# BDSIM SIMULATION OF THE COMPLETE RADIONUCLIDE PRODUCTION BEAM LINE FROM BEAM SPLITTER TO TARGET STATION AT THE PSI CYCLOTRON FACILITY

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### *Abstract*

The beam line for radionuclide production at the PSI Cyclotron Facility starts with an electrostatic beam splitter, which peels protons of a few tens of microamperes from the main beam around two milliamperes. The peeled beam is guided to a target station for the production of a variety of radionuclides. Beam Delivery Simulation (BDSIM), a Geant4 based simulation tool, enables the simulation of not only beam transportation through optics elements like dipoles and quadrupoles, but also particle passage through components like collimators and degraders. Furthermore, BDSIM facilitates user-built element with its accompanying electromagnetic field, which is essential for the modelling of the first element of the beam line, the beam splitter. With a model, including all elements from the beam splitter to the target, BDSIM simulation delivers a better description of the beam along the complete line, for example, beam profile, beam transmission, energy spectrum, as well as power deposit, which is of importance not only for present operation, but also for further development.

## INTRODUCTION

The beam line for radionuclide production at the PSI Cyclotron Facility starts with an electrostatic beam splitter [1]. The splitter peels a beam of a few tens of microamperes from the main 72 MeV beam up to 2.4 mA intensity. The peeled beam gets a horizontal kick from the electrostatic field of the beam splitter, which creates a clearance more than 40 mm at the entrance of a septum magnet 3.395 m downstream. The peeled beam is then bent 17.5° away from the main beam, after passing the septum magnet, and is thereafter guided by the beam line to a target station for the production of a variety of radionuclides. The splitter is essential for the beam transportation. However, the splitter has so far been excluded from beam optics calculations, for example the envelope fit applying the program TRANSPORT [2]. The beam splitter is not a conventional beam transportation element. It is made of special materials, has a peculiar geometric form, and is accompanied with a 3D electrostatic field, while the beam transportation is correlated with all of these factors. It is therefore difficult to be defined by a conventional beam optics program, such as TRANSPORT or MADX.

Beam Delivery Simulation (BDSIM), a Geant4 based simulation tool, enables the simulation of not only beam transportation through optics elements like dipoles and quadrupoles, but also particle passage through components like collimators and degraders. Furthermore, BDSIM facilitates user-built elements in a wide range of geometrical forms and of practically any material. Importantly, an electromagnetic field can be attached to such a user-built element [3-5]. With a model, including all elements from the splitter to the target, BDSIM simulation delivers a better description of the beam along the complete line, for example, beam profiles at certain places, beam transmission through a degrader, power deposit on a component, as well as energy spectrum upon reaching the target. This is of importance not only for present operation, but also for further development.

## SIMULATION

### *Electrostatic Field Analysis*

The electrostatic field of the beam splitter is simulated with the program ANSYS. Figure 1 shows a quarter of the geometrical model of the splitter, as it is symmetrical about both horizontal and vertical middle planes. The septum consists of 117 tungsten strips 0.05 mm thick and 2 mm wide. The strips are tensioned onto a C-shaped structure with a 4-mm distance between the neighbouring strips, which gives a total length of 698 mm along the beam direction.

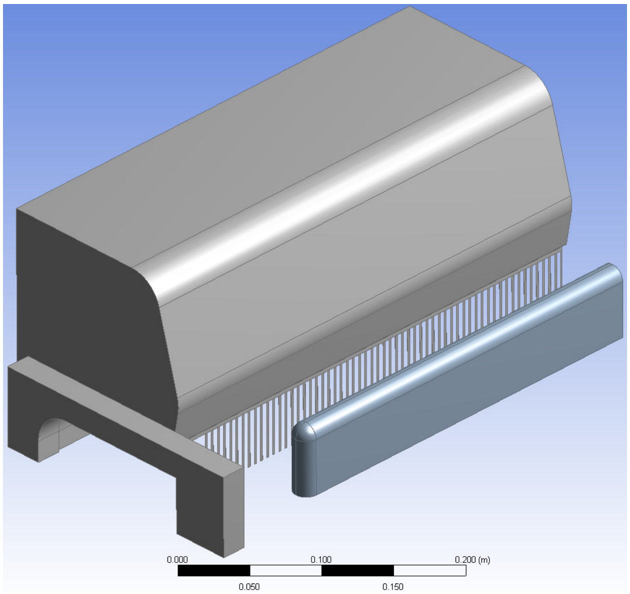

Figure 1: Geometrical model of beam splitter.

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The septum and the C-structure are grounded. The main beam passes through the field-free region inside the C-structure, a channel approximately 110 mm wide, 750 mm long, and 90 mm high. The cathode, 20 mm thick, 110 mm high, and 620 mm long, is placed 40 mm from the septum. A negative voltage of -105 kV is applied to the cathode. The peeled beam passes through the channel between the septum and the cathode and gets a kick towards the cathode. The cathode and the C-structure are protected by copper collimators. The electrostatic field analysis produces a 3D field map for BDSIM simulation. Figure 2 shows the electrostatic field on the horizontal middle plane. The field map is characterized with an approximately uniform field between the tungsten strips and the cathode, a fringe field at the entrance, and field fluctuation near the strips.

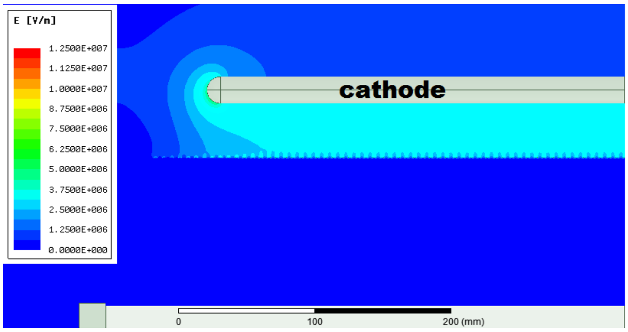

Figure 2: Electrostatic field on the horizontal middle plane.

### *Beam Line*

Figure 3 shows the complete beam line from the beam splitter (left side) to the target (right side) for the BDSIM simulation. The specification for a dipole (in blue) or a quadrupole (in red) is similar to that of the program MADX. If necessary, yoke and coil may also be added. The collimator (in green) or the beam pipe is described by its aperture, length, and material.

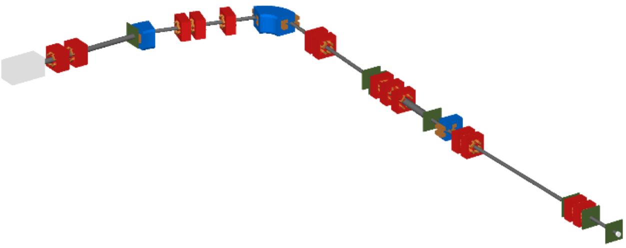

Figure 3: Complete beam line for BDSIM simulation.

For a special element like the beam splitter or the target assembly, the geometrical form and the material composition are specified with the Geometry Description Markup Language (GDML) [6]. For the target assembly, the shape and the material for each layer, e.g., Nb degrader or cooling water, are specified by a GDML file. The beam splitter is defined by the GDML file and the corresponding electrostatic field map. The beam line is then built up with each element lined in sequence.

### *BDSIM Simulation*

The protons extracted from the Injector II cyclotron have energies around 72 MeV with a momentum spread of 0.1%. The beam is made wide and divergent in both directions when hitting the septum. The multiple Coulomb scattering inside the tungsten strips is the most interesting process. Nevertheless, a wide range of physics processes, including electromagnetic, hadronic and radioactive decay, are activated for the BDSIM simulation.

The septum is set to x=0, while the beam direction is parallel to the z-direction. The simulation starts at the entrance of the beam splitter. In consequence, the beam centroid has to be shifted to a negative position, $x_0$. The beam from the Injector II cyclotron is typically 1.8 mA in recent years, while the peeled beam is normally set to 50 µA. If the standard deviation of proton distribution along the x-axis is $\sigma_x$, $x_0$ is approximately $-1.9\sigma_x$.

BDSIM can generate a specified number of protons with ($x$, $p_x$, $y$, $p_y$, $t$, $E$) from a 6D sigma matrix with additional shifts for any components. The sigma matrix can be defined in the form of sigma$11$=64·mm·mm, sigma$12$=6·mm·mrad, and sigma$22$=0.64·mrad·mrad. Here sigm$ii$ is the square of the standard deviation of the $i^{th}$ component, whereas sigma$ij$ represents the correlation between $i^{th}$ and $j^{th}$ components. The elements of the sigma matrix may be manually optimized so that the simulated beam size fits better with the measured one.

Protons can also be provided by an input file which specifies ($x$, $p_x$, $y$, $p_y$, $t$, $E$) for each proton. In this way, protons passing through the field-free region may be excluded from the simulation to save CPU time. Only protons hitting the septum and/or passing through the channel between the septum and the cathode will be tracked. As the peeled beam is typically 50 µA, while the main beam is typically around 1.8 mA, the simulation is, thus, more efficient.

## RESULTS

Initially, two million protons are generated at the entrance of the vacuum chamber of the beam splitter, and then tracked along the beam line. Figure 4 (top, bottom) shows an $x$-$p_x$ plot and a $y$-$p_y$ plot, respectively, for all protons at the exit of the vacuum chamber, which is 0.206 m downstream from the last tungsten strip. The peeled beam gets a horizontal kick around 13.9 mrad. The peeled beam is no longer in an elliptical shape on the $x$-$p_x$ plot. Most protons in the peeled beam are from the tip of the original $x$-$p_x$ ellipse. In contrast, the elliptical shape on $y$-$p_y$ phase space is almost undistorted.

Figure 5 (top) shows an x-y plot in front of the collimator of the septum magnet, which is 3.395 m downstream from the last tungsten strip. The beam is focused in the x-direction. A clearance around 45 mm is created, which is enough for the coil of the septum magnet. There are approximately 56000 protons in the peeled beam and 1.927 million protons in the main beam, respectively. In comparison, Fig. 5 (bottom) also shows an x-y plot, but only by tracking protons hitting the tungsten strips and/or passing through the channel between the septum and the cathode. Here, only

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-WEB04

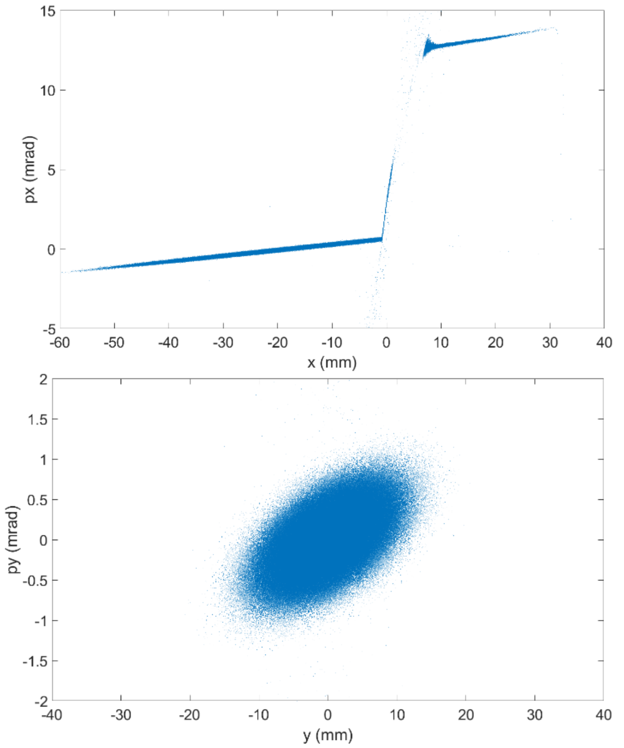

Figure 4 top: x-$p_x$ plot, bottom: y-$p_y$ plot at the exit of the vacuum chamber for the beam splitter.

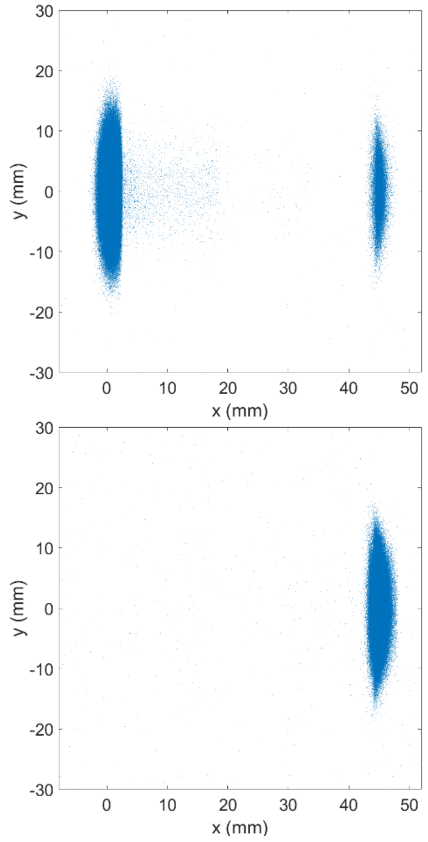

Figure 5: x-y plot for protons at the entrance collimator of the septum magnet. Top: all protons sampled from a 6D sigma matrix. Bottom: only protons hitting the tungsten strips and/or passing the channel between the strips and the cathode are tracked.

1.227 million protons are started. However, 1.113 million protons will pass through the collimator of the septum magnet. The simulation is, thus, far more efficient.

Figure 6 (top, bottom) shows the simulated horizontal and vertical beam profiles along with the measured ones at the location of the first and the last pairs of beam profile monitors, which is 6.771 m and 23.785 m downstream from the last tungsten strip, respectively. The horizontal profile is no longer symmetrical about its peak position and shows a longer tail on the left side.

Figure 7 shows a contour plot of the power deposited on-the vacuum window shortly before the target. The colour-bar indicates the power deposited in a 0.5×0.5 mm$^2$ area. The total power deposited in the 0.6 mm thick aluminium layer is around 63.28 W, while the beam power of 50 μA beam is 3.6 kW. Figure 8 shows the energy spectrum for the protons upon reaching the target after passing through cooling water and Nb degraders. The mean energy and the standard deviation are 16.35 MeV and 2.00 MeV, respectively, which is in agreement with an SRIM-2013 calculation [7].

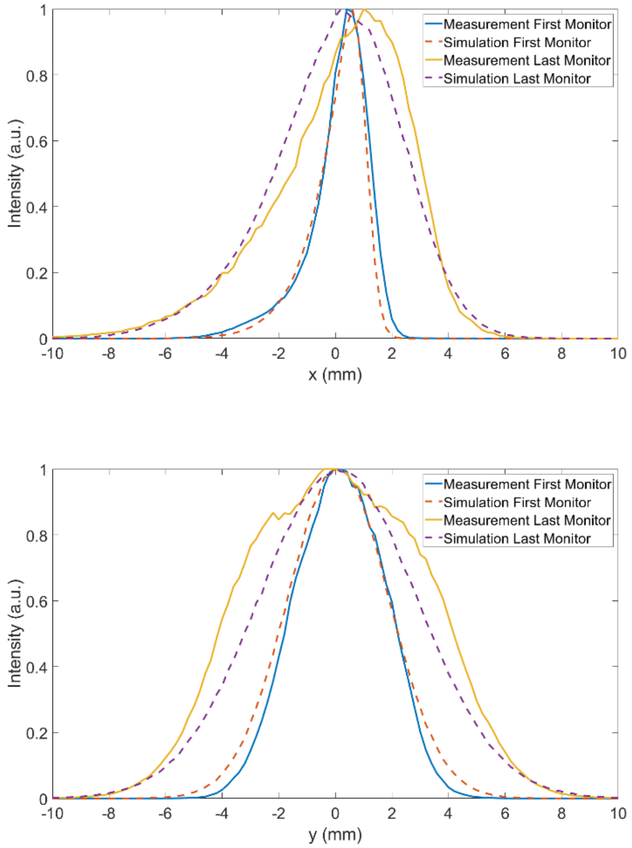

Figure 6: Measured and simulated beam profiles at the positions of the first and last pairs of beam profile monitors. Top: horizontal. Bottom: vertical.

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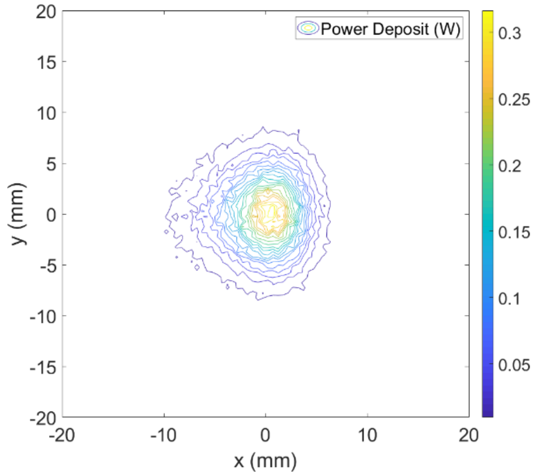

Figure 7: Power deposited on 0.6 mm thick aluminium vacuum window.

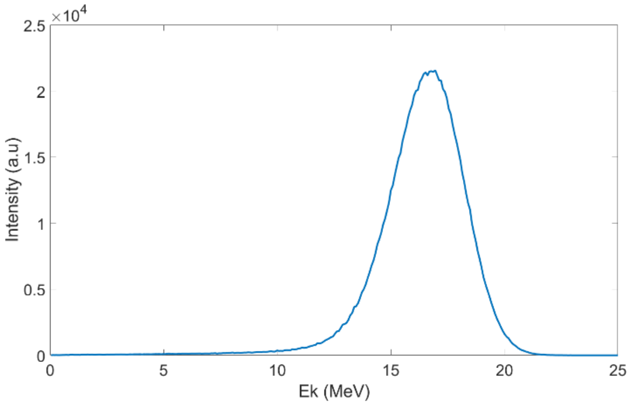

Figure 8: Energy spectrum upon reaching the target.

## DISCUSSION

BDSIM simulation covers the complete beam line from the splitter to the target. The simulation predicts beam profiles at positions where beam profiles may also be measured. The beam size fits well with each other, especially in the vertical direction. The simulation also correctly predicts one-sided tails for horizontal profiles. Nevertheless, the simulated profiles deviate somewhat from the measured ones. The deviation arises from the following factors.

Firstly, it is a simplification to generate protons from a 6D sigma matrix. Although the beam profiles measured along the main beam line could be approximated with Gaussian peaks, many profiles differ significantly from Gaussian distribution. This indicates that it is rather an approximation to generate protons from a 6D sigma matrix for BDSIM simulation.

Secondly, for the simulation in horizontal direction the protons are not only scattered upon hitting the tungsten strips, but also kicked by the electrostatic field. The field is not uniform, but fluctuated, especially in the region near the strips. The strip has a special shape with extensions of 0.05 mm, 2 mm, and 90 mm in horizontal, longitudinal and vertical direction, respectively. However, the electrostatic analysis has to cover a volume with extensions of 566 mm, 1110 mm, and 360 mm in horizontal, longitudinal and vertical direction, respectively. The extremely thin strips make meshing difficult. The total number of elements reaches the computational limit, while the meshing around the thin edge is still not sufficiently refined. In consequence, the field near the thin edges is likely not as accurate as for other regions. Even if the field analysis could be significantly improved, it would still be difficult to create a field map to keep all details near the strips, especially near the thin edges. The field map created for present BDSIM simulation has steps of 0.05 mm, 2 mm and 5mm in horizontal, longitudinal, and vertical direction, respectively. The map is already large in size, but the field is still not accurate enough, for the region near the strips, in particular. Therefore, the proton passing nearby the strips is likely getting a different kick to an actual one.

Thirdly, several quadrupoles are specially constructed. For example, two quadrupoles directly after the beam splitter have a relatively larger aperture, specifically, an aperture 150 mm in diameter and 423 mm long. The fringe field effect can, thus, be no longer ignored, but has not yet been included in BDSIM simulation.

In summary, the improvement may come from all these three fronts, a better specification of the initial beam, an improved electrostatic field analysis and an optimized field map, and a better description of the quadrupoles with large apertures.

## CONCLUSION

A model of the complete radionuclide production beam line is established for BDSIM simulation. The simulated beam profiles are comparable with the measured ones. The simulation also delivers power deposit on components of interest such as vacuum window and degrader. Energy spectrum of protons upon reaching the target may also be derived from the simulation. BDSIM simulation is, therefore, of importance not only for present operation but also for further development.

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