Physikalisch-Technische Werkstätten Dr. Pychlauer GmbH, Lörracher Str. 7 79115 Freiburg, Germany

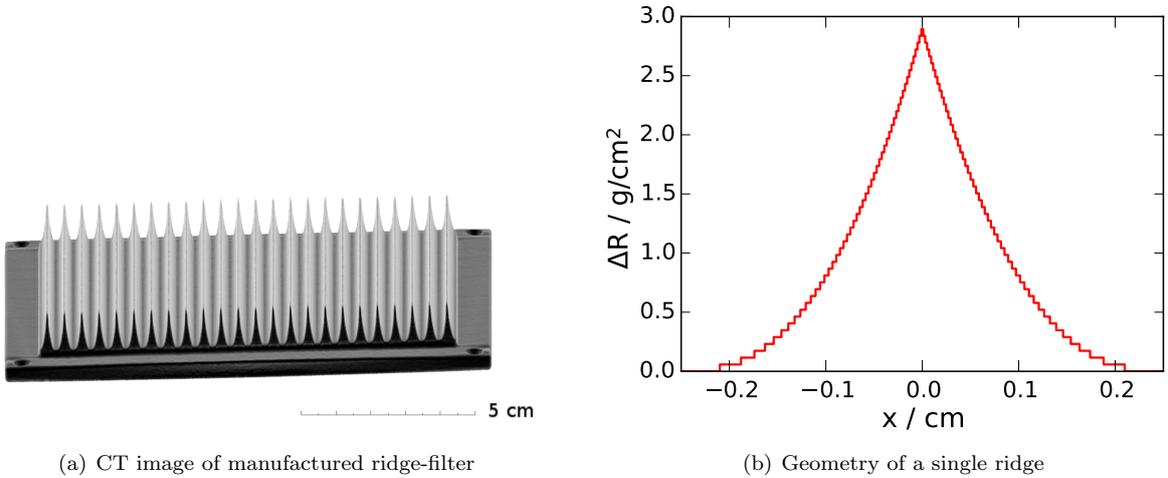


Figure 2: (b) Water equivalent thickness of a single element of the ridge filter. (a) Computed tomography image of the ridge filter acquired using a Siemens Somatom Sensation Open device. Image reconstruction was carried out using a protocol optimized for teeth imaging. The colors were inverted to visibility reasons.

88 wall (17.16 mm), the spacer thickness and the WET of the entrance window of the advanced Markus chamber
 89 (1.06 mm).

90 The desired homogeneous lateral dose plateau P had a width of $a = 10$ cm centered at the midpoint
 91 between the lateral 50% dose points. Normalization was done by dividing the lateral dose distribution by
 92 the mean value of P . The distances between the lateral 50% and 90% dose levels were considered as the two
 93 widths W_{50} and W_{90} , respectively. A linear fit, F_l , with slope parameter, s_l , was applied to the measured
 94 dose in the plateau region P for quantitative evaluation.

95 The depth dose distributions were normalized as follows: First, the curve was normalized to its maxi-
 96 mum. Second, the interval was selected, in which the dose was greater or equal 95%. From this interval,
 97 the proximal and distal quarters were subtracted. Third, the curve was normalized to the mean of the
 98 aforementioned remaining central interval. The ranges R_{50} and R_{90} were defined as the depths of the distal
 99 50% and 90% dose level, respectively. The distance between the proximal and distal 95% dose level was
 100 considered as the modulation width M of the SOBP. Similar to the lateral evaluation, linear fits F_d and F_f
 101 were used to quantify the slope s_d within the SOBP region and s_f of the distal fall-off. F_d was applied to a
 102 region, which was half the modulation M wide and centered within the SOBP, and F_f was applied between
 103 the distal 80% and 20% dose.

104 3. Results

105 3.1. Simulation and optimization

106 Figure 3 shows the profiles through the dose distribution obtained in the simulation study. Though
 107 statistical fluctuations are visible in the lateral and horizontal profiles, an acceptable dose distribution was
 108 obtained.

109 3.2. Implementation and setup of nozzle

110 The double-scattering nozzle was set up as shown in figure 4. A table specifying detailed measures of the
 111 beam-shaping nozzle elements can be found in Appendix A. The lower part of figure 1 visualizes the effect
 112 of the beam shaping elements in terms of proton and neutron fluences as simulated by SHIELD-HIT12A.
 113 Here, also the role of the first collimator is illustrated, namely, to keep unnecessary proton fluence away
 114 from the second collimator and, hence, lower the neutron production in the proximity of the target region.

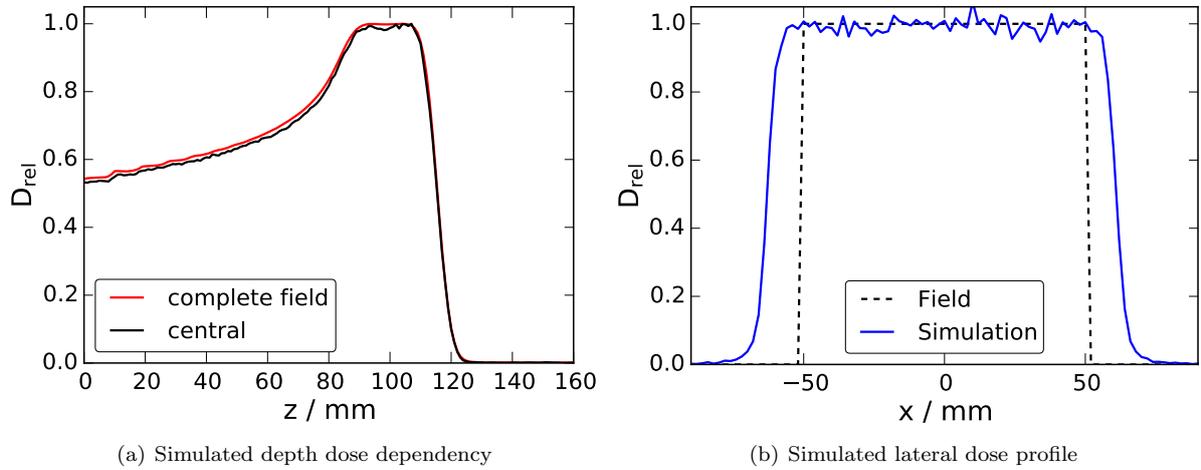


Figure 3: (a) Depth dose profiles obtained in the Monte Carlo simulation. Red line: dose averaged over the desired lateral field width; black line: dose along the central beam axis. (b) Simulated lateral dose distribution in the SOBP (100 mm depth). The dashed line shows the desired field extension.

115 The simulations revealed a relatively high efficiency of the design with 30% of all protons entering the setup
 116 also finally reach the homogeneous target region.

117 Prior to any proton experiment that required the nozzle, the latter had to be mounted in front of the
 118 exit of the proton beam line and removed afterward. As a first step, the rail system supporting the nozzle
 119 elements was adjusted relative to a positioning laser. Second, by using the Lynx⁶ detector for 2D dose
 120 acquisition, the nozzle elements were conveniently aligned with the proton beam axis with sub-millimeter
 121 accuracy in less than an hour. Thereby, a high degree of dose homogeneity could be ensured each time the
 122 system was set up.

123 3.3. Lateral dose distribution

124 Measurements of the lateral dose distribution were performed for different settings of the ridge-filter:

- 125 1. no ridge-filter in place
- 126 2. ridge-filter with $\alpha = 0^\circ$
- 127 3. ridge-filter with $\alpha = 45^\circ$

128 where α denotes the angle between the beam axis and the normal vector of the base plane of the ridge-filter.
 129 Dose characteristics in lateral direction, both horizontally and vertically, are summarized in Tab. 1.

130 For settings 1 to 3 a linear dose increase of up to 0.03%/mm was observed in the lateral dose plateau,
 131 figure 5(a). Such a tilt is a result of a slight misalignment of the second scatterer. Therefore, an additional
 132 measurement was carried out after the optimization of the mounting of the scatterer, referred to as setting
 133 4. Using this refinement a high level of dose homogeneity could be achieved in lateral direction, figure 5(b),
 134 with a variation of dose $\leq 1\%$ within the desired field size of $10 \times 10 \text{ cm}^2$. It should be noted, that the width
 135 is (intentionally) greater than the minimally desired homogeneous field width of $10 \times 10 \text{ cm}^2$. The openings
 136 of the collimators have been manufactured with an extra margin to avoid a decrease in dose at the edges
 137 when irradiating cell probes.

⁶iba Dosimetry GmbH, Bahnhofstrasse 5, 90592 Schwarzenbruck, Germany

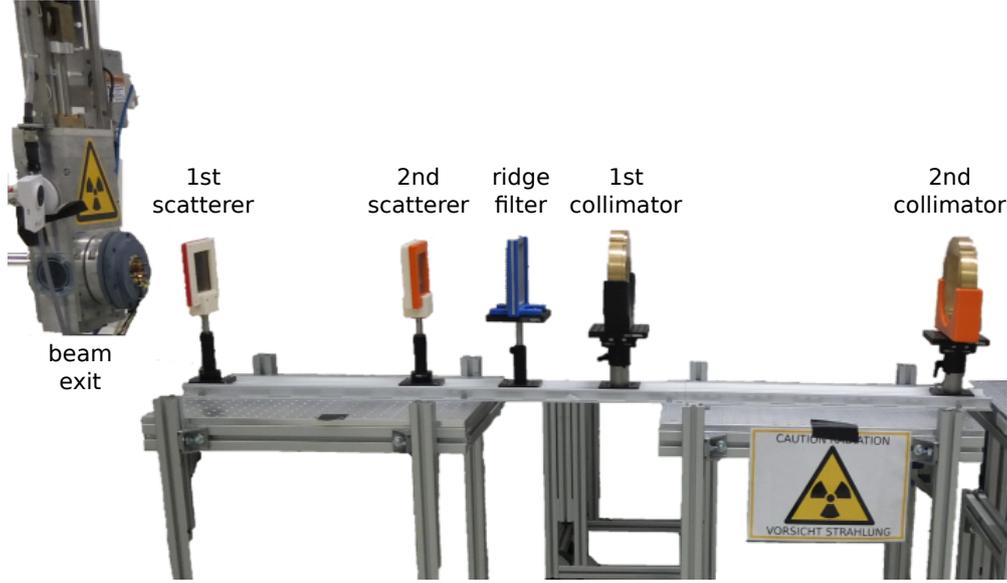


Figure 4: Complete setup of the scattering system with the two scatterers, the ridge-filter, and the two collimators.

Table 1: Characterization of radiation field in the lateral directions at a water-equivalent depth of 77 mm and 112 mm for settings 1-3 and setting 4, respectively. Dose given in %.

#	Setting	W_{50}/mm	W_{90}/mm	$\text{STD}(D_p)$	$\min(D_p)$	$\max(D_p)$	$s_1/\%/ \text{mm}$
Horizontal (x)							
1	no RiFi	129	122	1	98	103	0.016
2	RiFi $\alpha = 0^\circ$	129	121	1	99	102	0.013
3	RiFi $\alpha = 45^\circ$	129	119	1	97	101	0.021
4	after adjustment	129	119	1	99	101	0.019
Vertical (y)							
2	RiFi $\alpha = 0^\circ$	130	120	1	98	103	0.031
3	RiFi $\alpha = 45^\circ$	130	122	1	97	103	0.005
4	after adjustment	129	118	0	99	101	0.000

RiFi: ridge-filter; STD: standard deviation; D_p : dose distribution in plateau; s_1 : lateral slope

138 3.4. Depth-dose distribution

139 Depth-dose curves were measured for the same three settings of the ridge-filter as for the lateral case.
 140 Dose characteristics of the depth-dose profile are summarized in Tab. 2. For settings 1 and 2, measured
 141 depth-dose distributions are shown in Fig. 6. By rotation of the ridge-filter from 0 to 45 degrees (cf. [13]
 142 for details), it was possible to (continuously) increase the modulation width M of the SOBP from 19.9 mm
 143 to 31.9 mm. A high level of dose homogeneity within the central SOBP was found with only a small slope
 144 toward the distal end. The ridge-filter reduced the ranges and the steepness of the distal fall-off of the
 145 SOBPs in comparison to the pristine Bragg peak.

146 3.5. Customization for different experiments

147 Depending on the demands of a specific experiment, the scattering setup can be further customized:
 148 Range compensators can be inserted up- or downstream the second collimator to adjust the particle energy.
 149 To create more complex radiation fields, customized collimators – just as apertures for patient treatment –
 150 can be inserted in the holder of the second collimator. Such a setup has, e.g., be used for an in-beam PET
 151 experiment [14].

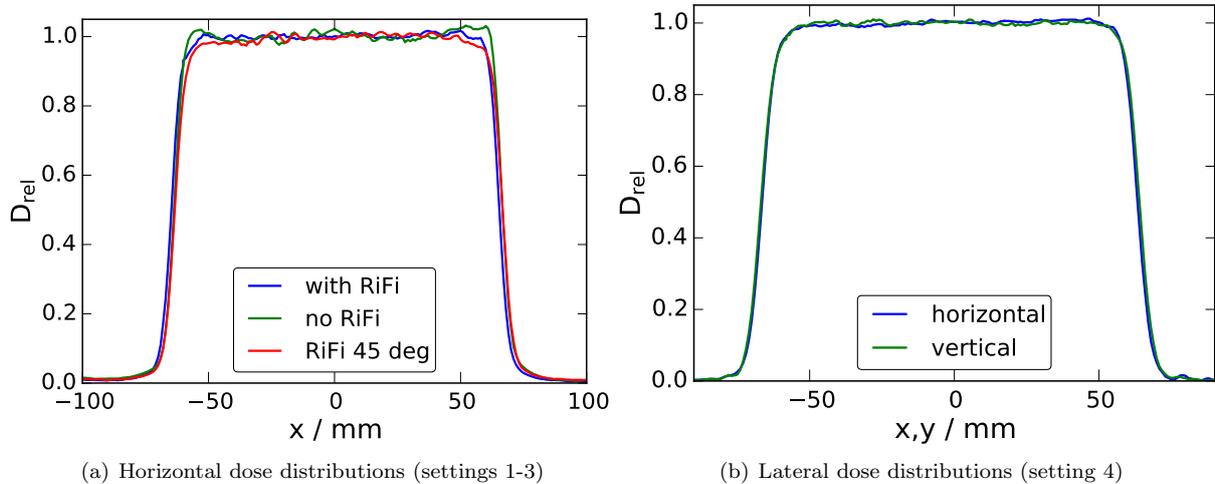


Figure 5: Measured lateral dose distributions. (a) Horizontal dose profiles with different settings of the ridge filter at a water equivalent depth of 77 mm. (b) Lateral dose profiles after refinement of the positioning of the second scatterer in the depth of the SOBP (112 mm).

Table 2: Characteristic measures of the depth-dose distributions. Dose given in %.

#	Setting	R_{50}/mm	R_{90}/mm	M/mm	$s_d/\%/mm$	$s_f/\%/mm$
1	no RiFi	125.5	123.0	–	–	-18
2	RiFi $\alpha = 0^\circ$	119.4	115.8	19.9	0.077	-13
3	RiFi $\alpha = 45^\circ$	117.3	113.6	31.9	0.038	-13

RiFi: ridge-filter; s_d : slope within SOBP; s_f : slope of distal fall-off

152 Absolute dosimetry is performed as in clinical operation. The dose measured by a sensor in the radiation
 153 field, e.g. an ionization chamber or film, is correlated to the charge acquired by the transmission chamber
 154 at the beam exit. This procedure yields a number of so called monitor units, required to deliver the desired
 155 dose. Absolute dose as function of MU should be determined prior to an experiment to verify the stability
 156 of this relation on a daily basis as part of a QA procedure. The control system at the experimental beamline
 157 of UPTD allows also for a direct connection of a PTW⁷ Unidos electrometer, to switch the beam off when
 158 a certain dose has been reached.

159 4. Discussion

160 We present a design of a mobile, robust, and cost-effective double scattering proton nozzle prototype that
 161 is useful to produce clinically relevant homogeneous dose distributions at horizontal proton beamlines. The
 162 radiation field specifications were verified by extensive dose measurements showing a high degree of dose
 163 homogeneity in lateral (10 cm \times 10 cm) directions at all depths down to the distal edge and, when applying a
 164 ridge-filter, also in longitudinal direction. The mobility and reproducibility of the setup allows for switching
 165 between pencil beam and extended field irradiation in double scattering mode at the experimental beamline.

166 Other double scattering solutions, such as a contoured second scatterer [15], have been proposed. We
 167 employed the dual ring approach primarily because of its low complexity and potentially higher robustness.
 168 In general, the most critical point of the nozzle setup turned out be the alignment of the nozzle with
 169 the proton beam axis and in particular the symmetric positioning of the second scatterer. However, the

⁷PTW-Freiburg, Germany

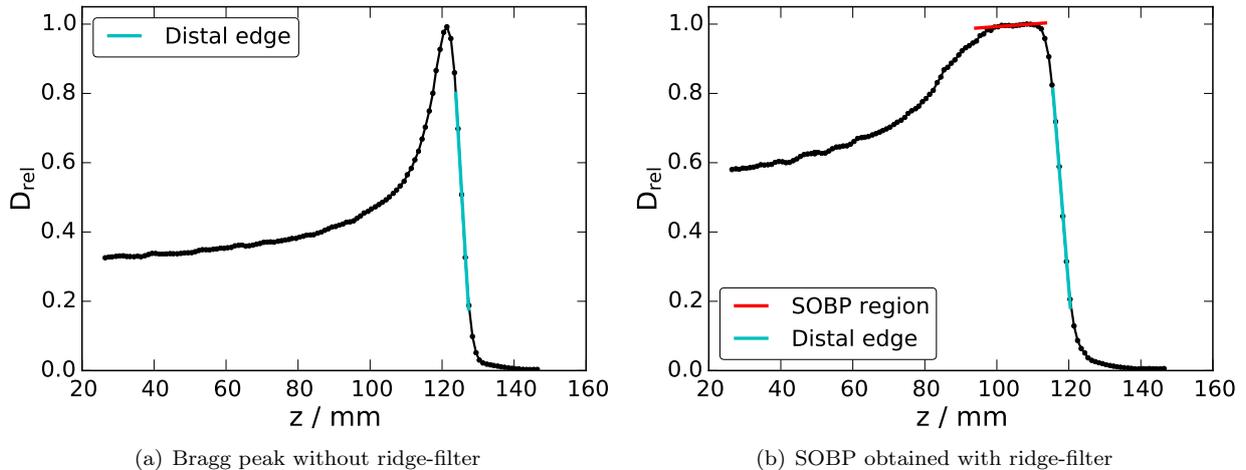


Figure 6: Depth-dose distributions of the double-scattering setup acquired by means of a water phantom measured (a) without (setting 1) and (b) with (setting 2) ridge-filter. Linear fits were applied to the distal fall-off, F_f , and the central SOBP region, F_d . Black bullets: dose measurement; cyan solid line: fit F_f ; red solid line: fit F_d .

170 alignment can be fast and conveniently performed using a 2D-dose measuring device – such as the Lynx in
 171 our case – until a homogeneous dose distribution is obtained along both orthogonal lateral directions. Since
 172 an asymmetry of the lateral dose distribution is directly related to a misalignment of the second scatterer,
 173 the adjustment was found to be straightforward.

174 Due to the requirements regarding mobility and robustness we abandoned any moving parts from the
 175 nozzle design. In particular, we favored a ridge-filter over a rotating range modulator wheel to produce
 176 spread-out Bragg peaks. The ridge-filter produced by convenient 3D-printing of aluminum showed a com-
 177 parable performance as by demanding micro fabrication [16]. It was discussed, based on a Monte Carlo
 178 study, whether to use PMMA as ridge-filter material instead of the standard aluminum to reduce the num-
 179 ber of those secondary neutrons in the target region by about 25% that originate from the ridge-filter [17].
 180 However, based on the Monte Carlo simulations of the presented setup the main sources of neutrons are the
 181 scattering foils and the primary collimator made of lead and brass, respectively. Essentially, it is the function
 182 of the primary collimator to stop most of the protons that will otherwise hit the main collimator to reduce
 183 the load of secondary radiation in the target volume. Due to the same aim, a proton efficiency of about
 184 30% was envisaged despite the compact nozzle design and without compromising the dose homogeneity in
 185 the entire target volume.

186 The close vicinity of lead and brass parts to the target area may cause radiation protection issues. After
 187 approximately 8 hours of experiments, local dose rates of up to $500 \mu\text{Sv/h}$ were measured in 10 cm distance
 188 to the lead scatterers. While most of the radiation components decay within hours or days, the dose rates
 189 need to be carefully evaluated and should be considered when planning experimental workflows.

190 In its current state, the designed nozzle can be set up prior to proton radiation experiments requiring an
 191 extended homogeneous field. So far, it has been used for a whole range of different experiments regarding
 192 (*in vivo*) proton range verification measurements and radiobiological cell irradiation experiments. *In vivo*
 193 mouse irradiation of xenograft models is in preparation.

194 Currently, irradiation of small animals with orthotopic tumors receives a lot of attention in the radio-
 195 therapy community. Such irradiations are performed using, e.g., dedicated small animal devices integrating
 196 X-ray imaging and irradiation [18, 19]. We plan to apply the concept described in this paper also for setting
 197 up a specific proton irradiation site for small animals using an industrial robot, which is installed above the
 198 beam line for positioning based on previous small animal imaging.

199 **5. Conclusion**

200 Extended proton radiation fields are required for physics and radiobiology experiments in translational
201 cancer research. A double-scattering and double-collimating system has been designed and built, that
202 provides homogeneous extended treatment fields at fixed horizontal proton beams.

203 The system has already proven its usability in different experiment campaigns and is now available for in-
204 ternal as well as external users. The design is also interesting for other centers equipped with an experimental
205 beamline with a need for beam formation. Especially, the application of the latest manufacturing techniques
206 like 3D printing of plastics and metals allows for rapid, convenient and cost-effective implementation.

207 **Acknowledgments**

208 The construction and supervision of manufacturing of the components by Anne Dreyer, Institute of
209 Radiooncology, Helmholtz-Zentrum Dresden-Rossendorf, is gratefully acknowledged by the authors. We
210 kindly thank Partick Wohlfahrt, M.Sc., for the CT imaging of the ridge-filter.

211 **References**

- 212 [1] O. Jäkel, The relative biological effectiveness of proton and ion beams, *Z. Med. Phys.* 18 (4) (2008) 276–285.
 213 doi:10.1016/j.zemedi.2008.06.012.
 214 URL <http://www.sciencedirect.com/science/article/pii/S0939388908000822>
- 215 [2] H. Paganetti, Relative biological effectiveness (RBE) values for proton beam therapy. variations as a function of biological
 216 endpoint, dose, and linear energy transfer, *Phys. Med. Biol.* 59 (22) (2014) R419.
 217 URL <http://stacks.iop.org/0031-9155/59/i=22/a=R419>
- 218 [3] Y. Takada, Dual-ring double scattering method for proton beam spreading, *Jpn. J. Appl. Phys.* 33 (1R) (1994) 353.
- 219 [4] V. Highland, Some practical remarks on multiple scattering, *Nucl. Instr. Meth.* 129 (2) (1975) 497–499.
- 220 [5] A. Lühr, J. Toftegaard, I. Kantemiris, D. C. Hansen, N. Bassler, Stopping power for particle therapy: The generic
 221 library libdEdx and clinically relevant stopping-power ratios for light ions, *Int. J. Radiat. Biol.* 88 (1-2) (2012) 209–212.
 222 doi:10.3109/09553002.2011.595877.
 223 URL <http://www.tandfonline.com/doi/abs/10.3109/09553002.2011.595877>
- 224 [6] T. Bortfeld, W. Schlegel, An analytical approximation of depth - dose distributions for therapeutic proton beams, *Phys.*
 225 *Med. Biol.* 41 (8) (1996) 1331.
 226 URL <http://stacks.iop.org/0031-9155/41/i=8/a=006>
- 227 [7] D. Jette, W. Chen, Creating a spread-out bragg peak in proton beams, *Phys. Med. Biol.* 56 (11) (2011) N131.
 228 URL <http://stacks.iop.org/0031-9155/56/i=11/a=N01>
- 229 [8] D. C. Hansen, A. Lühr, N. Sobolevsky, N. Bassler, Optimizing SHIELD-HIT for carbon ion treatment, *Phys. Med. Biol.*
 230 57 (8) (2012) 2393.
 231 URL <http://stacks.iop.org/0031-9155/57/i=8/a=2393>
- 232 [9] N. Bassler, D. C. Hansen, A. Lühr, B. Thomsen, J. B. Petersen, N. Sobolevsky, SHIELD-HIT12A - a Monte Carlo particle
 233 transport program for ion therapy research, *Journal of Physics: Conference Series* 489 (1) (2014) 012004.
 234 URL <http://stacks.iop.org/1742-6596/489/i=1/a=012004>
- 235 [10] S. Helmbrecht, F. Fiedler, M. Meyer, P. Kaefer, T. Kormoll, Proton beams for physics experiments at oncoray, *Radio-*
 236 *ther. Oncol.* 118, Supplement 1 (2016) S60 – S61, ICTR-PHE 2016, 15-19 February 2016, CICG, Geneva, Switzerland.
 237 doi:[http://dx.doi.org/10.1016/S0167-8140\(16\)30124-4](http://dx.doi.org/10.1016/S0167-8140(16)30124-4).
 238 URL <http://www.sciencedirect.com/science/article/pii/S0167814016301244>
- 239 [11] J. Petzoldt, K. Roemer, W. Enghardt, F. Fiedler, C. Golnik, F. Hueso-Gonzalez, S. Helmbrecht, T. Kormoll, H. Rohling,
 240 J. Smeets, T. Werner, G. Pausch, Characterization of the microbunch time structure of proton pencil beams at a clinical
 241 treatment facility, *Phys. Med. Biol.* 61 (6) (2016) 2432.
- 242 [12] IAEA, Absorbed Dose Determination in External Beam Radiotherapy.
 243 URL <http://www-pub.iaea.org/books/IAEABooks/5954/Absorbed-Dose-Determination-in-External-Beam-Radiotherapy>
- 244 [13] T. Nakagawa, K. Yoda, A method for achieving variable widths of the spread-out bragg peak using a ridge filter, *Med.*
 245 *Phys.* 27 (4) (2000) 712–715. doi:<http://dx.doi.org/10.1118/1.598933>.
 246 URL <http://scitation.aip.org/content/aapm/journal/medphys/27/4/10.1118/1.598933>
- 247 [14] S. Helmbrecht, W. Enghardt, F. Fiedler, M. Iltzsche, G. Pausch, C. Tintori, T. Kormoll, In-beam pet at clinical proton
 248 beams with pile-up rejection, *Z. Med. Phys.* submitted.
- 249 [15] E. Grusell, A. Montelius, A. Brahme, G. Rikner, K. Russell, A general solution to charged particle beam flattening using
 250 an optimized dual-scattering-foil technique, with application to proton therapy beams, *Phys. Med. Biol.* 39 (12) (1994)
 251 2201.
 252 URL <http://stacks.iop.org/0031-9155/39/i=12/a=005>
- 253 [16] T. Akagi, A. Higashi, H. Tsugami, H. Sakamoto, Y. Masuda, Y. Hishikawa, Ridge filter design for proton therapy at
 254 Hyogo Ion Beam Medical Center, *Phys. Med. Biol.* 48 (22) (2003) N301. doi:10.1088/0031-9155/48/22/N01.
 255 URL <http://stacks.iop.org/0031-9155/48/i=22/a=N01>
- 256 [17] Z. Riazzi, H. Afarideh, R. Sadighi-Bonabi, Influence of ridge filter material on the beam efficiency and secondary neutron
 257 production in a proton therapy system, *Z. Med. Phys.* 22 (3) (2012) 231–240. doi:10.1016/j.zemedi.2012.06.001.
 258 URL <http://www.sciencedirect.com/science/article/pii/S0939388912000621>
- 259 [18] F. Verhaegen, P. Granton, E. Tryggestad, Small animal radiotherapy research platforms, *Physics in Medicine and Biology*
 260 56 (12) (2011) R55.
 261 URL <http://stacks.iop.org/0031-9155/56/i=12/a=R01>
- 262 [19] F. Tillner, P. Thute, R. Bütof, M. Krause, W. Enghardt, Pre-clinical research in small animals using radiotherapy tech-
 263 nology a bidirectional translational approach, *Z. Med. Phys.* 24 (4) (2014) 335–351. doi:10.1016/j.zemedi.2014.07.004.
 264 URL <http://www.sciencedirect.com/science/article/pii/S0939388914000956>

265 **Appendix A. Design parameters**

266 Table A.3 shows relevant geometric measures necessary to rebuild the scattering system. The most
 267 critical measures are the thicknesses and positions of the lead foils. Note that, while lead is a soft metal
 268 which tends to deformation, a change in thickness is likely to cause a variation of the field shape.

Table A.3: Design parameters of the scattering system. Data have been measured where feasible. Otherwise, they origin from the engineering drawing or from the data sheet provided by the supplier.

Parameter	data source	Value
Scatterer 1 (SC₁):		
Position z	measurement	0.0 mm
Area	measurement	$81 \times 81 \text{ mm}^2$
Thickness of lead foil	construction	3.1 mm
Scatterer 2 (SC₂):		
Position z	measurement	430.0 mm
Area	measurement	$81 \times 81 \text{ mm}^2$
Thickness lead foil complete field	construction	0.7 mm
Thickness central lead foil	construction	3.3 mm
Diameter central lead foil	construction	37.4 mm
Thickness PMMA compensator	construction	17.1 mm
Ridge filter		
Position z	measurement	630.0 mm
Material	construction	Aluminum
Density	supplier	2.7 g cm^{-3}
Area	measurement	$120 \times 120 \text{ mm}^2$
Thickness of base	measurement	3.0 mm
Maximum ridge thickness	measurement	13.4 mm
Number of ridges	measurement	24
Ridge orientation		horizontal
Angle ridges / beam		$0 \dots 45^\circ$
Collimator 1		
Position z	measurement	830.0 mm
Material	construction	Cu58Zn39Pb3
Density	supplier	8.5 g cm^{-3}
Thickness	measurement	33.0 mm
Area of opening	measurement	$77.5 \times 77.0 \text{ mm}^2$
Collimator 2		
Position z	measurement	1500.0 mm
Material	construction	Cu58Zn39Pb3
Density	supplier	8.5 g cm^{-3}
Thickness	measurement	33.0 mm
Area of opening	measurement	$115.0 \times 115.5 \text{ mm}^2$