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REAL TIME DETERMINATIONS OF THE RANGE AND BRAGG PEAK OF PROTONS WITH A DEPTH PROFILE CAMERA AT HZB

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Abstract

The cyclotron at HZB provides a 68 MeV proton beam for therapy as well as for experiments. By using a novel camera setup, the range of the proton beam is measured optically. The setup consists of a phantom with a luminescent layer inside and a CMOS camera. By measuring the emission of the luminescent layer, the Bragg peak and the range of the proton beam can be visualized for different energies. In contrast to a water phantom, the camera system offers much shorter measurement times. A dedicated LabVIEW code provides various evaluation possibilities: the Bragg curve and the lateral beam profile are generated and displayed. The system is sensitive to energy differences of less than 400 keV. The results were obtained with a beam intensity of less than 10 pA/cm^2 homogenous proton beam in front of the degrader. The measurement is done in real time and provides live feedback on changes such as beam energy and beam size. The results of the camera are presented and compared to water phantom measurement.

MATERIALS AND METHODS

Cyclotron at HZB and Water Phantom

The HZB cyclotron provides protons for the eye tumor therapy since 1998. More than 4400 patients from all over the world have been treated here [1]. There are two injectors and a cyclotron as main accelerator which provides a 68 MeV proton beam for eye tumor therapy and for experiments. The facility is under continuous development for therapy.

A water phantom is normally used to determine the Bragg curve of the proton beam. To measure a complete Bragg curve with an energy of 68 MeV for the therapy, the measurement takes 5 minutes for a resolution of 0.1 mm [2]. A finer resolution with the water phantom is possible but means a much longer measuring time. For experiments where the Bragg curve is essential, the same water phantom has been used so far for calibration. This means for experiments with different energies a very long preparation time is needed. Even with smallest changes, the measurement of the Bragg curve must be repeated. Therefore, a measurement system had to be developed which reduces the preparation time and allows a real-time evaluation of the Bragg curve of the proton beam.

There are also other systems with different phantoms like liquid scintillators [3] or plate phantom systems [4]. Most of them need longer measuring time, have rather coarse resolutions and no real-time evaluation. Another system is a multi-leaf faraday cup [5]. This system can quickly evaluate a Bragg curve but is heavy and very expensive in commercial form.

Camera System

The camera system has a patent pending. It consists of a phantom, a luminescent layer (interaction layer), a housing and a camera shown in Fig. 1. The phantom is the main point of the system. It consists of two plastic blocks. The dimension of the phantom is matched to the maximum available energy of the proton beam. Between the blocks of the phantom is diagonal the luminescent layer (e.g., Gd_2O_2S) or interaction layer placed.

For the interaction layer, a material is used which exploits the effect of fluorescence. The proton beam is decelerated in the phantom. Depending on the position of the proton beam, it collides with the luminescent layer and the light intensity is equivalent to the energy loss.

Centered on the phantom is the camera. It is a FLIR camera with a CMOS sensor. The camera is equipped with a lens that focuses the detected signals of the luminescent layer. The captured image of the Bragg curve is readout by a LabVIEW (NI, Austin, USA) code. The entire setup is located in a housing sealed by light. A crosshair at the entrance of the beam in the system allows a fast optical alignment. The total size is as small as 35 cm x 20 cm x 20 cm and it's very light with only 1.5 kg. Due to the compactness of the system, it is easily transportable and can be used at different target stations. The system is easy and inexpensive to realize in contrast to conventional water phantoms.

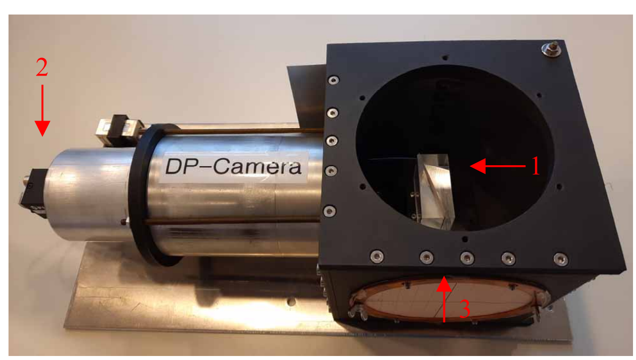

Figure 1: View inside the camera system. 1- shows the phantom block with the luminescent layer inside. 2 - position of the camera. 3 – beam direction.

LabVIEW Code

A LabVIEW code is used to evaluate and visualize the data from the camera system. Different aperture sizes can

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be used to define the beam spot size of the scattered proton beam (Fig. 2).

On the left side of the LabVIEW graphical interface is the live image in monochrome intensity displayed. The exposure time can be set from 1 - 2000 ms so the image is not overexposed. On the image a "ROI area" (region of interest) can be chosen. It is selectable in a rectangular size (green box) and can be marked freely on the image. This "ROI area" is displayed on the right side in a color-coded intensity. The violet parts show pixel with low intensities, and the red parts shows pixel with high intensities.

From this color-coded image both the distal and lateral profile of the beam can be generated at different positions on the image. The position can be chosen freely, and the profile histograms are plotted below the colour image. The white line shows the Bragg curve which is generated in the phantom. The red line shows a lateral beam profile and can be selected at any position on the phantom. It is live feedback of two important beam parameters.

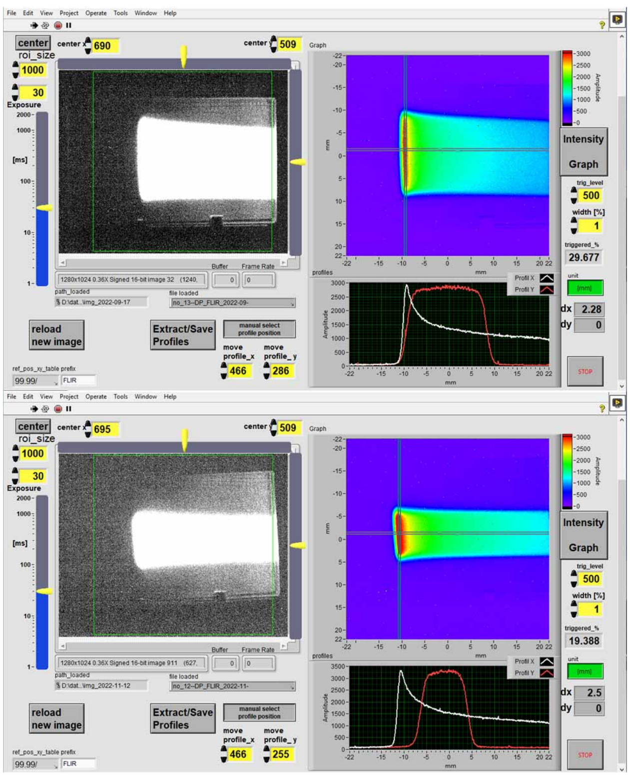

Figure 2: Two LabVIEW visualizations with different apertures. Upper image with a 20 mm x 20 mm aperture. Lower image with a 10 mm x 10 mm aperture.

By the function "extract/save profiles" a data file of the profiles is generated. It can be used for other programs for evaluating.

Measurements

Different Energies The measurement plotted in Fig. 3 shows different proton beam energies from 68 MeV down to 16 MeV. The nominal energy was 68.5 MeV. The proton beam was slowed down by using different absorber plates of aluminium. The first energy without absorber plates is 67.7 MeV where is to account the exit foil, the scattering foil and the air gap between the exit foil and the camera. The lower energies in Fig. 3 which were achieved with the absorber plates are calculated with SRIM [6].

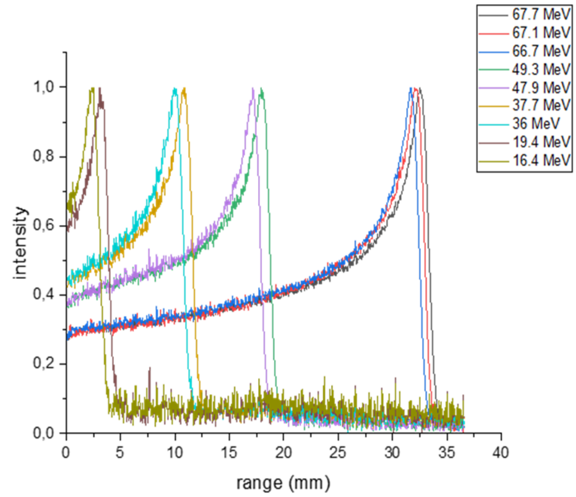

Figure 3: Measurement with depth profile camera for different proton beam energies of 16 MeV to 68 MeV.

The different energies are directly visible with the Bragg curve. Even small steps of 400 keV are visible. The system shows good results.

Table 1: Measured and Theoretical Values of Different Energies

Energy [MeV]	Camera Range [mm]	PSTAR Range [mm]
67.1	32.96	32.61
66.7	32.46	32.20
19.4	3.86	3.45
16.4	3.02	2.57

The measured range with the camera system were compared with the theoretic ranges of PSTAR at different energies [7]. All measured ranges are taken at 80% of the Bragg-peak. The values are larger at lower energies (Table 1). For higher energies is a difference of 1% and for lower energies is the difference more than 10%. For low energies a correction factor must be defined to reduce the strong difference between the measured and theoretic ranges. An adjustment of the phantom could be a benefit.

Camera System vs Water Phantom The measurement plotted in Fig. 4 shows the camera system compared to a water phantom. All measured ranges with the camera system are converted to water ranges for comparability. The solid line with the noisiness shows the measurement with the camera system. The dashed line shows the measurement with the water phantom. The measurements range from 68 MeV down to 18 MeV.

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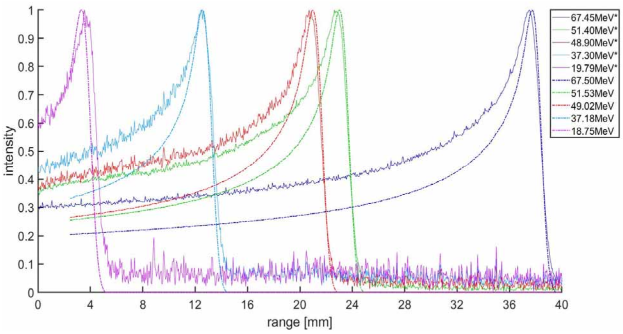

Figure 4: Measurements for different ranges with the camera system compared to a water phantom. Solid line shows camera measurement. Dashed line shows water phantom measurement.

In direct comparison the Bragg curves of both systems are very similar. The noise of the camera system graphs can be reduced. For this measurement the scattering system from the eye tumor therapy was used. This scattering system is more than 5 meters away from the camera system. With the scattering system close to the camera system (1 meter), the influence of the beam scattering system should be reduced. Other factors are:

- uncertainties for phantom and absorber materials of interaction layers
- geometry of camera lenses
- warming of the camera chip by longer power-on time

Minimum Energy Resolution The camera system should have a single pixel resolution of 40 keV for a 68 MeV proton beam. The measurement is shown in Fig. 5 and thin aluminium foils were used with 20 µm to 150 µm to try if this minimum resolution is possible.

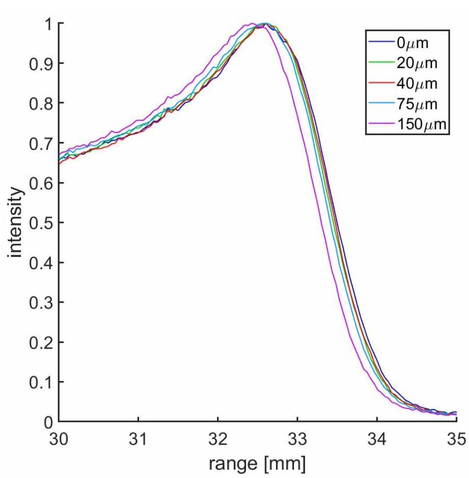

Figure 5: Measurement with camera system for minimum energy resolution of a 68 MeV proton beam with thin aluminium foils of 20 µm up to 150 µm.

An optically evaluation of the minimum resolution is difficult. This is especially the case for the very thin foils of 20 µm and 40 µm. For the foil with 75 µm thickness is a difference in the graph visible. It is clearer with the profile data from the LabVIEW visualization (Table 2). The measured ranges show small differences. The measured values are bigger than the expected values.

Table 2: Energy Resolutions for Different Foils and the Measured Ranges

Foil Thickness [µm]	Measured Range [mm]	Calculated Energy [MeV]
0	33.20	67.90
20	33.16	67.84
40	33.13	67.81
75	33.08	67.75
150	32.96	67.61

For the camera system an energy loss of 100 keV is easily measurable with 68 MeV proton beam parameters.

Different Ion Species For this measurement is a 90 MeV helium beam ($^4He^{2+}$) chosen. Figure 6 shows the measured Bragg curve. For this measurement the scattering system near to the camera system is used. Less noise was observed.

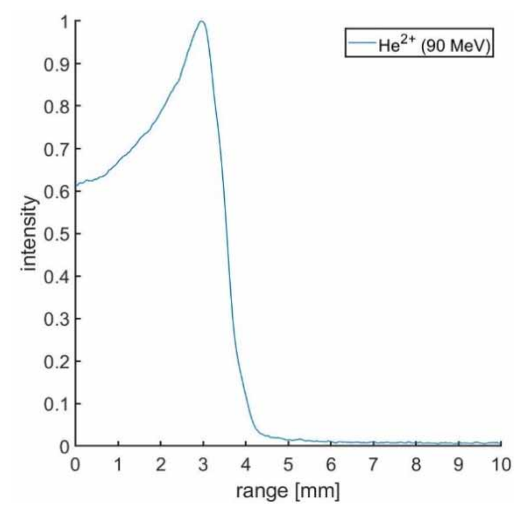

Figure 6: Measurement with the camera system of a 90 MeV helium beam.

For the ion a calculated and a measured energy is available (Table 3). The calculated energy is the nominal energy from the accelerator taking into account the exit foil at the target station and the air pass between the exit foil and the camera system.

The energy values show a good agreement. Between the calculated energy and measured energy, the difference is less than 2%.

Table 3: Ion Energy Difference from Calculated and Measured Energies

Ion	Nominal Energy [MeV]	Calculate Energy [MeV]	Measured Energy [MeV]
$^4He^{2+}$	90	78.48	76.02

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This shows that the camera system can also detect and evaluate different ions with very good results. The camera system has to be matched for other ions with different ranges.

CONCLUSION

The camera system is an inexpensive and lightweight invention. With only a few components excellent results are shown. The camera system works for different ions and energies. A minimal energy resolution of 100 keV is shown for a 68 MeV proton beam. There is a very good agreement in comparison with a water phantom with only small differences in the measurements.

A system upgrade with different phantom materials, luminescent layer, camera and camera lens could give more opportunities. The noise can be further reduced, and beams with higher and lower intensities can be used. A correction factor for low energies can give a better agreement to theoretically values.

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