Simulating Very High Energy Electron (VHEE) radiation therapy with Xenos

Stanley Humphries, Ph.D.

Field Precision LLC
E mail: techinfo@fieldp.com
Internet: https://www.fieldp.com

The success of high-energy protons for the non-invasive treatment of deep-seated tumors has prompted renewed interest in the use of beams of very high-energy electrons (VHEE) in the range 100 to 250 MeV. In common with protons, high-energy electron beams maintain some coherence penetrating tissue allowing energy deposition at depths of 15-30 cm. The disadvantage is that the longitudinal deposition profile is not as favorable, electrons lacking the Bragg peak. There are some potential advantages:

- Electron accelerators in the energy range are generally more compact and less costly.
- Electron linacs are well-suited to pulsed duty cycle and could implement short pulses for ultra-high dose rate (FLASH) radiation therapy.
- Electron beams can be steered with moderate magnetic fields, raising the possibility of fast scanning and even obstacle avoidance.

The paper *Back to the Future: Very High-Energy Electrons (VHEEs) and Their Potential Application in Radiation Therapy*[1] reviews the current state of the field.

The **Xenos** software suite[2] is capable of modeling electron devices as well as dose deposition in biological structures. In this report, I will review some demonstration VHEE calculations to illustrate the data generated by **Xenos** and summarize its technical advantages for the application. The suite incorporates the **Penelope**[3] Monte Carlo physics engine. **Penelope** covers electron-photon-positron transport in the energy range from a few hundred eV to 1 GeV. The package does not handle nuclear reactions, so a question is whether this presents a limitation for VHEE modeling. Figure 1, taken from the paper *Dosimetry and radioprotection evaluations of very high energy electron beams* (A.M. Thongchai, et.al.)[4] provides an answer. It shows contributions to deposited energy from particles generated by a 200 MeV electron beam in a water phantom. Note that the vertical axis is logarithmic. Contributions from primary and secondary electrons, positrons and photons comprise almost 100% of the total. The deposition by nuclear reactions represents only 0.009%. If the goal is to predict dose distributions, then the contribution from nuclear processes is negligible and the physics models used in **Xenos** are quite accurate.

[1] https://www.mdpi.com/2072-6694/13/19/4942
[2] https://www.fieldp.com/tutorials/Xenos_PAC2021.pdf
[3] https://www.oecd-nea.org/science/pubs/2006/nea6222-penelope
[4] https://www.nature.com/articles/s41598-021-99645-7

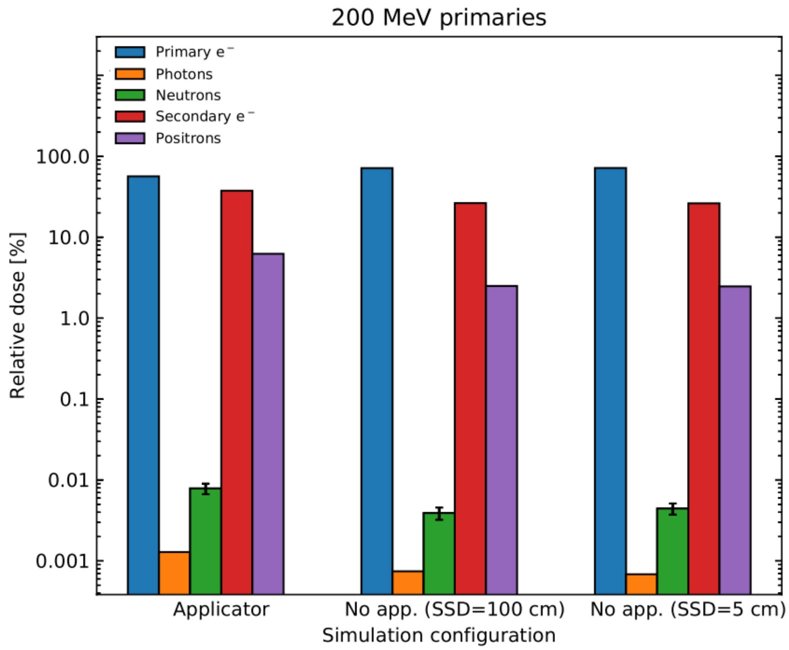

Figure 1: Relative contribution of primary and secondary particles to the dose in a water phantom from a 200 meV electron beam.

I base my calculations on parameters in the paper *An experimental study of focused very high energy electron beams for radiotherapy* (K. Kokurewicz, *et.al*)[5]. The incident pulsed electron beam has kinetic energy 158 MeV and carries 1.0 nC of charge. The first 2D calculation has cylindrical symmetry. A beam of radius 10.0 mm enters a target of striated muscle tissue. The electrons are either collimated (parallel) or focused to a point a distance 140.0 mm from the entrance surface. The `Circular Beam Generator` tool of the **Trak** program provides a quick way to create the input distribution. Figure 2 shows the parameter entries. The outer radius is 10.0 units – spatial dimensions will be defined in the control file for the **GamBet** Monte Carlo program. The utility creates 250 particles uniformly spaced in radius that carry a current of 1.0 A. In a cylindrical calculation, model particles represent an annular segment of charge with area proportional to radius r. Therefore, the routine assigns current between model particles current weighted by r so that the current density is uniform and sums to 1.0 A. The entries 0.0 amu and charge -1.0 signal that the particle should be assigned the properties of electrons. The envelope angle of 4.09^o equals $\tan^{-1}(10.0/140.0)$. The negative value signals a converging beam. In response to a user specification, the routine creates a text file `BeamFocused.PRT` of electron parameters. The

[5] https://www.nature.com/articles/s42005-021-00536-0

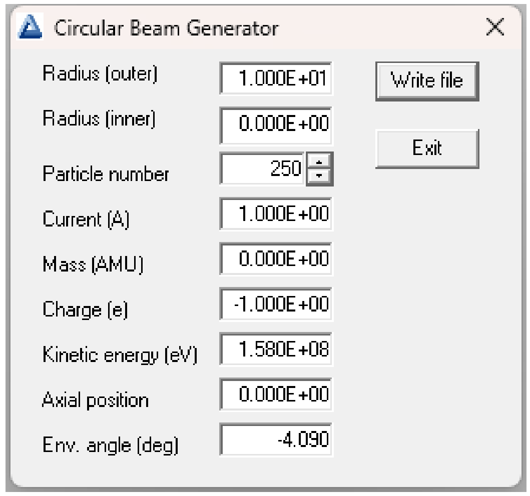

Figure 2: Parameter entries in the `Circular Beam Generator` tool for the cylindrical two-dimensional calculation.

`PRT` format is an exchange common to all **Xenos** programs. Besides incident particle definitions, a **GamBet** calculation requires geometry information in the form of a conformal finite-element mesh created by the **Mesh** utility. In this case, the geometry is simple, a cylinder of length $z_0 = 300.0$ mm and radius $r_0 = 150$ mm. The triangular elements are about 2.5 mm long in z. The radial width is 1.0 mm in the range $0.0 \leq r \leq 30.0$ mm and 2.5 mm at larger radius.

Input to **GamBet** is through an interactive dialog that creates the file of text information shown in Table 1. The value in the `DUnit` command signifies that dimensions in the geometry and particle files should be interpreted in millimeters. In response to the command `GFile2D`, **GamBet** reads the listed file and assumes cylindrical symmetry. In the `Composition` section, Material 1 is taken as **Penelope** predefined material 202 (skeletal muscle) and mesh Region 1 is associated with Material 1. Following commands in the `Source` section, **GamBet** reads the particle file and creates 100 showers for each primary. Energy deposition in the elements is based on a beam pulse length of 1.0 ns for a total charge of 1.0 nC. The commands of the `Process` section set a maximum energy for table generation of 250.0 MeV and specify termination of showers when a particle energy drops below 50 keV.

Figure 3 shows calculation results. The top plot shows elements color-coded by dose (in Gy) for the collimated beam, entering from the left. The dose rises initially because of knock-on electrons and positrons and then falls off with distance. Figure 3b plots the dose distribution for a focused beam. Note the scale change of the color code. Figure 3c shows the trajectories of fifty primary electrons in the focused beam. For quantitative information,

Table 1: **GamBet** input file for the cylindrical beam example.

```
GEOMETRY
  DUnit =   1.0000E+03
  GFile2D = Muscle.MOU  (Cylin)
END
COMPOSITION
  Material = 202
  Region(1) =   1
END
SOURCE
  PFile = BeamFocused
  NPMult =    100
  TPulse =   1.0E-9
END
PROCESS
  EMax =   2.5000E+08
  EAbs(Electron) =   5.0000E+04
  EAbs(Photon) =   5.0000E+04
  EAbs(Positron) =   5.0000E+04
END
ENDFILE
```

Figure 4 plots the on-axis dose for focused and collimated beams. For the focused beam, the maximum dose occurs at a depth of 86.0 mm in the muscle tissue.

A second calculation of a 158.0 MeV beam penetrating a water phantom allows comparisons with results described in the Kokurewicz paper. In this case, the beam geometry is three dimensional. Following Fig. 4a in the paper, I assume a uniform current-density beam with half-widths of 7.2 mm in x and 2.2 mm in y. I modeled both a collimated beam and a focused beam. In the second case, the beam is focused in the x direction to a point 115 mm from the water entrance and in the y direction to a point at 83 mm. The corresponding envelope angles are -4.13^o and -1.0^o respectively. In this case, I use the **GenDist** utility with the input specifications

```
FileType = PRT
RestMass =   0.0000E+00
Charge =  -1.0000E+00
Energy =   1.5800E+08
Current =   1.0
Def(Rect) =   7.200  2.2000    100     50
Shift 0.00 0.00 -8.99
Distribution = Uniform
EnvAngle  -4.13 -1.00
EndFile
```

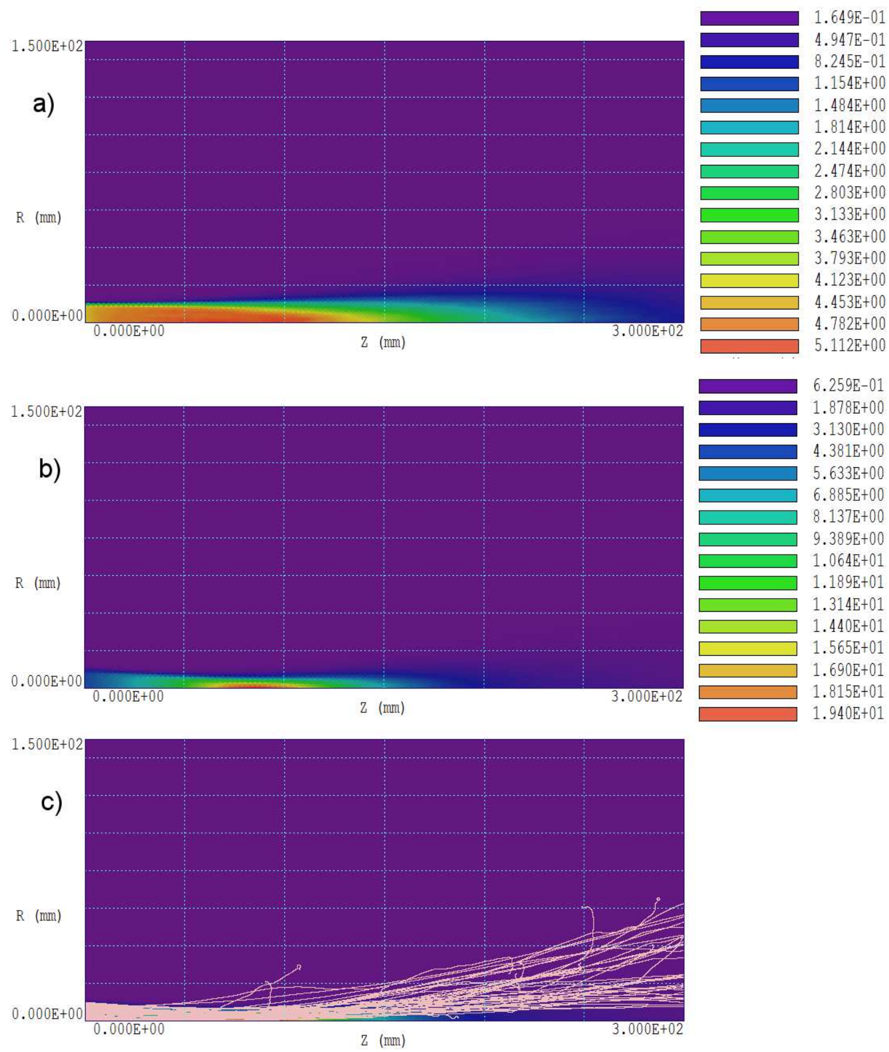

Figure 3: Circular electron beam with kinetic energy 158 MeV directed into a uniform medium of skeletal muscle, dose in Gy. a) Dose distribution for a parallel beam. b) Dose distribution for a beam focused to a point 140 mm from the entrance. c) Selected trajectories of primary electrons for the focused beam.

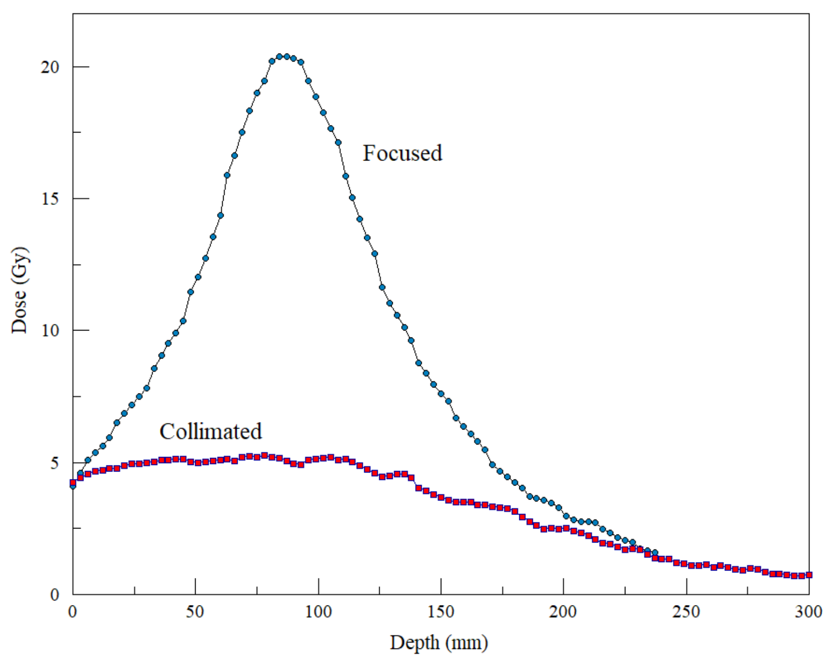

Figure 4: Circular electron beam with kinetic energy 158 MeV directed into a uniform medium of skeletal muscle. On-axis dose as a function of depth in the medium.

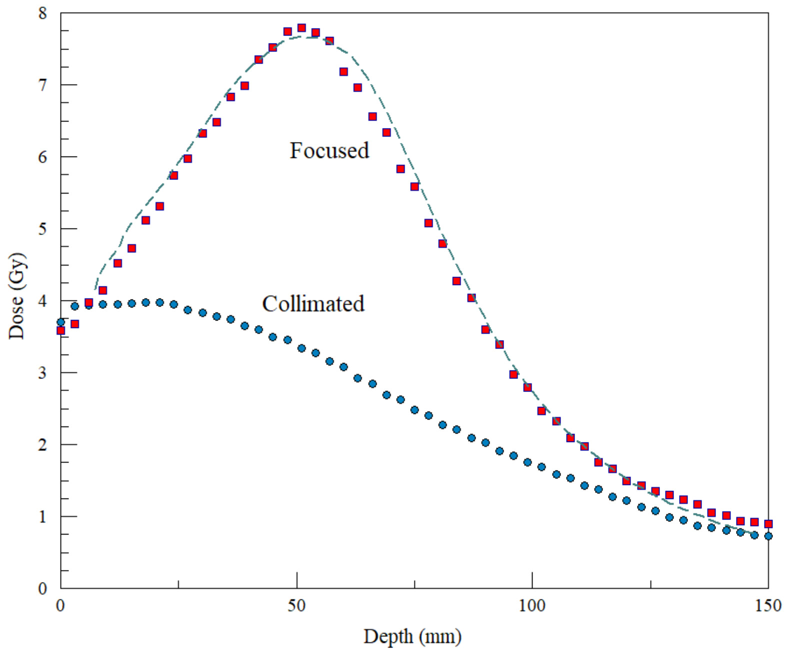

Figure 5: Rectangular electron beam with energy 158 MeV directed into a water phantom through a Lucite sheet. On-axis dose as a function of depth in the water for a parallel beam and a beam with different focal lengths in the x and y directions. The dashed line shows a prediction by the **FLUKA** code normalized to the **GamBet** result.

The calculation geometry includes a 7 mm thick Lucite sheet followed by a 150 mm length of water. It is defined by a conformal hexahedron mesh generated by the **MetaMesh** program with element size 2.0 mm in z and 0.5 mm in x and y. Input to GamBet is similar to the previous example except there are two materials assigned to two regions: water (**Penelope** material 278) and Lucite (material 224). Figure reffig:vhee shows scans of the on-axis dose for collimated and focused beams as a function of distance into the water volume. The dashed green line is a prediction from the **FLUKA** code for the focused beam. The data were supplied supplied by Enrico Brunetti, a co-author of the paper[6]. Figure 6, showing the relative dose deposition profiles in the transverse plane as a function of distance in the water, illustrates **Xenos** graphical capabilities.

[6]The precise beam density distribution in the **FLUKA** simulation was not known, so the results are normalized for the best fit.

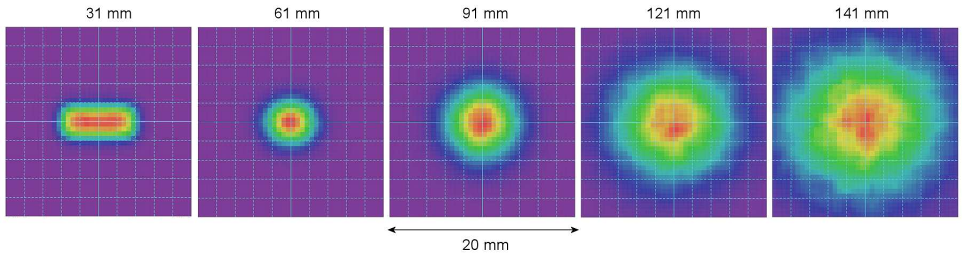

Figure 6: Rectangular focused electron beam with kinetic energy 158 MeV, transverse dose profiles as a function of depth in a water phantom. The color scales are normalized for visibility – there is a strong decrease in the intensity with depth.

The major Monte Carlo radiation packages have been optimized and tested for decades, so it is safe to assume that they all correctly predict dose deposition and secondary particle generation. Beyond physical validity, **Xenos** does have some unique features of interest for VHEE applications:

- It is an integrated multi-physics suite that addresses electron beam generation and transport as well as thermal effects of energy deposition.
- Scoring on conformal meshes gives accurate representations of physical structures and boundaries.
- The mesh generators supprt import of geometric data from medical images and the Zubal and GSF human phantoms.
- Numerically exact three-dimensional electric and magnetic fields can be determined and applied in the Monte Carlo calculation.
- **Penelope** is particularly strong in modeling atomic processes at low energy.