14 October 2023
daniel.petri.sorvisto@cern.ch

Summer student report: BDSIM models for T4 wobbling station and H6 & H8 beamlines

Daniel Sorvisto, CERN, CH-1211 Geneva, Switzerland
Supervisors: Fabian Metzger, Florian Stummer

Keywords: BDSIM, North Area, H6, H8, T4, wobbling, MAD-X

Summary

The North Experimental Area at CERN hosts a multitude of experiments and is designed to be flexible in terms of beams it can provide. The T4 target is one of the primary targets in the North Area, and receives a 400 GeV c^{-1} proton beam from the Super Proton Synchrotron. This project focuses on constructing 3D models and performing simulations on the T4 wobbling station and its secondary beamlines, H6 and H8. BDSIM models were made using a new builder tool from BE-EA-LE which is able to convert MAD-X models into BDSIM very rapidly. Most of the analysis was done on the T4 simulations, and show that the model works very well and is able to provide an accurate input beam for the H6 and H8 models.

Contents

1 Introduction **2**

2 BDSIM models **3**

3 Results and discussion **4**
3.1 QTS quadrupole magnet model . . . 4
3.2 TAX models . . . 5
3.3 T4 wobbling station . . . 5
3.4 H6 beamline . . . 12
3.5 H8 beamline . . . 13

4 Conclusions and outlook **14**

1 Introduction

CERN, or the European Organization for Nuclear Research, is one of the most well-known research organizations in the world, and has established itself as a global leader in the field of particle physics. Although CERN is most well-known for its flagship particle accelerator, the Large Hadron Collider (LHC), the organization hosts several other accelerators, the next largest one being the Super Proton Synchrotron (SPS). The North experimental Area, which the SPS provides beams to, hosts a multitude of physics experiments as well as test beam and R&D activities. It was designed to provide flexible and effective beam lines that can adapt to a variety of purposes [1]. A view of the North Area is shown in figure 1.

Figure 1: The North Experimental Area from an aerial view, showcasing the experimental halls EHN1 and EHN2, as well as the beamline system [1].

In the North Area, a 400 GeV c^{-1} proton beam is extracted from the SPS and directed into the TCC2 cavern, containing the stationary primary targets T2, T4, and T6. Splitter magnets split the beam into three beams, one for each target. Primary target units consist of several beryllium plates with different lengths [1], allowing for easy selection of optimum target length as required by the beam users downstream. In this project, we concentrate on the T4 target, which was set to a length of 100 mm in the simulations.

After the 400 GeV c^{-1} primary beam hits the T4 target, secondary particles of varying types and momenta are produced. The purpose of the T4 wobbling station is to select the particles with the right momenta for the secondary beamlines H6 and H8, as well as the P42 transfer line. H6 and H8 are user beamlines going towards the EHN1 experimental hall, whereas the P42 beamline transfers the unscattered primary protons towards the T10 target, followed by the K12 beamline that ultimately leads to the NA62 experiment. The name 'wobbling' is derived from how the beam is directed to swing from side to side in the station. Since the turning radius of a particle in a dipole magnet is proportional to its momentum, the wobbling station will assign a specific angle and offset for each momentum. A TAX [2] (Target Attenuator eXperimental areas) is a large block of dense material with the purpose of stopping most of the particles with unwanted momenta, direction, and offset. It is a specific type of collimator designed to block secondary particles soon after a target. A TAX block has one or more holes in it, varying in location and size, to let particles with specific momenta go through with a certain acceptance range. At the end of the T4 wobbling station there are 4 TAX blocks, two joint ones back to back for H6 and H8, and another two for P42. Each TAX at the T4 station consists of 4 sub-blocks. [3]

2 BDSIM models

Beam Delivery Simulation (BDSIM) [4] is a program based on C++ and the Geant4 (GEometry ANd Tracking) toolkit [5] for simulating both particle transport and interaction with material. The North Area experiments use BDSIM for the analysis and optimization of beam delivery systems and backgrounds. Contrary to programs like MAD-X, which do numerical calculations on the functions that describe the beam state and beamline elements, BDSIM is a Monte Carlo style tool which simulates each particle and its interactions individually. BDSIM uses 3D models of every beamline element and is able to simulate the interactions of element material and individual particles.

The purpose of this project is to construct BDSIM simulation models of the T4 wobbling station, along with H6 and H8, and perform simulations on them. 3D models of the QTS quadrupole magnet and the two tax blocks are constructed. The wobbling station is set for positively charged particles, where the H6, H8, and P42 beamlines are set to 120 GeV c^{-1}, 180 GeV c^{-1}, and 400 GeV c^{-1} momenta, respectively. Simulations can be performed also on other settings but they are not discussed in this report.

Previously, the construction of a BDSIM beamline model required a lot of work due to the tedious manual placement of beamline elements. A recent tool developed by BE-EA-LE allows for a considerable speedup of model building by converting existing MAD-X model files into Previously, the construction of a BDSIM beamline model required a lot of work due to the tedious manual placement of beamline elements. A recent tool developed by BE-EA-LE allows for a considerable speedup of model building by converting existing MAD-X model files into BDSIM input. Another purpose of this project is to serve as a first use-case and a validation for the builder tool.

Other tools used for the analysis of the data created include the Python programming language, ROOT, and the HTCondor high-performance computing environment.

3 Results and discussion

This section presents and discusses each of the results of the project, which include 3D models of the QTS magnet and the TAX blocks, BDSIM models of T4 wobbling station, H6, and H8, and the simulation results and insights.

3.1 QTS quadrupole magnet model

A quadrupole magnet is a very common beamline element in particle accelerators and beamlines. In comparison to a dipole magnet, which produces a (more or less) homogeneous magnetic field and is used to bend the particle beam using the Lorentz force, a quadrupole is used to focus and defocus the beam [6]. Contrary to light optics, where a convex lens is able to focus a beam of light in both of the transverse planes, in charged particle beam optics this is not possible. Due to the mechanics of electromagnetism, a quadrupole magnet can only produce a focusing effect in one plane while defocusing the beam in the other plane. However, a combination of several quadrupoles may produce a focusing effect on both planes.

The QTS magnet [7] is a quadrupole magnet which is used in several places along the H6 beamline. It was the only magnet without a pyg4ometry [8] model in H6, and it needed to be constructed using blueprints as a part of the project. The 3D model is not perfect and makes some geometric simplifications, like approximating a curved surface with a finite amount of points, but the model is accurate enough for the purpose of these simulations. A view of the 3D model is shown in figure 2.

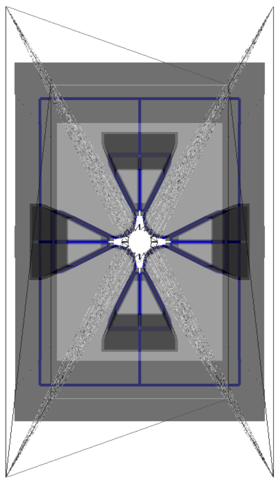

Figure 2: Pyg4ometry model of the QTS quadrupole magnet.

3.2 TAX models

As mentioned before, proper 3D models of the two TAX blocks needed to be constructed using blueprints. The blocks also need to be accurately placed at the end of the model in terms of offset and rotation. For the P42 TAX, we used a predefined offset (588.2 mm) in the s-direction from the vacuum chamber and aligned the transverse offset (−288.0 mm in the x-direction) and rotation (11.22 mrad) using a nominal particle as given by the T4 wobbing station layout.

For the joint TAX for H6 and H8, the offset and rotation were defined relative to the P42 TAX. The rotation was set identical to the P42 block, and it was placed on the left side of the block with a 10 mm gap in between, as this was the setting in a previous model at BE-EA-LE.

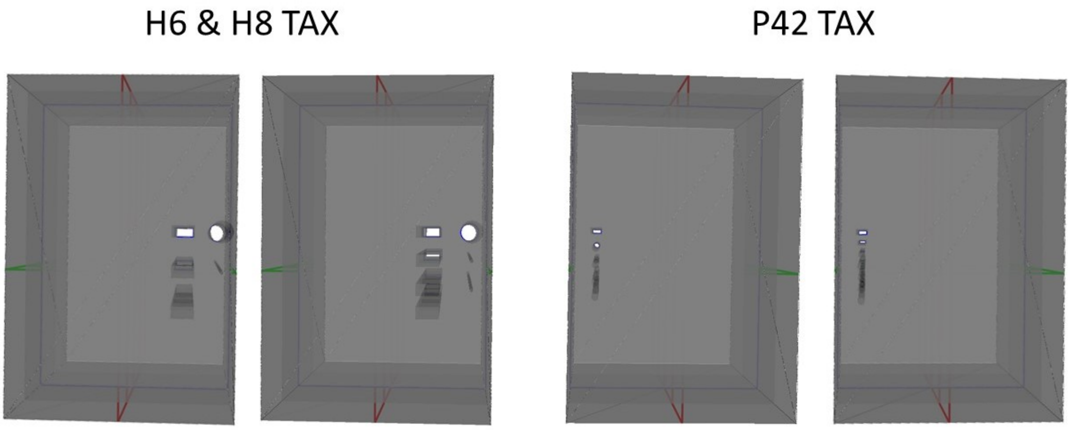

Figure 3: Pyg4ometry models for the TAX blocks visualized. Viewpoint does not represent the alignment in the real BDSIM model.

3.3 T4 wobbling station

Like previously mentioned, the purpose of the T4 wobbling station is to align the secondary beams produced in the T4 target such that particles with the right momenta go through the right holes into the right beamlines, and to stop unwanted particles from entering them with the help of the TAX blocks. The wobbling station consists of three sets of bending dipoles, the T4 target, and the TAX, as depicted in figure 4. The BDSIM visualization of the model can be seen in figure 5.

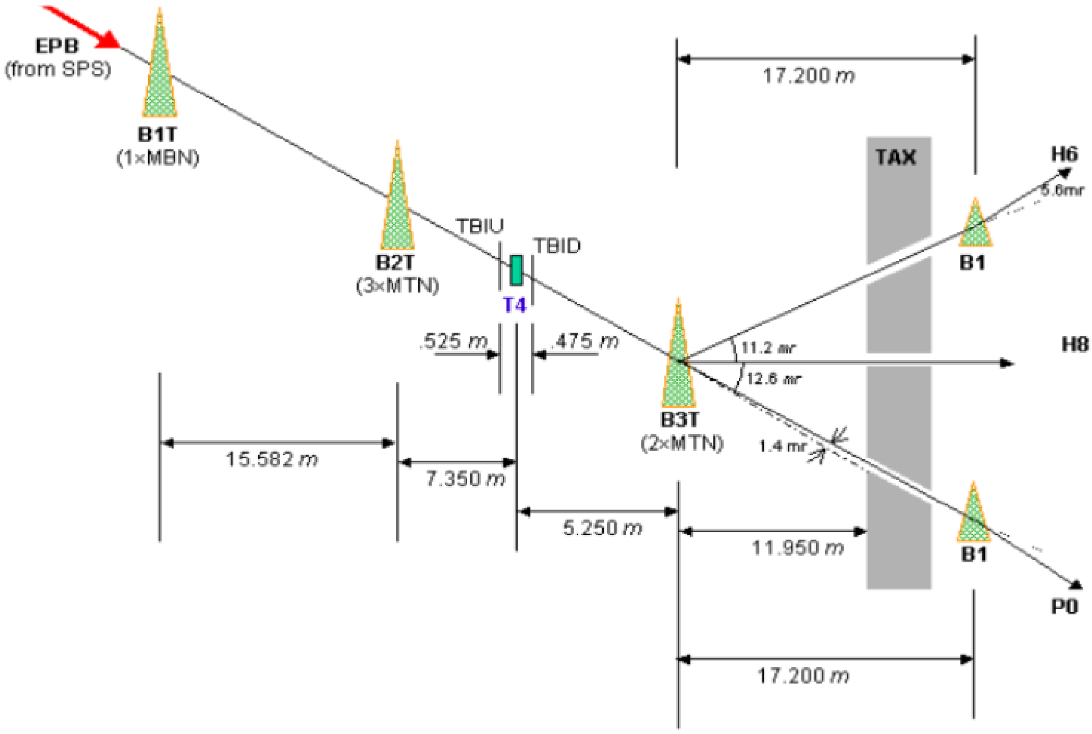

Figure 4: Layout of the T4 wobbling station, showcasing the bending magnets, the T4 target, and the TAX, along with the angles of the three beamlines. [1]

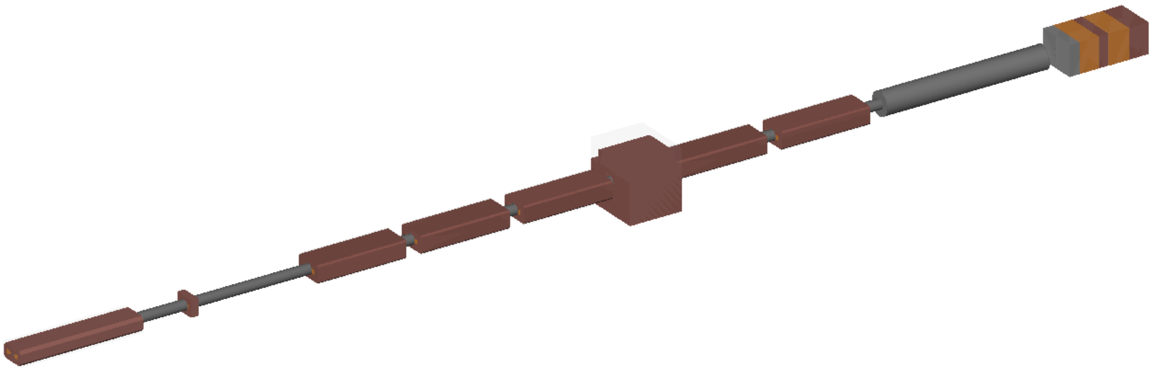

Figure 5: BDSIM visualization of the T4 wobbing station model.

Figure 6 shows the profile of the beam at the end of the T4 wobbling station, after the TAX. We can see that most of the protons barely interact with the target or do not interact at all, as the P42 hole gets almost one particle per primary proton.

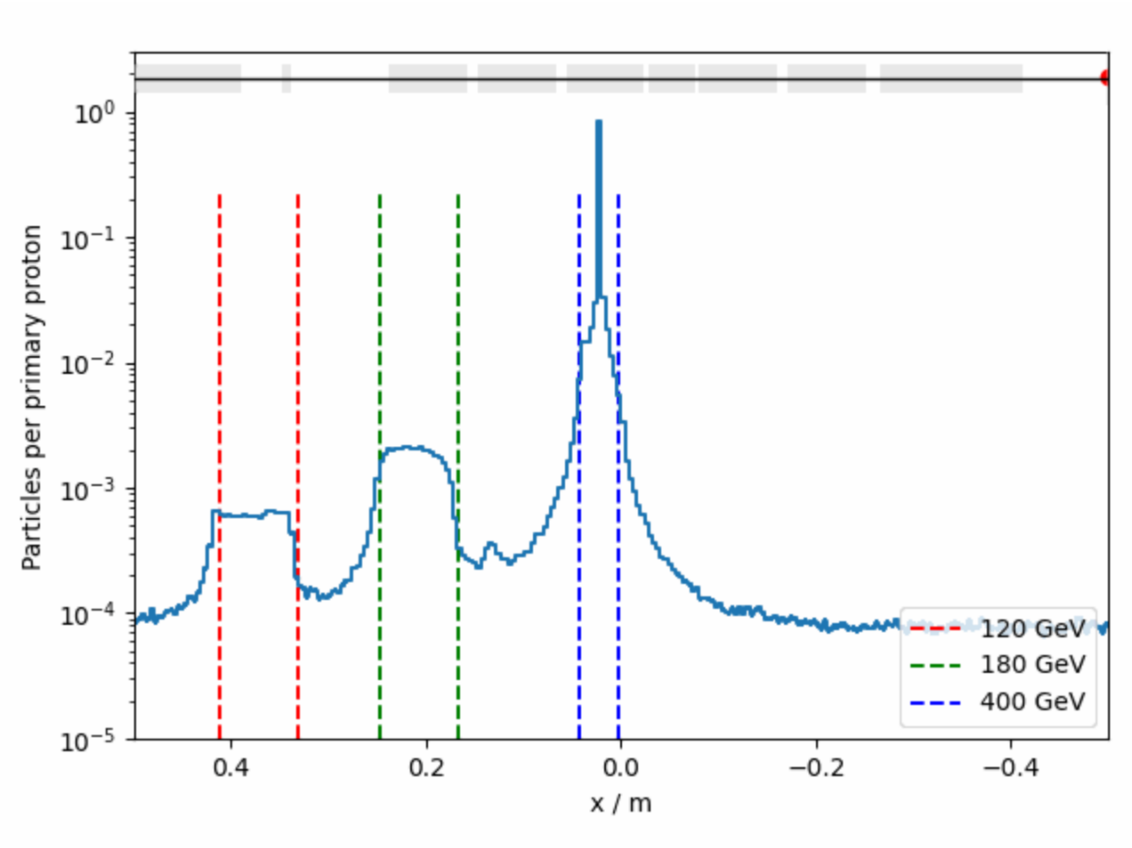

Figure 6: Beam profile at the end of the TAX. Vertical lines mark the edges of the TAX holes for each beamline at the end of the TAX. Red dot in the lattice diagram at the top points out the location of the snapshot.

Figure 7 shows the momentum-angle correlation of the beam at the end of the TAX. Each beamline TAX hole is clearly visible, although the spread seems to be quite large, both in terms of momentum and angle. This may be explained by particles entering the hole from barely missing the hole wall on one side, and leaving the hole almost touching the wall on the other side. The histogram is also logarithmic, and may therefore visually exaggerate the amount of highly deviating particles in each hole, especially since the very dense spot at $400\,\mathrm{GeV}\,c^{-1}$ sets the scale of the z-axis.

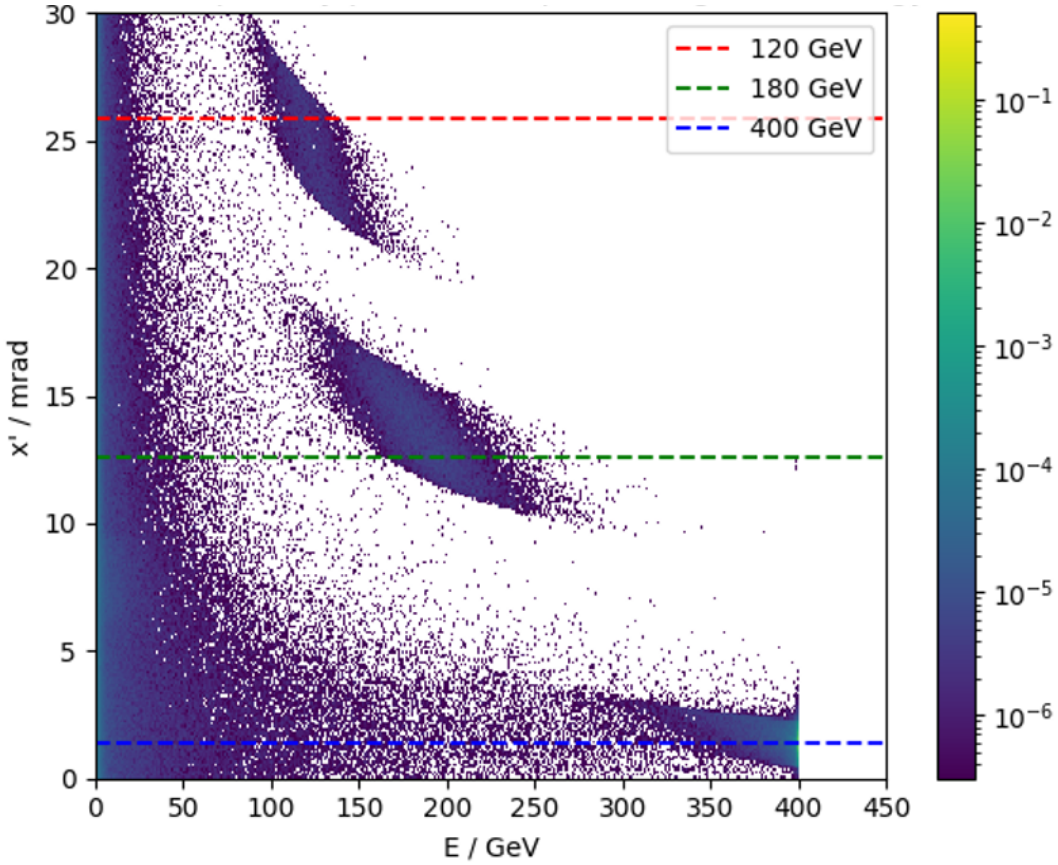

Figure 7: Angle as a function of energy for particles after the T4 TAX. Angles for The H6, H8, and P42 holes are marked with lines.

Figure 8 shows the momentum-offset correlation of the beam, again at the end of the TAX. Similarly to the previous plot, the momentum spread is quite large in each hole, but this may be explained by particles moving diagonally through the holes.

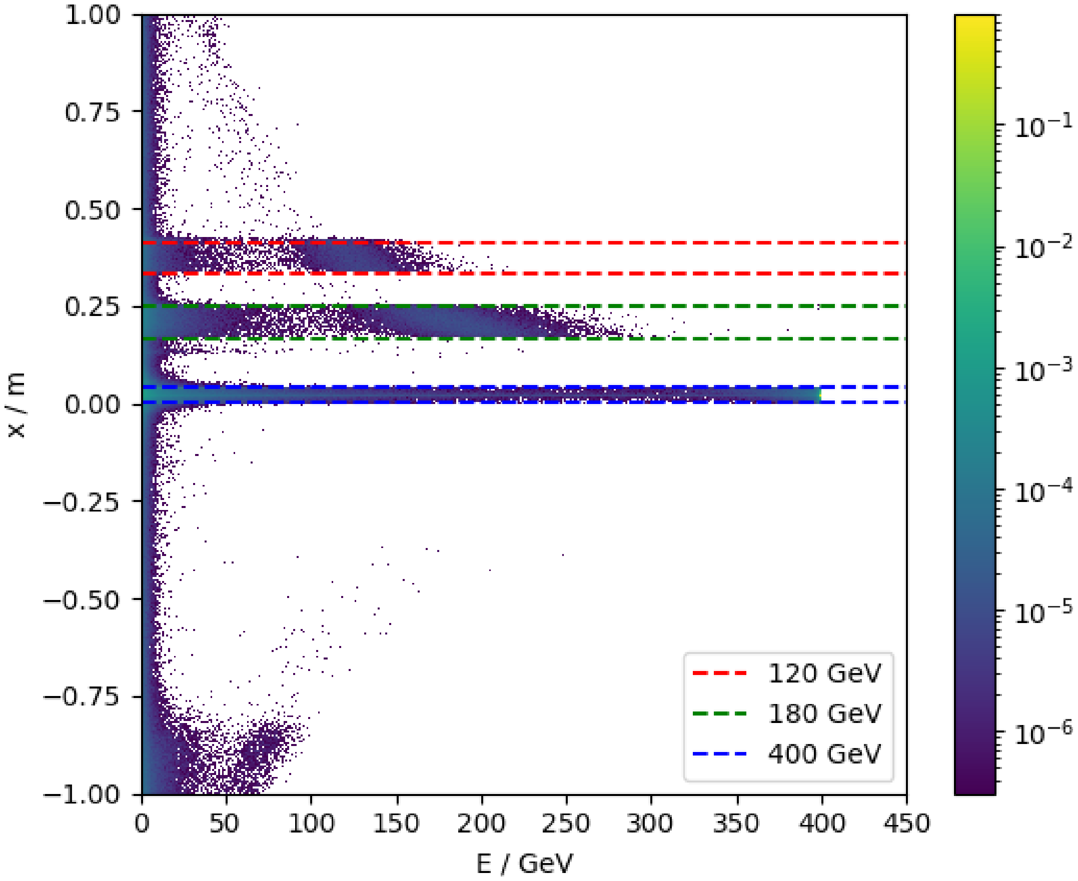

Figure 8: X-directional offset as a function of energy for particles after the T4 TAX. Location of the edges of the holes for H6, H8, and P42 at the end of the TAX are marked with lines.

Figure 9 illustrates the offset-angle correlation of the beam after the TAX. The main beam can be seen in each hole at their respective angles, marked by the horizontal lines. The 180 GeV c^{-1} H8 beamline seems to be receiving additional particles from somewhere, as can be seen from the two bright lines above and below its vertical line. Note that extrapolating the line below (at 7 mrad, 0.2 m) does not get us to the 400 GeV c^{-1} beam (2 mrad, 0.03 m). Still, these particles may have something to do with the few 400 GeV c^{-1} particles in the 180 GeV c^{-1} H8 hole that can be seen in figure 7. The upper line may be explained by a scattering happening at the end of the TAX.

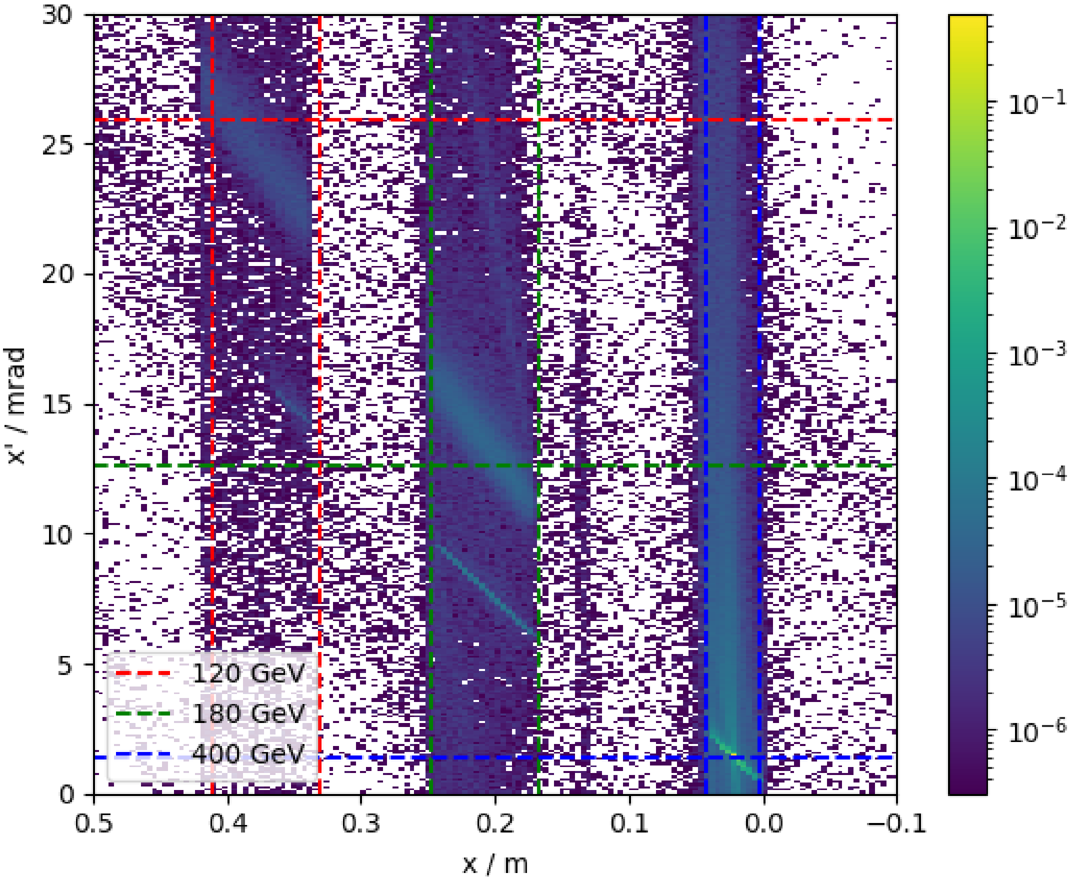

Figure 9: Angle as a function of x-directional offset for particles after the T4 TAX. Angles for H6, H8, and P42 are marked with horizontal lines, and their respective hole edges at the end of the TAX with vertical ones.

In figure 10 we see where the particles which pass the TAX originate from. A large virtual sampler, which records the particles passing through, is placed at the end of the TAX and the particles are traced back to their origin. We can clearly see the outlines of the two dipole magnets right after the target, and the vacuum chamber just before the TAX. Many of the particles seem to originate from interactions with air in the TAX holes.

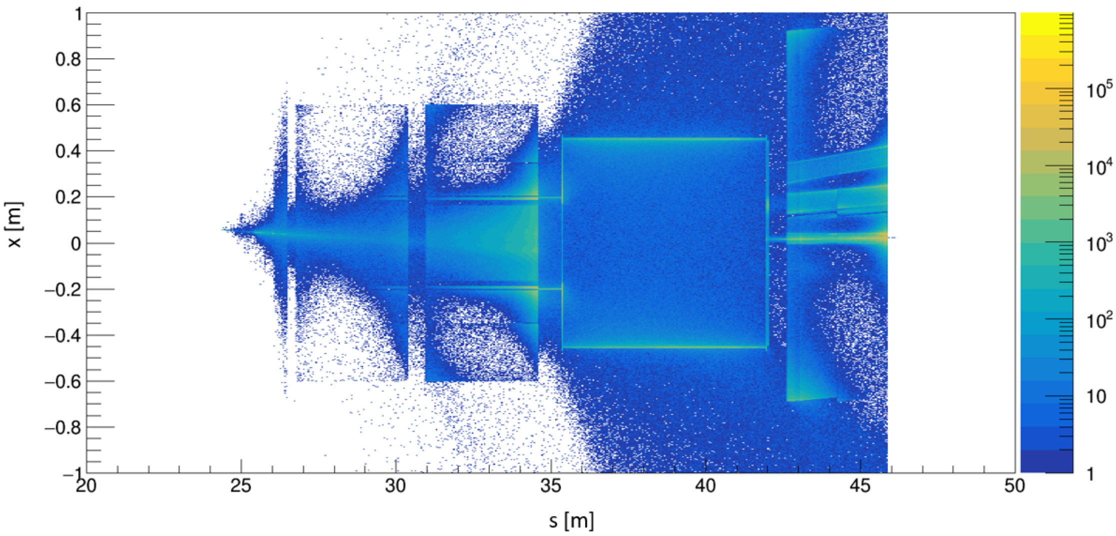

Figure 10: Histogram showcasing the traced-back origin for particles which hit the large virtual sampler placed after the TAX.

3.4 H6 beamline

As mentioned before, a part of this project was constructing a BDSIM model of the H6 beamline, and running simulations on it. Since the process of converting the model from MAD-X to BDSIM went very smoothly using the recently made builder tool, the main problem was actually aligning the H6 model to the T4 wobbling model, which is needed since the H6 model uses the beam from T4 at a specific location as input. This was done by tracking a single, ideal H6 particle through the simulation and finding the setting where the particle stays in the center through the whole model. The simulations and analysis performed on the H6 model were not as rigorous as for the T4 model, so they will not be included in this report, but since the model now exists, performing analysis is very easy for the group. A BDSIM visualization of H6 can be seen in figure 11.

Next steps in the H6 model analysis would include generating more data with different beam settings, and comparing the beam parameters of the output between the new BDSIM model and the old MAD-X model to evaluate the accuracy of the BDSIM model.

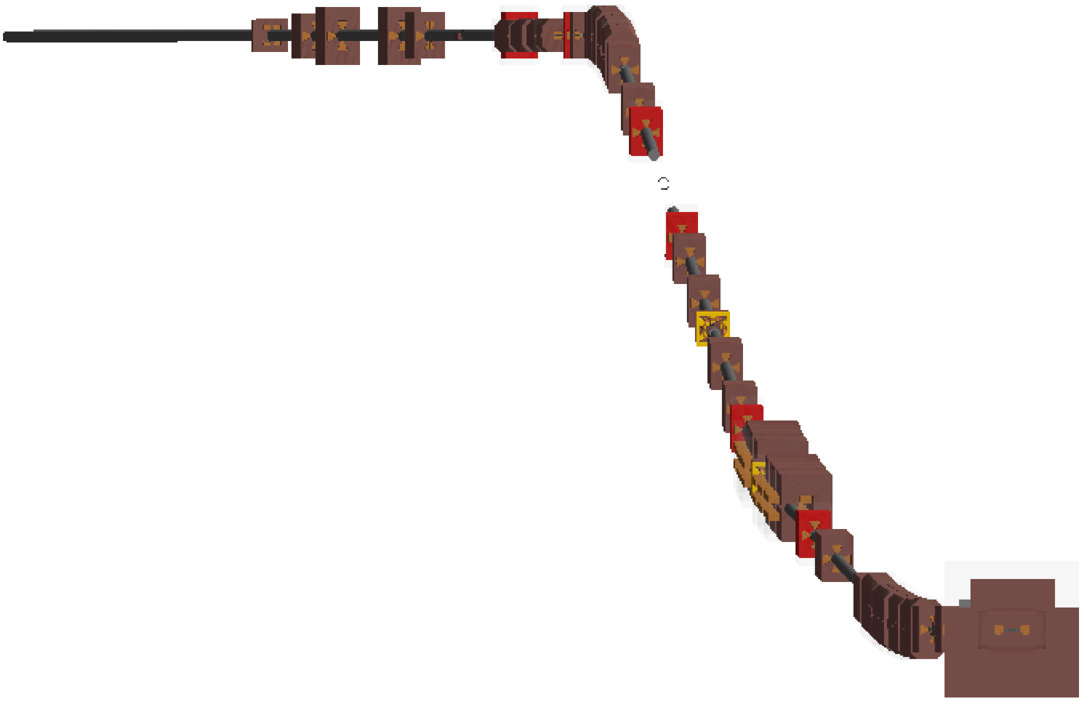

Figure 11: The H6 BDSIM model visualized. The direction of the beam is away from the viewpoint.

3.5 H8 beamline

The H8 beamline BDSIM model was also made from the MAD-X counterpart, and although a few simulations were performed on the model, no analysis was done. Also, proper alignment of the model with respect to the T4 model still needs to be done to get the most meaningful results from the analysis. Similar to the H6 beamline model, an interesting thing to investigate would be to compare the beam paramenters of the BDSIM and MAD-X models. A BDSIM visualization of the H8 model can be seen in figure 12.

Figure 12: The H8 BDSIM model visualized. The direction of the beam is away from the viewpoint.

4 Conclusions and outlook

The main part of summer project at BE-EA-LE was to construct BDSIM models for the T4 wobbling station, H6 beamline, and H8 beamline. The models required the construction of 3D models for the QTS magnet and the four TAX blocks at the end of the T4 wobbling station. Under this project, most of the simulations and analysis was done for the T4 model, although simulations are now easy to perform on H6 and H8 as well, since the models now exist.

The models produced allow for precise simulations of the T4 wobbling station, the H6 beamline, and with minimal additional work, the H8 beamline as well. The simulations performed for the T4 wobbling model show that the model works very well and is able to be used as a reliable beam input for the H6 and H8 models. The simulation models for the North Area beamlines are crucial for providing high-quality particle beams for the numerous beam users, and for ensuring the safety, reliability, and preciseness of the facility.

An interesting next step for the T4, H6, and H8 models would be to compare the beam parameter output of the BDSIM models with the corresponding MAD-X models to evaluate the preciseness of the new BDSIM models. In the T4 wobbling model, an additional thing to analyze would be to investigate the origin of the extra particles seen in figure 9 to see where the potential scattering happens.

References

[1] Dipanwita Banerjee et al. 'The North Experimental Area at the Cern Super Proton Synchrotron'. In: (2021). Dedicated to Giorgio Brianti on the 50th anniversary of his founding the SPS Experimental Areas Group of CERN-Lab II and hence initiating the present Enterprise. URL: https://cds.cern.ch/record/2774716.

[2] CERN Engineering Department. *XTAX Description*. URL: https://sba.web.cern.ch/sba/Documentations/Informations&Training/Beam_Equipments/target_attenuator/index.htm.

[3] *TAX block drawings*. URL: /cern.ch/dfs/Workspaces/s/SBA/GENERAL/Equipments/XTAX_T2_T4_T6/Blocks_T4.

[4] L. J. Nevay et al. 'BDSIM: An accelerator tracking code with particle–matter interactions'. In: *Computer Physics Communications* 252 (2020), p. 107200. ISSN: 0010-4655. DOI: https://doi.org/10.1016/j.cpc.2020.107200. URL: https://www.sciencedirect.com/science/article/pii/S0010465520300400.

[5] S. Agostinelli and other. 'Geant4—a simulation toolkit'. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 506.3 (2003), pp. 250–303. ISSN: 0168-9002. DOI: https://doi.org/10.1016/S0168-9002(03)01368-8. URL: https://www.sciencedirect.com/science/article/pii/S0168900203013688.

[6] Helmut Wiedemann. 'Periodic Focusing Systems'. In: *Particle Accelerator Physics: I Basic Principles and Linear Beam Dynamics II Nonlinear and Higher-Order Beam Dynamics*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2003, pp. 184–224. ISBN: 978-3-662-05034-7. DOI: 10.1007/978-3-662-05034-7_6. URL: https://doi.org/10.1007/978-3-662-05034-7_6.

[7] *QTL magnet drawing*. URL: https://edms.cern.ch/ui/file/719748/0/sps8033070007-v0_tif_cpdf.pdf.

[8] S. Boogert et al. 'Pyg4ometry: A Python library for the creation of Monte Carlo radiation transport physical geometries'. In: *Comput. Phys. Commun.* 272 (2022), p. 108228. DOI: 10.1016/j.cpc.2021.108228. arXiv: 2010.01109 [physics.comp-ph].