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FOCUSING OF HIGH-ENERGY ELECTRON BEAM USING SILICON CRYSTALS FOR APPLICATION IN RADIOTHERAPY

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Abstract

By using a high-energy electron beam (beam energy of several hundred MeV) strongly focused on the tumor lesion area, radiotherapy can be performed with a relatively simple beam generation and handling system while resulting in a suitable shape of the deposition energy curve in a tissue-like material. Quadrupole magnets are typically used for beam focusing, which makes the beam delivery system complex and challenging from an engineering point of view. In the Geant4 simulation toolkit, we performed a feasibility study of an alternative solution, in which focusing is achieved by using a bent silicon crystal with an appropriately shaped exit surface. However, the focusing strength is still not high enough. Research to find the optimal crystal shape to achieve the ideal focusing strength is ongoing. Such a crystal lens can be a very light object (mass in the order of grams), allowing for a much simpler beam delivery system for radiotherapy facilities.

INTRODUCTION

The advantages of the two most common radiotherapy methods (photon and hadron therapy), such as the low cost of the apparatus, ease of beam generation, and a suitable shape of the energy deposition curve in tissues, can potentially be achieved by using a very high-energy electron beam (VHEE 60 - 250 MeV [1]) focused on the area of the tumor lesion. Quadrupole magnets are typically used to focus the beam, which adds extra complexity and challenge to the beam delivery system from an engineering standpoint. This study investigates the feasibility of an alternative method in which a bent silicon crystal with a suitably shaped exit performs the focusing. Such a crystal lens can be a very light object (mass in the order of grams), allowing for much simpler beam delivery systems for radiotherapy facilities.

CHANNELING

Crystals have ordered atomic patterns, with aligned atoms forming planes and axes. Strong electromagnetic fields occur between them. Channeling occurs when charged particles are guided through a crystal's periodic structure. The strong electromagnetic field creates a collective potential that captures charged particles upon entry [2]. Both positively and negatively charged particles can be channeled through crystals. Their paths are influenced by the crystal's collective potential, which varies with the particle's charge. Channeled particles oscillate between or across crystal planes or axes. Positively charged particles can penetrate deeper into the crystal, repelled by nuclei with a positive charge. Negatively charged particles, however, are more prone to interacting with atomic centers, leading them to exit the channeling process more easily [3]. Due to interactions with the crystal structure, not all particles entering the crystal are channeled successfully. Except of channeling, there are other potential events that particles can encounter, such as dechanneling, volume capture, volume reflection, and amorphous scattering [4]. Choosing the correct crystal parameters is crucial for maximizing the number of channeled particles.

Critical radius (R_c) can be understood as the radius for which the centrifugal force is equal to the maximum interplanar field of the crystal:

$$R_c = \frac{pv}{U'(x_{max})}, \tag{1}$$

where $U'(x_{max}) \approx 20$ eV for silicon crystals, p is particle momentum, and v is particle velocity. The critical beam incoming angle for a straight crystal (θ_c) is a value of the angle above which the particles cannot achieve stable channeling:

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}. \tag{2}$$

Critical beam incoming angle for a curved crystal (θ_c^b):

$$\theta_c^b = \theta_c \left(1 - \frac{R_c}{R}\right), \tag{3}$$

where R is the bending radius of the crystal and $R > R_c$. To achieve focusing the crystal's exit is cut with a cylinder, as shown in Fig. 1, where a beam of accelerated particles enters the crystal from the left, is channeled inside, and upon exiting, is focused at a distance F [5].

Crystal length (L):

$$L = R * \theta_b \tag{4}$$

The radius of the cutting cylinder (r):

$$r = \frac{1}{2}\sqrt{F^2 + R^2} \tag{5}$$

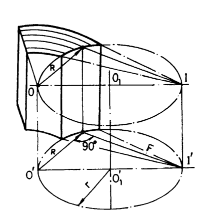

Figure 1: The shape of the focused electron beam after passing through the crystal. Figure taken from Ref. [5].

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NUMERICAL SIMULATIONS

To conduct this study, a Geant4 [6] simulation model has been developed by extending the available *channeling* example. Features implemented into the code cover: shaping the bent Si crystal to provide focusing; five more detectors placed behind the crystal which can detect beam distribution, as a way to be able to check the trajectory of the beam more precisely; water phantom which serves as a detector to check the energy deposition of the focused beam inside a tissue-like material; and new expanded macros to include more options for controlling the beam and the geometry of the simulation.

At first, it was checked whether the channeling phenomenon simulated in Geant4 gave the expected results. In this case, a silicon non-profiled bent crystal was used. The parameters of the crystal are listed in Table 1. The value of the deflection angle (1000 µrad) was an arbitrary choice. The deflection angle was not extremely large, but at the same time, it was large enough that the electrons that were not channeled could be stopped by potentially adding a shield in front of a patient. In every simulation prepared for this study, the energy of the electron beam is equal to 200 MeV. This is typical energy of VHEE beams, already used in some previous studies (e.g. in [1]), and within reach of modern, compact electron linacs developed for potential use in radiotherapy (e.g. [7]).

Table 1: Parameters Defining the Crystal

Material	Silicon Si
Crystal Lattice	110
Critical Channeling Angle	447 µrad
Critical Bending Radius	0.35 mm
Deflection Angle	1000 µrad
Bending Radius	4000 mm
Length	4 mm

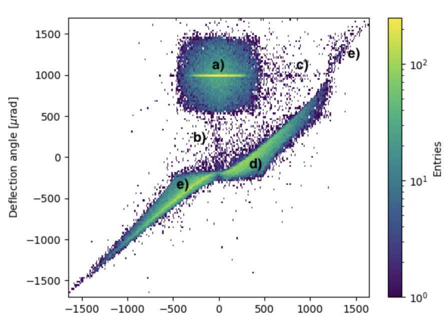

Figure 2: Distribution of the deflection angle of particles with energy 200 MeV that passed through a 4 mm long crystal, depending on the incoming angle; a) channeled particles, b) dechanneling, c) volume capture, d) volume reflection, e) amorphous scattering.

Figure 2 shows a two-dimensional histogram of the distribution of the deflection angle of particles that passed through a 4 mm long crystal, depending on the incoming angle. The presented result is from the detector positioned at a distance of 1 m behind the crystal. The distribution of the incoming beam was Gaussian and the spread of incoming angles ranged from -1500 to 1500 µrad. The beam was flat and only had a spread on the horizontal plane. The result of the channeling phenomenon from the simulation is as expected.

Optimization of crystal parameters, such as length and bending radius, was performed for a number of different crystal lengths in the range of [0.004, 40] mm. The channeling efficiency stands for the ratio of channeled particles to all electrons entering the crystal. A single-point source beam without any radial spread was used. The amount of channeled particles was checked in three ranges of angle. The angular spread in the range of [500, 1500] µrad translates into 1 mm of position spread at a distance of 1 m behind the crystal. With tumor sizes typically being in the order of centimeters (cm) [8], 1 mm of position spread is less than a typical tumor size so there is no need to limit the range for channeled particles and this entire range of channeled electrons can be considered useful. Its efficiency was at around 94% (see Fig. 3).

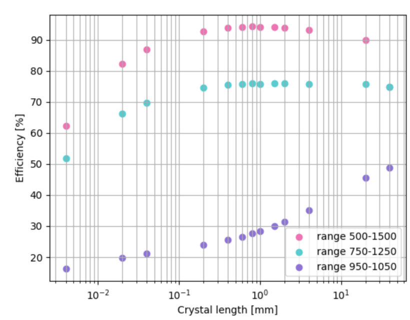

Figure 3: Efficiency of electron beam channeling as a function of crystal length. The ranges are the same as in Fig. 4. Statistical errors, calculated as the standard error of the binomial distribution, are barely visible due to high statistics.

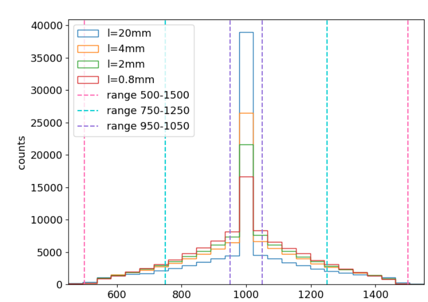

Figure 4: Angular distribution of channeled electrons for four crystal lengths of 0.8 mm, 2 mm, 4 mm, and 20 mm.

To focus the beam the exit of the crystal must be profiled. The profiling is strictly geometric. This means that the output from the crystal is cut with a cylinder that has appropriately adjusted parameters depending on the bending radius of the crystal and the focal length. The focal length was chosen

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Table 2: Parameters of Focusing the Beam for a Profiled Crystal with Bending Radius 4000 mm

Beam distribution	Width type	Width in [mm]	Width at 1m [mm]	Ratio out/in
Gaussian	std, std	0.2973 ± 0.0009	0.2313 ± 0.0007	0.778
Uniform	std, std	0.5776 ± 0.0018	0.2250 ± 0.0007	0.389
Uniform	full, std	2.0	0.2250 ± 0.0007	0.113

to be 1 m, so the only parameter that changes, depending on the crystal length, is the radius of the cutting cylinder. As an example, a bent crystal with a length of 4 mm was chosen. The focusing ability was checked for the horizontal direction, for two types of pencil beams: one with a 2-mm-wide uniform distribution and the other with a Gaussian distribution of a standard deviation of 2 mm. The bending radius of the crystal was 4000 mm, and the radius of the cutting cylinder was 2061.55 mm. The result of focusing the beam by profiling the exit of the crystal is presented in Fig. 5. To numerically represent the focusing of the beam, a range from which the particles were considered, was determined by the mean value +/- 3 times the standard deviation, and then the standard deviation of this range was calculated. The error for this parameter was calculated as the standard error of the mean (SEM). The obtained values are listed in Table 2. The results obtained from two types of beams, with a Gaussian and uniform distribution are similar. The focusing is stronger in the case of uniform beam distribution because there are significantly more particles at positions further from the middle of the beam approaching the crystal. The presented graphs and parameters prove that focusing the beam using a crystal with a properly profiled output is possible and such a crystal can be used as a focusing lens.

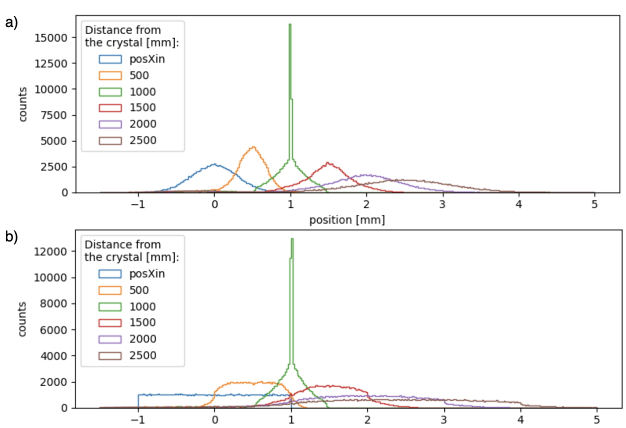

Figure 5: Distribution of the beam position before entering the profiled crystal with bending radius 4000mm, and after passing through the crystal at distances 0.5 m, 1 m, 1.5 m, 2 m, and 2.5 m respectively, a) for a beam of Gaussian distribution, and b) for a beam of uniform distribution. Bin width 20 μm.

The energy deposition curve inside a water phantom is presented in Fig. 6. It is unfortunately far from expected. The aim is to make the energy deposition curve a few mm wide and with a maximum at depth of around 15 cm into the phantom. The obtained result resembles an outcome that can be acquired by a non-focused or weakly focused VHEE beam. The strong focusing is considered to be for focused beams with the f-number equal to f/3.8 or lower value [9]. The strength of focusing (f-number (F/D)) in this case is not enough and is equivalent to f/500. The main reasons for such a weak strength might be the limitation of the beam width approaching the crystal lens, which is around 2 mm at the maximum, and the focal length of 1 m might not be the optimal choice, it should be shorter.

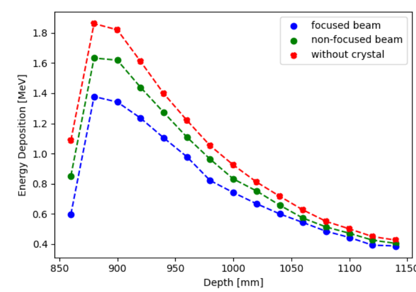

Figure 6: An example result of the averaged energy deposition as a function of phantom depth for an electron beam with an energy of 200 MeV, a crystal length of 4 mm, and a cylinder radius length of 2061.55 mm. The phantom is placed at a distance of 850 mm behind the crystal. Statistical errors, calculated as the standard error of the mean (SEM), are barely visible due to high statistics.

CONCLUSION

As a result of this feasibility study, a simulation of a bent silicon crystal with a profiled exit was prepared in Geant4. The outcome obtained from the simulation proved the focusing ability of such a profiled crystal. However, the focusing strength of the crystal is not strong enough. The search for optimal crystal parameters, including the bending radius, crystal length, and focal length, is still ongoing. By shortening the focal length and lengthening the crystal transverse dimension, the focusing strength can be improved. As an alternative, it is possible to create something resembling a Fresnel lens by assembling a collection of focusing crystals.

REFERENCES

[1] K. Kokurewicz *et al.*, "An experimental study of focused very high energy electron beams radiotherapy", *Commun. Phys.*, vol. 4. p. 33, 2021.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPR61

[2] V. M. Biryukov *et al.*, *Crystal Channeling and Its Application at High-Energy Accelerators*, Springer, 1997.

[3] E. Bagli *et al.*, “A model for the interaction of high-energy particles in straight and bent crystals implemented in Geant4”, *Eur. Phys. J. C*, vol. 74, p. 2996, 2014.

[4] D. Mirarchi, “Crystal collimation for LHC”, Ph.D. thesis, High Energy Phys. Dept., Imperial College, London, England, 2015.

[5] Y. Chesnokov, “Review of IHEP experiments for focusing and deflection 70 GeV proton beam with bent crystals”, *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 119, pp. 163–171, 1996.

[6] GEANT4, `https://geant4.web.cern.ch`

[7] FLASH Radiotherapy (CERN’s website), `https://kt.cern/flash-radiotherapy`

[8] National Cancer Institute, `https://www.cancer.gov`

[9] K. Kokurewicz, “Investigation of focused Very High Energy Electrons (VHEEs) as a new radiotherapy method”, Ph.D. thesis, University of Strathclyde, 2020.