Focusing of High Energy Electron Beam using Crystal Lenses for Applications in Radiotherapy – Feasibility Study

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Introduction

Conventional electron radiotherapy is often used to treat tumors located close to the skin surface or during surgery. This is because of a low penetration depth (some cm) for the most common energy range of electron beams used in medicine of 4 MeV to 25 MeV. Very high energy electron (VHEE) beams, with energies in the range of 50 MeV to 250 MeV, can also be used in radiation therapy. However, their use in medicine is rare. The performance of the VHEE therapy is improved by focusing the electron beam in the region of the tumor [1].

Currently, in accelerator physics, magnets are typically used to focus and curve the beam. Magnets, such as dipoles or quadrupoles, are usually very large, heavy, and expensive. Their weight often ranges from tens to hundreds of kilograms, depending on the need. It makes the beam delivery system challenging from the engineering point of view. This paper investigates the use of crystal lenses to focus the beam, which are far more compact objects and weigh up to a few grams allowing the system to be simplified. In this case, a beam channeling process is exploited.

Focusing

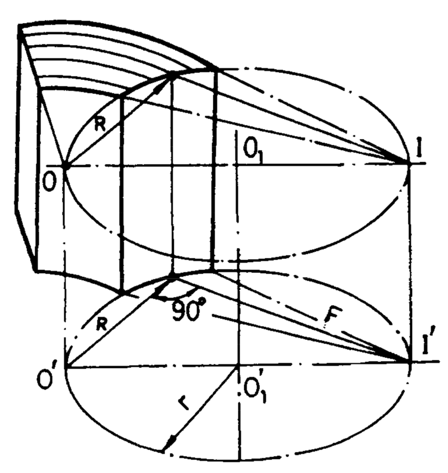
In order to focus the beam after it passes through the crystal, the output of the crystal must be properly profiled. Such a crystal is supposed to behave like a focusing lens. To profile the exit of the crystal, it is cut with a section of a cylinder to make a solid like the one shown in Figure, where a beam of accelerated particles enters the crystal from the left side and is channeled inside the crystal, and after exiting it, is focused at a distance F [2].

Crystal length (L):

$$L = R * \theta_b \tag{1}$$

The radius of the cutting cylinder (r):

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



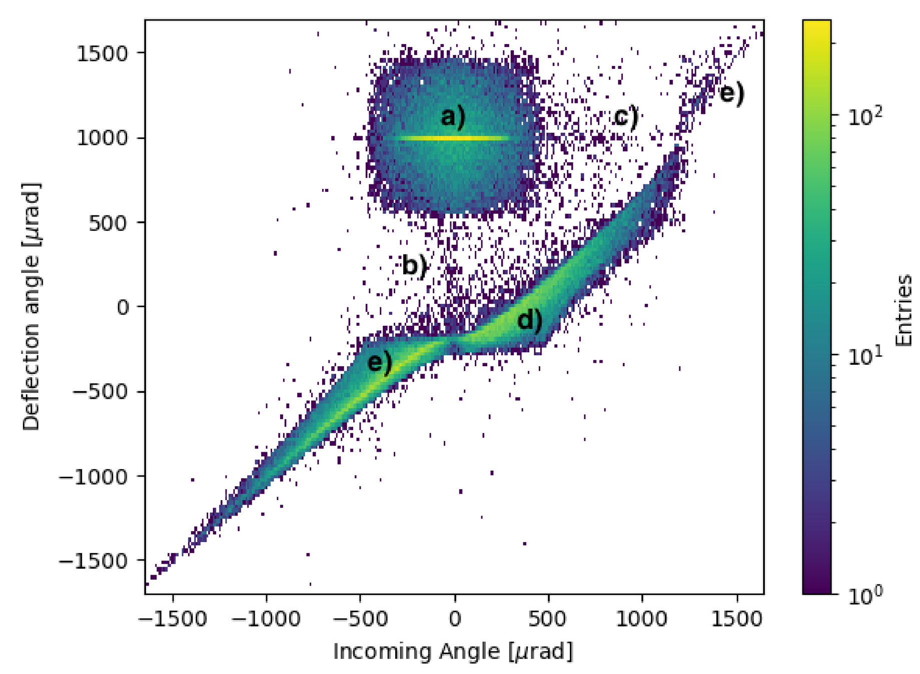
Crystal length	Cylinder radius lengths
2 mm	1118.03mm
4 mm	2061.55mm
20 mm	10012.49mm

Numerical simulation

A simulation in GEANT4 was prepared. This simulation is based on an existing channeling example from the available Extended Examples database. Features added to the simulation code include a water phantom (300x300x300 mm) placed behind the crystal, the ability to change the beam width, the ability to record the position in which the beam is in front of and behind the crystal, and the ability to profile the exit of the crystal.

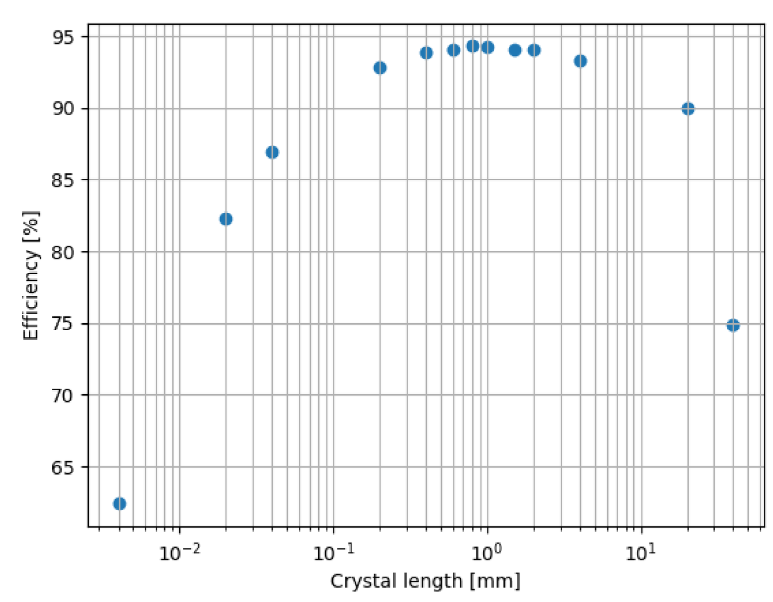
Channeling

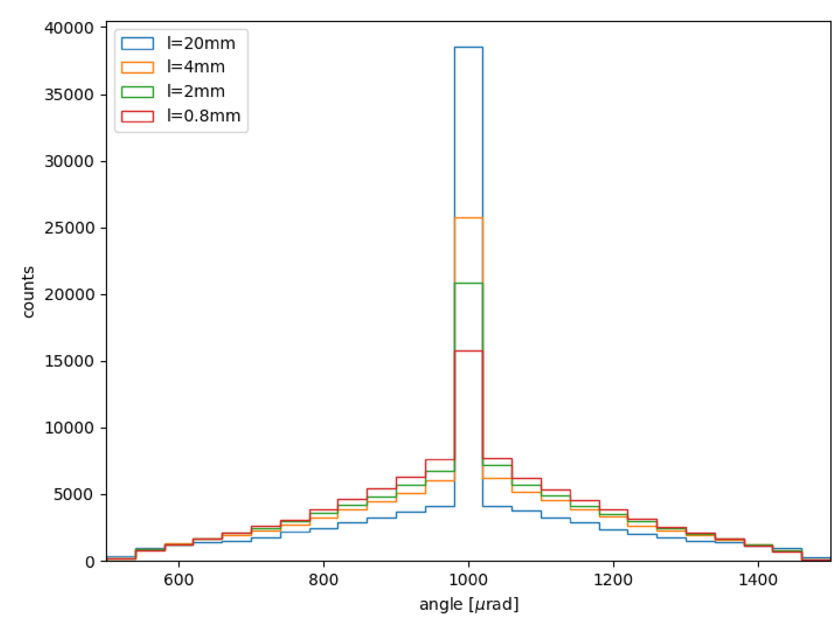
Crystals have ordered patterns of atoms. Aligned atoms can be seen as planes or axes. A strong electromagnetic field occurs between planes and between axes of the crystals. Channeling is the phenomenon of guiding charged particles through a periodic internal structure of a crystal if particle direction is aligned with its planes or axes. The strong electromagnetic field creates a collective potential derived from crystal structure that captures charged particles as they enter the crystal [3]. Distribution of the deflection angle of particles with energy 200 MeV that passed through 4 mm long crystal, depending on the incoming angle; a) channeled particles, b) dechanneling, c) volume capture, d) volume reflection, e) amorphous scattering.



Optimal parameters

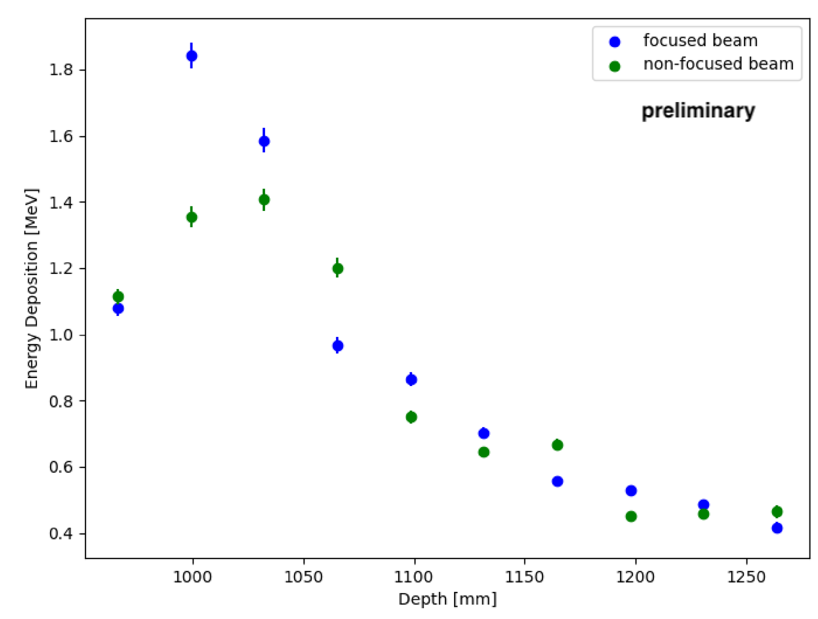
It was checked what length of crystal gives the best results of channeling an electron beam of 200 MeV energy so that the beam is deflected by an angle of 1 mrad, which is a large enough angle to have a practical application and also small enough to still observe channeling. The statistics for which the results were obtained are 10^6 and 10^5 for lengths of 0.004-0.4 mm and 0.6-40 mm, respectively. The choice is driven by the channeling efficiency (percentage of particles successfully channeled), and by the angular distribution of channeled particles. A plateau of channeling efficiency of more than 90% is observed for crystals of length from 0.2 mm to 20mm, but the angular distribution of channeled particles improves with longer crystals. From these two observations, we conclude that an optimal choice is to use a crystal of some single mm of length.





Results

The expected outcome of this study is to demonstrate that the energy deposition of the high-energy electron beam in a water phantom has a more favorable (narrower) shape in the case of using the crystal lens compared to the situation when the beam goes through a similar crystal without the cut at its exit face. A preliminary result is showing energy deposition inside the phantom, depending on the depth in the water phantom.



Conclusion

The aim of this study is to investigate whether it is possible to use crystal lenses for high-energy electron beam radiotherapy. This poster presents selected parameters of the crystal lens and shows preliminary results of the simulated energy deposited in the water phantom for the beam focused by using the channeling phenomenon. The work is still in progress. More conclusive results, based on further optimization of crystal parameters and larger statistics, will be delivered soon.

References

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