Simulation of a proton beam through a phantom of water using Geant4

Carmen Jacobs[1,2]

[1] Radiation & Reactor Theory (RRT) Section, Research & Development Department, Necsa, Building 1900, PO Box 582, Pretoria, 0001

[2] Physics Department, University of the Western Cape, Bellville, Western Cape, South Africa

E-mail: carmen.jacobs@necsa.co.za

Abstract. Radiation therapy is used in the cure or control of certain cancers. Traditional radiation therapy use X-ray (photon) beams. This result in the healthy tissue surrounding the cancerous volume receiving high doses of radiation. This study looks at proton beam radiation where the radiation can be concentrated inside the tumour volume and the dose to the surrounding tissue can be minimized. Geant4 is a calculational toolkit using Monte Carlo methods. The Geant4 toolkit allows for the simulation of particles through matter. In this study hadronic scattering models as well as electromagnetic scattering models are used within the Geant4 toolkit to simulate the transport of a proton beam through a water phantom. Both models yield similar results and are in close agreement with the experimental data obtained from the iThemba Laboratory for Accelerator Based Sciences in the Western Cape.

1. Introduction

Radiation therapy, also known as radiotherapy, uses ionising radiation to destroy cancerous or deformed cells, prohibiting the deformed cells from multiplying. Sometimes radiotherapy is the only treatment used, other times it is used in conjunction with surgery and/or chemotherapy. Radiotherapy is known to be helpful with the relief of pain associated with the symptoms of cancer, this is called palliative radiotherapy. Some cancers can be completely cured by radiotherapy alone, this form of treatment is known as radical radiation therapy.

The problem is that X-ray beams (photons) provide a high radiation dose to the healthy tissue surrounding the tumour. One need to fill the volume of the tumour with a radiation dose, without affecting the surrounding tissue too drastically. When looking at the Bragg curve, or depth dose curve, which plots the energy loss of ionizing radiation as a function of position during its travel through matter, it is noticed that most of the radiation from ion beams can be concentrated inside the tumour volume being treated whilst minimizing the effects on the surrounding healthy tissue. To minimize the damage to the healthy tissue even further, the tumour is 'hit' from several angles.

The objective here is to simulate the transport of a proton beam in a water phantom to determine the depth dose curve. The ideal result from proton beam radiotherapy is to obtain a spread-out Bragg peak (SOBP). In this way the entire volume of the cancerous tumour can be irradiated. In practice this is done by using a range shifter. The range shifter is placed between the nozzle of the beam and the patient. Each section of the range shifter has a different thickness. The range shifter rotates during the treatment, allowing different intensities of the same proton beam to enter the patient. Energy deposition is 'smeared out' as evenly as possible throughout the tumour volume. Thus spatially large tumours can be irradiated successfully. Most of the secondary radiation observed during proton therapy treatment is due to the production of neutrons when protons interact with human tissue.

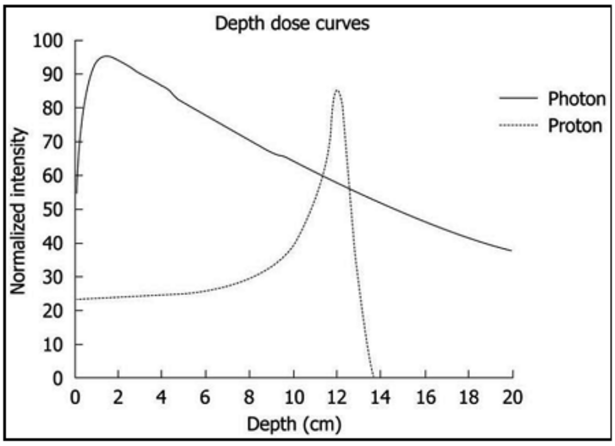

Figure 1. Typical depth dose curve for photons and protons as pictured by Studenski & Xiao (2010) [1]

2. Geant4 background

The Geometry and Tracking (GEANT) toolkit was developed at CERN [2]. It is now supported and maintained by the GEANT collaboration team at CERN. GEANT is an object orientated toolkit for the simulation of radiation transport in matter. It offers a set of physics models based on experimental data, theory and parameterization.
GEANT works on a C++ platform. The experimental set-up has to be explicitly described in the code, the primary particles have to be provided and the specific physics models to be used in the simulation should be included in the code. GEANT also offers some extra visualization tools such as Wired, RayTracer, OpenGL, etc.

2.1. Example structure of the GEANT4 code

The code should include the **main program**. Geant4 does not provide the *main()* [3]. The *main()* is used to construct the G4RunManager, and to set the mandatory user classes (G4VUserDetectorConstruct, G4VUserPhysicsList, G4VUserPrimaryGeneratorAction, etc.) to RunManager. Some optional user classes (VisManager, GUI session, etc.) can also be defined in the *main()*.
The **geometry and materials** section of the *main()* is used to describe the detector. One has to derive a concrete class from the G4VUserDetectorConstruction abstract base class. In the virtual method all the necessary materials, the volume of the detector geometry, and the sensitive detector classes have to be constructed. The sensitive detector classes should be set to the detector volumes.
The **physics** part of the code is where the physics processes are selected and the particle interactions with matter are defined. Geant4 does not have any default particles or processes; it has to be explicitly defined within the code. A concrete class can be derived from the G4VUserPhysicsList abstract class. This concrete class should define all the necessary particles, all the necessary processes which should in turn be assigned to proper particles, and the

cut-off ranges applied to the world.
A **step** in Geant4 has two points and carries information such as the energy loss on the step and time-of-flight spent by the step of a particle. In case a step is limited by a volume boundary, the end point physically stands on the boundary and it logically belongs to the next volume. Since each step knows two volumes, boundary processes such as transition radiation and reflection can be simulated. Geant4 **tracking** is general, it is independent of the particle type, and of the physics process related to a particle. While a process is being tracked in Geant4, it contributes to any possible changes in the physical quantities of the track. Each process can also generate secondary particles and suggest changes in the state of the track.
At the beginning of a process, an **event** contains primary particles. To generate the primary event, the concrete class has to be derived from the G4VUserPrimaryGeneratorAction abstract base class. A G4Event object is passed to one or more primary generator concrete class objects which generate primary vertices and primary particles. These primaries are pushed into a stack. When the stack is empty, the processing of an event is over. A G4Event class represents an event. Each event produces a list of primary vertices and particles, hits collections, trajectory collection, etc. This information is then sent to the **run manager**.
Conceptually, a **run** is a collection of events which share the same detector conditions. A run in Geant4 is started with the command 'BeamOn'. Within a run, the user cannot change the detector geometry or the settings of the physics processes. At the beginning of a run, the geometry is optimized for navigation, and cross-section tables are calculated according to the materials defined in the geometry.
For **visualization**, one has to derive a concrete class from G4VVisManager according to the computer environments. Geant4 provides interfaces such as DAWN, WIRED, RayTracer, OPACS, OpenGL and VRML to graphics drivers.

3. Results

Figure 2 represents the results obtained when running the Geant4 code using both electromagnetic and hadronic scattering models. The Bertini (black curve) model generates the

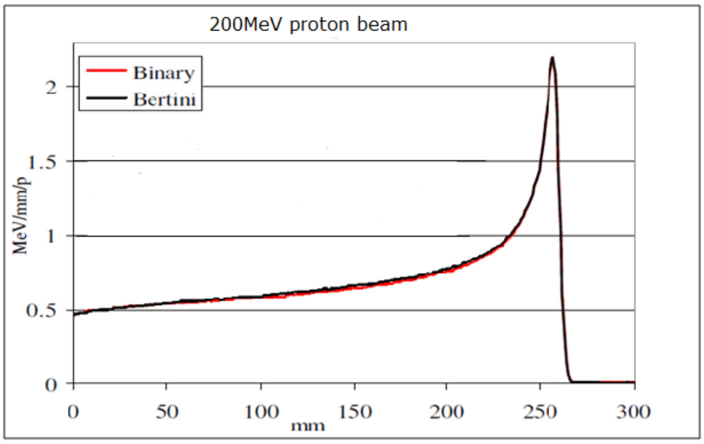

Figure 2. Stopping power of a 200MeV proton beam in a water phantom: electromagnetic + inelastic scattering models.

final state for hadron inelastic scattering by simulating the intra-nuclear cascade. The Binary (red curve) model signifies a method using ion irradiation physics to enable efficient computer

simulation of the penetration depth by energetic ions in a medium. Note that both models yield the same results.
Similar results were obtained for proton beams with initial energies of 100MeV, 150MeV and 250MeV. For the 100MeV proton beam the Bragg peak was observed at a depth of 140mm in the water phantom. The 150MeV proton beam travelled a distance of 210mm in the water phantom before losing all its energy.
The neutron spectrum (**Figure 3** below) from the 200MeV proton beam shows a number of secondary neutrons produced, when protons interact with water. Most of the neutrons produced have relative low energies; less than 20MeV. No neutrons with energies greater that 200MeV were produced. The Binary model generates slightly more secondary neutrons than the Bertini model.

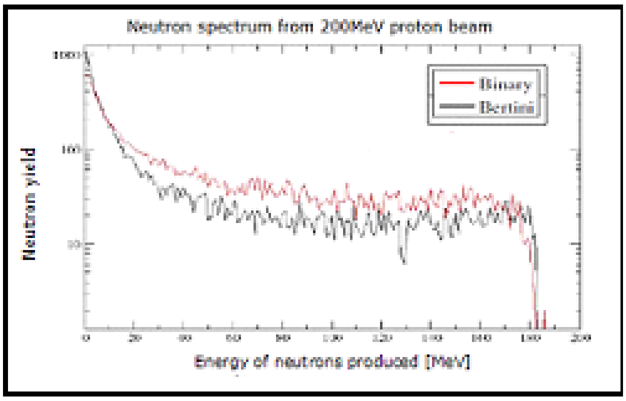

Figure 3. Secondary neutron production in different inelastic scattering models.

4. Proton beam validation

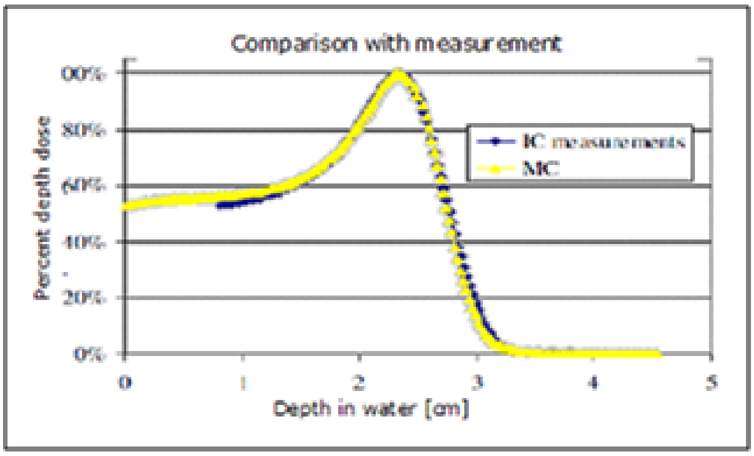

Figure 4. Comparison of the 200MeV proton beam Monte Carlo simulation with experimental measuremens.

The results obtained from the 200MeV (yellow curve) Monte Carlo simulation were compared to the experimental measurements (blue curve) obtained from the iThemba Laboratory for Accelerator Based Sciences (iThemba Labs) in the Western Cape. The experiment was run in 2007 by one of the then masters students based at the facility.
From **Figure 4** one can make the assumption that Geant4 is an excellent tool to use when preparing a patient for radiation therapy. During the treatment planning process of radiation therapy, Geant4 can be used to construct the planning cube, and to come up with solutions for treating the patient. Proton beam therapy can minimize the risk of radiation being delivered to vital organs close to the tumour volume.

References

[1] Studenski, M. T., Xiao, Y., 2010. *Proton therapy dosimetry using positron emission tomography.* World Journal of Radiology, Volume 2, pp: 135-142.

[2] http://geant4.cern.ch/ (20 June 2012)

[3] http://www.ge.infn.it/geant4/training/portland/basicStructure.pdf (20 June 2012)