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VERY-HIGH ENERGY ELECTRON (VHEE) STUDIES AT CERN'S CLEAR USER FACILITY

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Abstract

Here we investigate how inserts of various densities (0.001 – 2.2 g/cm^3) affect the dose distribution properties of VHEE beams at ∼150 MeV. A range variation comparison was also made with clinical proton beams using TOPAS/GEANT4 Monte Carlo simulations. In addition, we assess the viability of scattering foils for optimizing the size of VHEE beams for radiotherapy purposes. The experiments were conducted at CERN's CLEAR user facility.

INTRODUCTION

There has been an increase of interest in using VHEE beams in the energy range 50 – 250 MeV for treating deep-seated tumors in recent years. Currently deep-seated tumors are normally treated using megavoltage photons. However, VHEE beams can penetrate deeper tissues more efficiently. There are several potential advantages for VHEE radiotherapy: higher dose reach, more conformal dose deposition, higher dose rate and the possibility for magnetic beam steering [1–4].

We studied the effects of high and low density materials embedded in water phantoms on VHEE beam dose profiles and the corresponding beam spread. We also investigated the effect of varying thickness of aluminium foil on the beam.

The next sections provide a brief description of the experiment at CERN's CLEAR (CERN Linear Electron Accelerator for Research) user facility [5], a comparison between Monte Carlo simulations and experiments made at CERN and an overview of the experimental results obtained on dose penetration with various inserts and the effects of scattering foils on the electron beam.

EXPERIMENTAL SETUP

A series of experiments with VHEE beams were conducted at CLEAR in 2017 using 156 MeV electron beams. The experimental set-up and its schematic are shown in Fig. 1 and 2.

Dose deposition profiles were measured using 30 × 30 × 10 cm^3 water phantom with radiation sensitive films (EBT3 and EBT-XD) embedded at various depths. The water phantom was positioned on a remotely transversely movable stage 52 cm away from a 0.2 mm thick aluminum beam exit window. CLEAR beam parameters for the VHEE experiments at the VESPER test stand are given in Table 1.

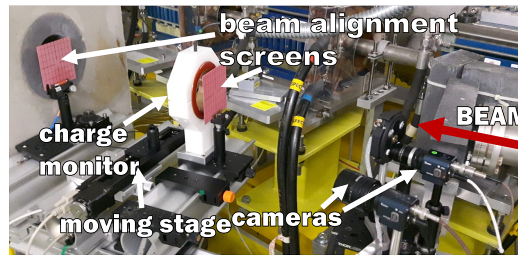

Figure 1: Layout of the VESPER (Very energetic Electron facility for Space Planetary Exploration missions in harsh Radiative environments) test stand at the CLEAR facility.

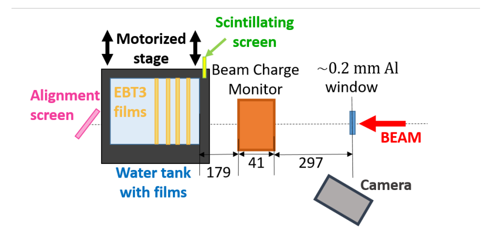

Figure 2: Schematic of the experimental set-up for film irradiation. All distances are in millimeters.

Currently there is no calibration data available for EBT-XD film's dose response to electron beams in the energy ranges 50 – 150 MeV. Therefore we conducted calibration measurements and found the optical density (OD) relating to the total charge delivered to the film summed along the pulse train at 156 MeV (an example of irradiated film is given in Fig. 3).

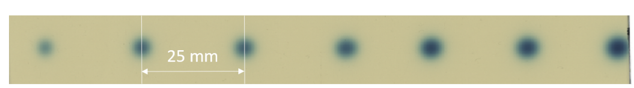

Figure 3: Irradiated EBT-XD film with delivered charges from 64 pC (leftmost spot) to 463 pC (rightmost spot).

MONTE CARLO SIMULATION SETUP

Dose profiles obtained from the experiments were compared to Monte Carlo simulation predictions. TOPAS (TOol for PArticle Simulation) particle tracking code was used to simulate VHEE dose delivery in various experimental setups [6]. TOPAS is a front-end user product that wraps and extends the Geant4 [7] (GEometry ANd Tracking) Simulation Toolkit.

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Table 1: Main beam parameters of CLEAR facility beam for the VHEE experimental campaign in 2017.

Beam parameter	Value
Energy	156 MeV
Energy spread (FWHM)	< 0.5 MeV
Bunch charge	15 pC
Train length	20 – 90 bunches
Charge jitter	≈ 20 %
Beam spot size (FWHM)	1.2 mm

We simulated VHEE beams impinging normally on a $30\times30\times10$ cm^3 water phantom surrounded by acrylic walls. All beam parameters correspond to those given in Table 1. Dose deposition within the phantom was tracked using dose scoring volumes with voxel sizes $0.1\times0.1\times0.1$mm^3.

Monte Carlo (MC) Simulation Verification

Simulations were made for the experimental set-up. Longitudinal dose profiles and the transverse beam spread were compared with experimental measurements. A example of this measurement is shown in Fig. 4 for VHEE dose deposition in EBT-XD films at various depths. A comparison between experimentally measured and simulated dose profiles and beam spread in water are shown in Fig. 5.

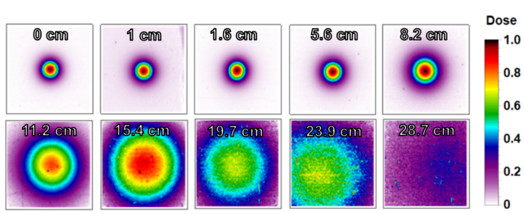

Figure 4: Normalized two-dimensional transverse dose profiles at various depths in the water phantom.

Scattering Foils

There are circumstances in which it would be advantageous to widen the beam transverse profile. For this reason we explored the effect of aluminium foils, of several thicknesses, on the beam properties.

Simulations with various thickness aluminium foils revealed that it is possible to increase the beam width significantly (4 to 12 mm) using scattering foils (0 – 2.5 cm thickness) without losing the characteristic features such as effective range of the VHEE dose profile. The entrance dose diminished significantly as the thickness of the foil increased. This is illustrated in Fig. 6 (the dose of a 250 MeV beam impinging on a 2.5 cm foil, for example, is attenuated by ≈97%).

VHEE and Proton Beams in Heterogeneous Media

It is well-known that the range of proton beams is highly dependent on the heterogeneities they pass through [8]. Here

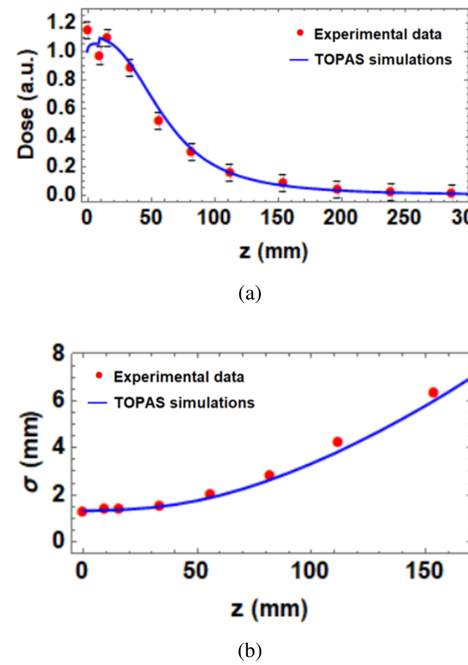

Figure 5: Longitudinal dose profiles (a) and beam spread in water (b) for 156 MeV electron beams. Red markers represent experimental data taken from CLEAR and the blue line corresponds to results obtained using TOPAS.

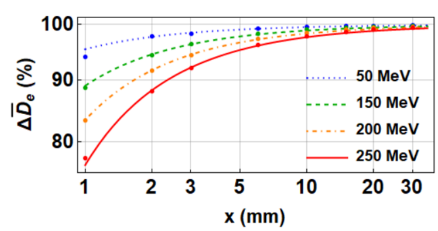

Figure 6: Decrease in the entrance dose $\Delta\bar{D}_e$ due to insertion of aluminium foil (foil-to-phantom distance was set to 45 cm and $\sigma = 2$ mm). The line is of the form $\Delta\bar{D}_e = 100 - a/x$ with x the foil thickness (a is 4.55, 10.97, 16.60 and 23.45 for beam energies of 50, 150, 200 and 250 MeV, respectively). The coefficient of restitution R^2 is 1.000 in all cases.

we compare the range of VHEE beams with proton beams through various media. Dose profiles have been simulated using TOPAS with inserts of thickness 2 cm. These material have similar densities (ranging from 0.001 to 2.2 g/cm^3) to those of the human body. Results are displayed in Fig. 7. We compute the integrated dose verus depth within the media. It is evident that VHEE beams are significantly less sensitive to heterogeneities than proton beams.

RESULTS FROM CLEAR

Dosimetric Effects of Scattering Foils

Effects of aluminium scattering foils on longitudinal dose profiles and beam spread were investigated experimentally by placing a scattering foil of various thicknesses (3−21 mm)

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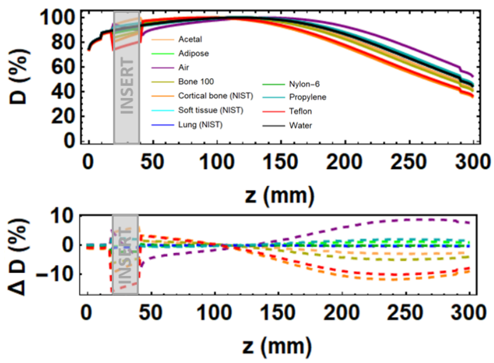
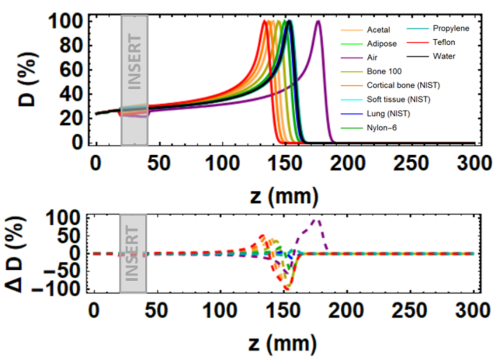


(a) VHEE beams



(b) proton beams

Figure 7: Dose-depth profiles for various media are compared for electron (a) and proton beams (b) both with σ = 5 mm at 150 MeV. Dose differences ΔD from a dose profile in water are shown with dashed lines.

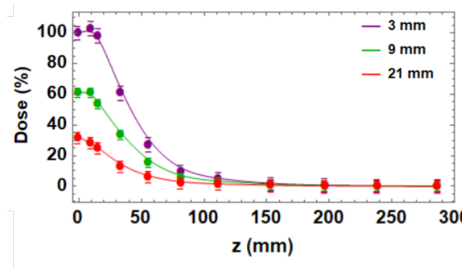
15 cm up-stream from the water phantom and measuring transverse dose deposition profiles at various depths. We found that by increasing the foil thickness from 3 to 21 mm the transverse σ of the beam increased from 1.2 to 2.3 mm and the corresponding entrance dose was attenuated in the range 30% to 61% (as shown in Fig. 8).

Dose Dependence on Heterogeneities

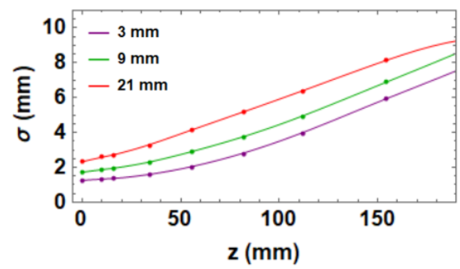
We added further density inserts to the experiments conducted at CLEAR in December 2016 (in which we had investigated 3 media) [9]. In December 2017 we performed measurements on 5 new tissue equivalent media. The results of these experiments are collated in Fig. 9. Plot markers correspond to experimentally measured data and the curve to a MC simulation in a clear water phantom. The dashed curves indicate the deviation from dose present in water alone, and this is no more than 10%. It is evident that the dose profiles are relatively unaffected for all additions of high and low-density media. This is consistent with MC simulation results shown in Fig. 7.

FINAL REMARKS

Measured and simulated dose deposition of VHEE beams in water were found to be consistent with each other. We



(a)



(b)

Figure 8: Longitudinal dose profile (a) and transverse beam dimension (b) of VHEE beams within a water phantom. An aluminium scattering foil (3 to 21 mm thick) was placed 6 cm in front of the phantom.

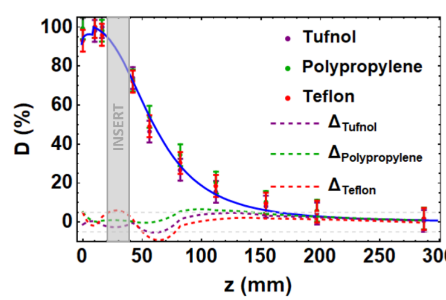


Figure 9: Normalized longitudinal dose-depth profiles in water with inserts of 2 cm thick various density embedded inserts at 2 cm depth in the phantom. The solid blue line corresponds to a MC simulation in water alone.

found scattering foils can be used to increase the transverse size of VHEE beams without appreciable loss in the features of the characteristic VHEE dose profile. Finally, observed dose profile and beam spread independence of the intervening media indicates that VHEE has the potential to be a reliable mode of radiotherapy for treating tumours in highly inhomogeneous and mobile regions such as lung and prostate.

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