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HADRON THERAPY MACHINE SIMULATIONS USING BDSIM *

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Abstract

Minimising the background radiation dose in hadron therapy from particle losses and secondary emissions is of the highest importance for patient protection. To achieve this, tracking particles from source to the patient delivery region in a single simulation provides a quantitative description that distinguishes the background radiation from the treatment dose arriving at the gantry's isocentre. We demonstrate the ability to simulate beam transport, particle loss studies, and background radiation tracking in an example hadron therapy machine using BDSIM, a Geant4 based Monte Carlo simulation code for tracking high energy particles within a particle accelerator and its surrounding environment. Machine optics verification is also demonstrated through comparison to existing accelerator tracking codes.

INTRODUCTION

The increasing demand for access to hadron therapy is driving novel research to both improve treatment efficacy and reduce costs. Such costs encourage facilities to accommodate several gantries that are supplied by a single particle accelerator, meaning facilities require significant design considerations to minimise the patient's background dose and maintain feasible machine efficiency, whilst providing treatment with highly accurate therapeutic dose distributions.

Monte Carlo simulation tools which can model both beam optics and quantify energy deposition resulting from particle losses are highly advantageous to hadron therapy accelerator design. They can provide an accurate description of the beam's physical properties whilst simultaneously optimising the machines configuration.

BDSIM [1], which uses the Geant4 [2] toolkit to construct a 3D model of an accelerator, has recently been developed for this purpose. The program provides accurate particle tracking through the machine's electromagnetic fields whilst using Geant4's physics processes to simulate particle-matter interactions and track any subsequent secondary emissions.

To demonstrate BDSIM's applicability to hadron therapy machines, we have chosen to simulate Gantry 2, a proton therapy beamline that forms part of the PROSCAN project at PSI [3]. Depending on treatment requirements, the gantry operates between 70-230 MeV through use of a degrader [4]. This type of energy selection system significantly alters the physical properties of the beam, consequently requiring modification of the machines optics to successfully deliver the beam to the gantry's isocentre.

A lattice description of the gantry is available at [5], originally written for use with Transport [6]. Here, we show predicted loss maps of this example machine for beams at the gantry's operational energy boundaries. We also compare the machine's optical functions to the Transport calculations, and to a common particle tracking code, PTC through the MADX program [7].

MODEL PREPARATION

Transport was used to generate a standard output file which contains the input lattice and calculated beam optical functions. To prepare a description of the machine for BDSIM and PTC, a Python utility tool included with BDSIM, *pybdsim* [8], converts the magnetic description of each of the machine's constituent elements, the beamline sequence, and input beam distribution. Other options for configuring the simulation were appended by hand.

Prior to conversion, a drift element with negative 6 cm length was removed from the Transport lattice description to ensure the optical functions comparisons would be correct. The converted elements were updated with any results from Transport fitting routine calculations.The beam pipe aperture was assumed to be circular, with the aperture radius taken to be the value of the vertical half aperture set in the description of dipole fringe field parameters, 3.75 cm.

Although the degrader affects the beams phase space distribution, varying significantly with target beam energy, as this is an exercise in demonstrating the applicability of BDSIM to such a machine, only the central momentum was modified in the Transport beam description. The degrader and beam collimation are represented in the Transport lattice as an instantaneous redefinition of the beam. As this is unphysical, the lattice was split into two machines and ran as separate simulations, with the results being combined during analysis. The first machine is about 3.79 m long and represents the beamline from the facility's cyclotron to the degrader and collimation sections. The 250 MeV beam for this section was unaltered. The beam for the second machine has a 1% momentum spread for all simulations.

As Geant4 provides the capability to select which physics processes are simulated, only physics lists applicable to the 70-230 MeV energy range were considered, in this case, *em*, *ftfp_bert*, *hadronic_elastic*, *em_livermore*, & *decay*.

For the optical comparison simulations, the beam was sampled after every element in the lattice. Simulation losses are expected, therefore to minimise the possibility of particle losses outside of the beam pipe being sampled and increasing the statistical uncertainty of the optical function calculations, only particles within the beam pipe aperture are considered.

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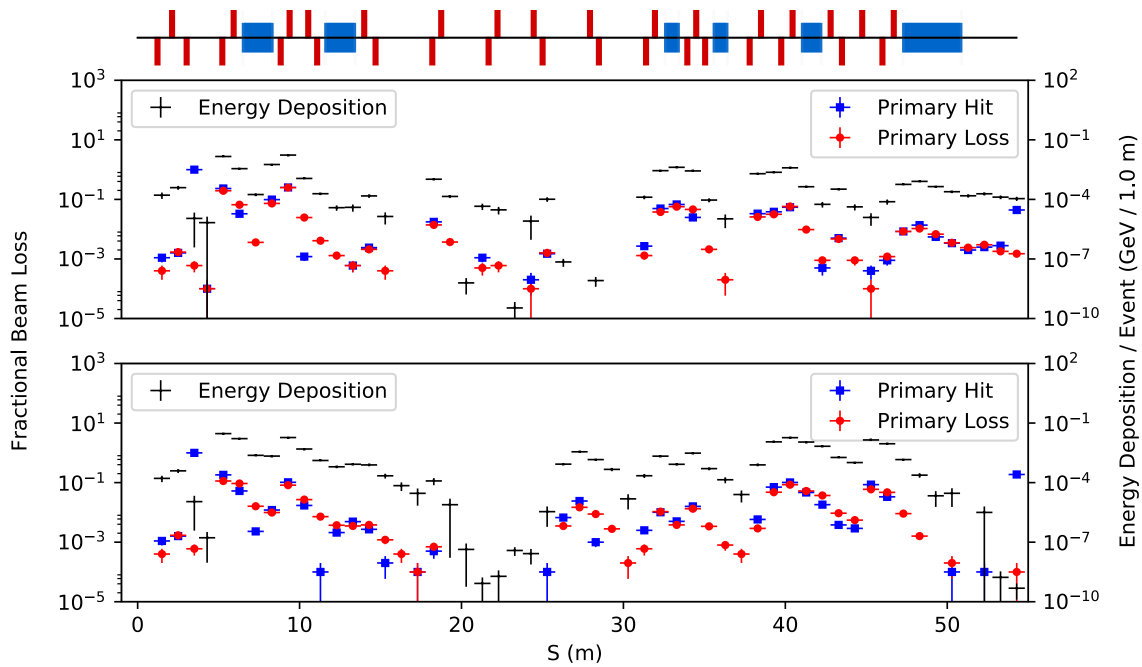

Figure 1: Fractional beam loss of the primary particles and energy deposition for beam energies of 70 MeV (top) and 230 MeV (bottom).

RESULTS

The initial beam distribution comprises 10k primary particles in each simulation. Every time a primary particle hits the accelerator geometry, the location along the machines curvilinear reference trajectory, the energy deposited in the volume and any secondary particles that were generated are recorded. The location where the primary particle is either lost or absorbed is also recorded. Dipole fringe fields that are crucial to particle tracking are included in these simulations.

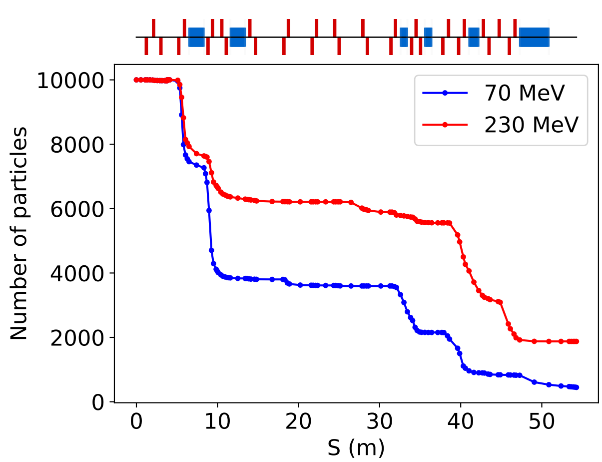

Figure 2: Number of primary particles recorded at the end of each beamline element.

Figure 1 shows the loss map and energy deposition per event, per metre of beamline, for the machine at both 70 and 230 MeV in the top and bottom plots respectively. It is evident that significant losses are observed throughout the machine at both energies. Many of the primary hits correlate with the primary losses indicating that the protons are absorbed into beam pipe wall . The rate of primary losses is more evident in Fig. 2 which shows the number of particles recorded in each sampler along the machine. A significant number of particles are lost after the first dipole due to the growth of horizontal beam size in this highly dispersive region. Further decreases in the number of primaries are also observed in subsequent dispersive regions.

By selecting an element known to have high energy deposition, it is possible to analyse this further using BDSIM's complimentary analysis utility, *rebdsim* [1]. A drift at $S = 41m$, the point about which the gantry beamline would rotate, was chosen in the 230 MeV model as previous simulations highlighted large numbers of secondaries in that region. The model was simulated a second time using 1×10^6 protons in the primary distribution to improve the statistical uncertainties of low frequency events. The analysis revealed energy deposition in the element by 5 species of secondary particles.

Inspection of the beam dimensions in the Transport output revealed a 1σ beam size comparable to the half aperture size, meaning a significant portion of the beam was expected to be lost, as has been observed. These non-Gaussian transverse distributions would not be quantitatively comparable to codes such as Transport that assume Gaussian distributions

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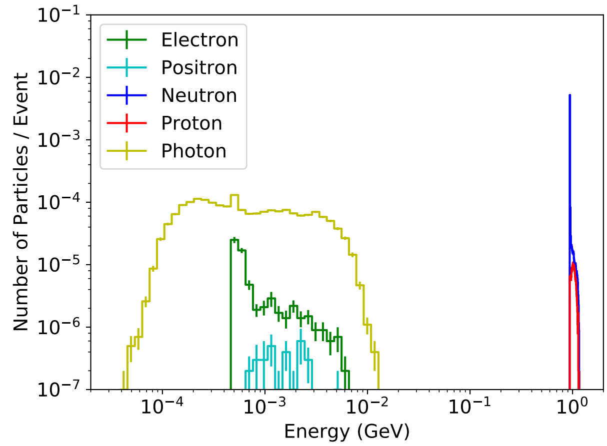

Figure 3: Number of secondary particles per event per energy as recorded in a drift at S=41 m, for a primary beam kinetic energy of 230 MeV.

for the beam envelopes. To reduce the losses and statistical fluctuations in the beam distribution, the beam pipe aperture was increased to 20 cm for the optics comparison studies only. As losses are still possible, all 6 dimensions of the phase space aperture in the *ptc_track* routine were increased, with the spatial dimensions set to same as the BDSIM model aperture. Secondary emissions were not considered for the optics comparison studies.

A comparison of the transverse beam sizes in BDSIM, Transport, and PTC is shown in Fig. 4 and Fig. 5 for the 70 and 230 MeV beams respectively. Good agreement is observed between BDSIM and PTC at both energies. The minor discrepancy seen after $S \approx 14$m can be attributed to a difference in losses still observed in the simulations. Approximately 10% and 12% of the primaries in BDSIM and PTC respectively are lost before the final sampling plane. Furthermore, PTC integrators track to higher numerical order than BDSIM which could introduce further discrepancies.

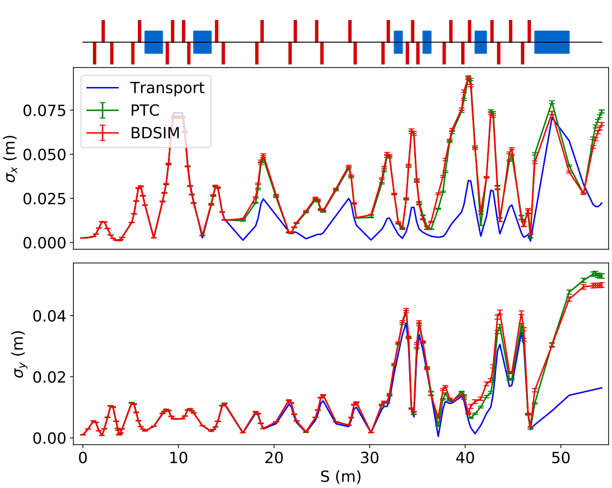

Figure 4: Comparison of transverse beam sizes for a beam energy of 70 MeV.

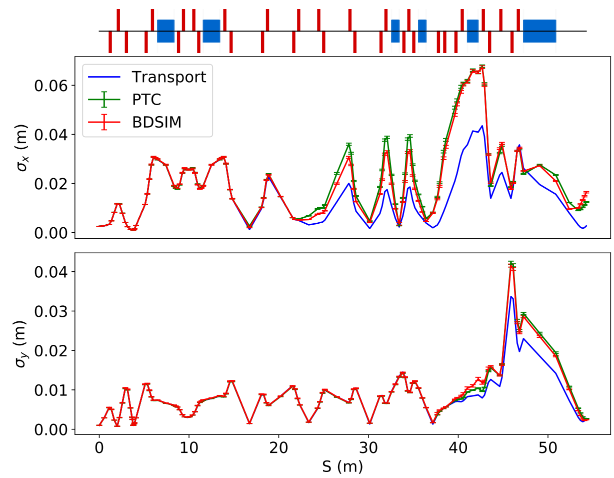

Figure 5: Comparison of transverse beam sizes for a beam energy of 230 MeV.

Codes such as Transport assume small transverse momentum and a small angle approximation is applied. In low energy machines with large momentum spread such as this gantry, this approximation becomes invalid. As the horizontal plane displays larger differences in the comparison, and both BDSIM and PTC display a constantly larger beam size, this suggest that dispersive growth is significant and that this machine cannot be reliably compared to Transport.

CONCLUSION AND OUTLOOK

The first energy deposition maps and optical function calculations of an example hadron therapy machine in BDSIM are presented. BDSIM demonstrates the capability of accurately tracking particles in a low energy machine and recording any losses. The machine's optical functions are shown to be valid compared to PTC, however, the combination of primary losses and large dispersion invalidating the small angle approximation assumption inhibits a reliable comparison to general accelerator optics codes.

Simulation results are highly dependent on the model and simulation conditions. A more detailed aperture model would improve the accuracy of the loss maps, and the inclusion of the degrader and collimation systems in the beamline would provide a more accurate representation of the beam distribution. Further developments of BDSIM for hadron therapy based applications are being considered that would provide even greater capabilities of running start to end simulations of such machines.

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