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CHARACTERISTICS OF FOCUSED VERY HIGH ENERGY ELECTRON (VHEE) BEAMS IN RADIOTHERAPY

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Abstract

Very High Energy Electron (VHEE) beams represent a promising alternative for treating deep-seated tumours. However, VHEE beams generate quasi-uniform dose distribution along the beam path, which can cause overexposure to healthy tissue. Focused VHEE beams are a revolutionary radiotherapy technology that enables concentrating doses into a small and well-defined spot with an extremely high dose rate. This paper estimates the dose deposition and presents the influence of different focus depths. A focused beamline is designed using two triplets of quadrupole magnets to transport and focus VHEE beams onto the water phantom.

INTRODUCTION

Cancer is a major cause of disease and death worldwide. The International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) has released the latest global cancer data, which estimates that there are approximately 19.3 million new cases of cancer and 10 million deaths from cancer worldwide in 2020. Its prevalence has led to significant investments in research and the development of innovative treatment options, including radiotherapy. Radiotherapy has proven to be a cost-effective and common clinical treatment for cancer without surgery. Radiation therapy aims to target cancer cells while minimizing harm to surrounding healthy tissues, with the ultimate goal of eradicating the disease and improving patients' quality of life.

Very high energy electron (VHEE) beams, in the energy range of 150 to 250 MeV, were first proposed for radiation therapy in 2000 [1]. Recent studies have shown that VHEE radiotherapy is applicable in treating deep-seated tumours, especially in tissues of high heterogeneity and prone to movement [2]. In addition, VHEE radiotherapy has several potential advantages over conventional external radiotherapy [3-5]. Furthermore, the availability of VHEE sources is expected to increase with the development of C-band radio-frequency (RF) accelerators and Laser Wake-Field Accelerators (LWFA) [6-8].

However, the collimated VHEE beam produces a quasi-uniform dose distribution, resulting in high surface and exit doses. To solve the problem of the quasi-uniform dose distribution along the penetration path inside the human body, this paper introduces beam optics based on magnetic lenses to focus VHEE beams into a small and well-defined spot. Particularly, the Monte Carlo code FLUKA is employed to simulate and evaluate dose characteristics, such as depth-dose and transverse-dose distribution, to ensure optimal treatment outcomes.

GENERATION OF FOCUSED VHEE BEAM

A schematic diagram illustrating the generation of the focused VHEE beam using an ideal magnetic lens is presented in Fig. 1. The focusing structure is achieved through the use of two triplets of quadrupole magnets, which first expand the collimated VHEE beam before focusing it onto a small spot. The desired focused beam is obtained by focusing a VHEE beam of initial diameter D to the centre of a water phantom.

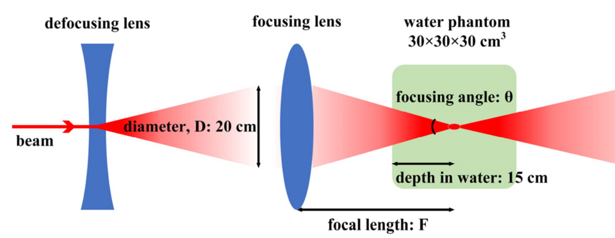

Figure 1: Schematic diagram of generating a focused VHEE beam using an ideal magnetic lens.

The focusing strength is indicated by the focus factor f, defined by Eq. (1) to indicate the focusing strength. The diameter D remains fixed in all simulations, while the focal length F is adjusted by changing the distance between the magnetic lens and the water phantom, thus varying the focusing strength. A larger focusing angle θ and a lower focus factor f means a stronger focused beam.

$$f = F / D . \quad (1)$$

We use two groups of quadrupoles to generate the focused beam, as shown in Fig. 2. The first group of quadrupoles (from Q1 to Q3) extends the original parallel beam diameter to 20 cm. The second group of quadrupoles (from Q4 to Q5) focuses the VHEE beam on the centre of the target with a relatively stronger focusing strength.

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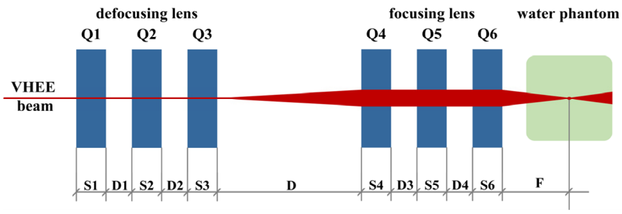
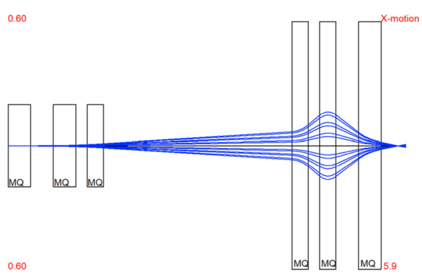


Figure 2: The layout of the focusing structure.

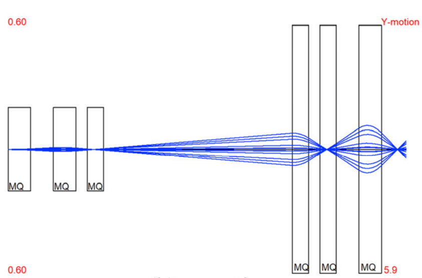
Different focusing strengths are obtained by adjusting the second group of quadrupole field gradients. The focusing structure and quadrupole parameters are designed and optimized using the beam optics simulation codes MAD-X and COSY. The VHEE beam transverse profile follows a Gaussian distribution, and the initial beam emittance is 6 mm·mrad with a radius of 4 mm. The initial energy is 250 MeV with a 0.75 MeV energy spread. Table 1 displays the gradients of the second group of quadrupoles. Figure 3 shows the beam envelope of the focused VHEE beamline at 250 MeV and *f*/1.2.

Table 1: Parameters of the Second Group of Quadrupoles with 250 MeV and *f*/1.2

f	***F* [cm]**	**Gradient [T/m]**		
		Q4	**Q5**	**Q6**
1.2	24	9.79	-9.98	11.23



(a) x-motion



(b) y-motion

Figure 3: The beam envelope of the focused VHEE beamline with 250 MeV and *f*/1.2.

DOSE DISTRIBUTION OF FOCUSED VHEE BEAM

To ensure the treatment's effectiveness, evaluating the dose characteristics is crucial. The ideal beam distribution achieves high doses in the target tumor while minimizing the dose to organs at risk. Based on the Monte Carlo simulation code FLUAK, the entire process of focused VHEE beam radiotherapy to the human body is investigated.

Depth-dose Distribution

The percentage on-axis depth-dose curve is used clinically to assess dose characteristics, such as the maximum, surface, and exit doses.

For photons, the maximum dose is deposited at the surface, while the dose at the depth of the target tumour (15 cm) is reduced to 70% of the maximum dose. For protons, the spread-out Bragg peak (SOBP) covers the target tumour, but the surface dose accounts for 50% of the maximum dose. The results show that the 250 MeV focused VHEE beam achieves a high local dose deposition at a depth of the target tumour, as shown in Fig. 4. The surface dose and exit dose of the focused VHEE beam are significantly lower than those of other beams.

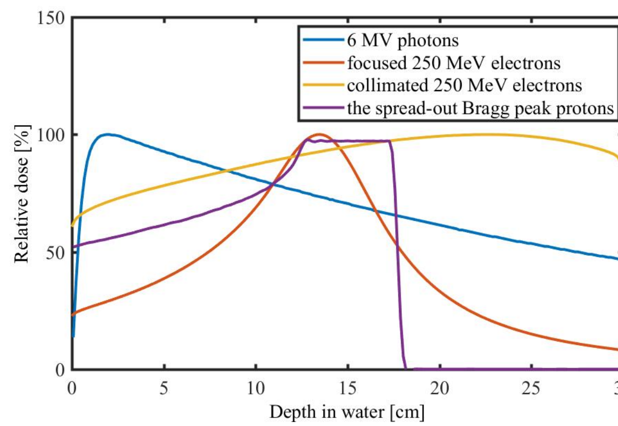


Figure 4: Percentage on-axis depth-dose (PDD) curves of different beams in the water phantom. The doses are normalized to the maximum doses, respectively.

Due to electron scattering in the water phantom, the peak dose depth of the focused electron beam with 250 MeV was slightly shifted forward on the central axis, which differed somewhat from the theoretical calculation of the optical focus, as shown in Fig. 5. If introduced into clinical trials, the dose focal point would need to be redetermined.

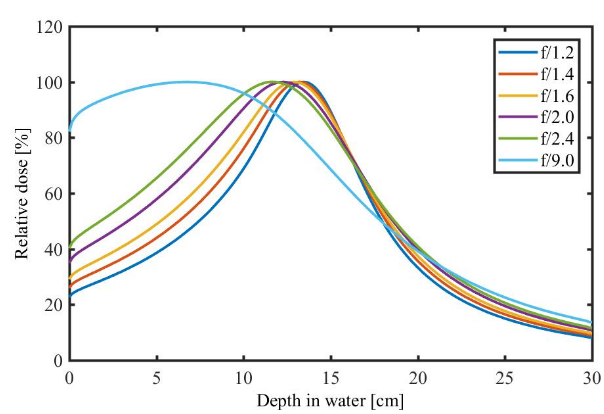


Figure 5: Percentage on-axis depth-dose (PDD) curves of focused VHEE beams with 250 MeV.

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Dose Profiles and Influence of Different Focus depth

Figure. 6 shows 2D dose distributions of different focusing strengths in the range of f/1.2 ~ f/9.0 in the water phantom. Compared with the collimated VHEE beam, the focused VHEE beam concentrates doses in a small area with a high local dose deposition. For strong focusing strength, which means a larger focusing angle θ and a lower focus factor f, the dose distributions have a smaller lateral spread to reduce the risk to normal tissue and organs.

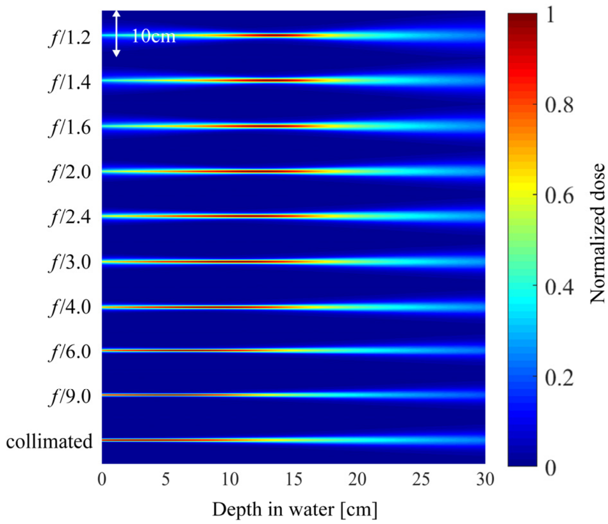

Figure 6: 2D depth-dose deposition colormap of focused VHEE beams with 250 MeV in the water phantom.

The focused beam deposits most of its energy at the focus point, creating a peak dose. Considering the possible depth differences of tumours, it is critical to investigate the effect of focus depth on dose distribution.

Figure 7 compares the dose deposition distributions of VHEE beams at different focus depths. The results show that shallower focus depths lead to less scattering and higher dose deposition at the focus, where the beam concentrates high local dose deposition at a reference depth.

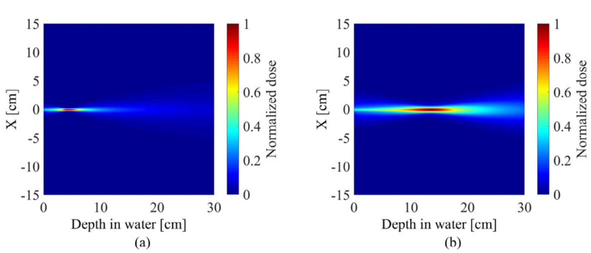

Figure 7: Dose depositions with different focus depths. The 250 MeV and f/1.2 electron beams are focused at 5 cm (a) and 15 cm (b) from the entrance of the water phantom, respectively.

Transverse Distribution

Due to the different energy and focusing strength, transverse distributions of beams are different, as shown in Fig. 8. Compared to the collimated VHEE beam, the focused beam deposits most of the energy within the target tumour and reduces harm to normal tissue. For the focused VHEE beam, the transverse distribution of the target depth has a clear peak at the central axis, which means the transverse FWHM at the central depth is the narrowest. Due to the scattering of electrons and secondary particles in the water phantom, the transverse distribution of the exit dose is flatter, and the transverse FWHM is wider than that of the surface dose.

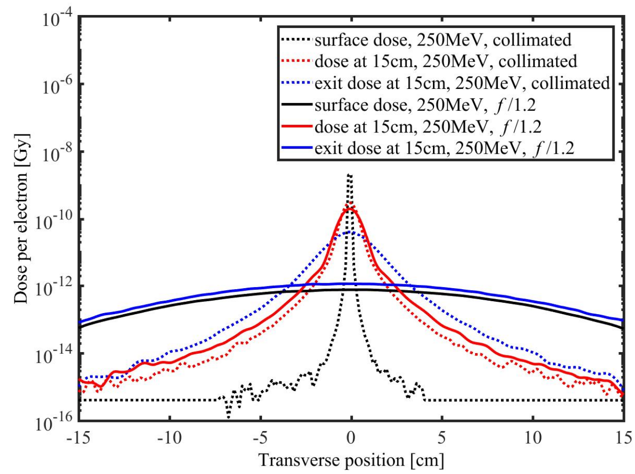

Figure 8: Transverse distributions at the surface, exit, and 15 cm depth of water phantom.

CONCLUSION

A method of focused VHEE radiotherapy is proposed to improve clinical dose rates and optimize the dose distribution. The focusing structure of focused very high energy electron beams is designed and optimized. The results show that the focused VHEE beam produces a high local dose deposition at the target tumour. Compared to collimated VHEE beams, the integrated dose of the focused VHEE beam in normal tissues is significantly lower, even by 34%, while maintaining the same absorbed dose at the target tumour. In addition, the dose rate at the target tumour is as high as 100 Gy/s, fully qualified for FLASH therapy (>40 Gy/s) in the future [9-11].

Target tumours of irregular shape and size can be precisely conformed and radiated by superimposing initial VHEE beams with different energy and spatial distribution or by scanning. In the future, optimizing and exploring how focused VHEE beams can be integrated into clinical treatment systems will be necessary.

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