Design of the 590 MeV proton beamline for the proposed TATTOOS isotope production target at PSI

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Abstract. IMPACT (Isotope and Muon Production with Advanced Cyclotron and Target Technologies) is a proposed initiative envisaged for the high-intensity proton accelerator facility (HIPA) at the Paul Scherrer Institute (PSI). As part of IMPACT, a radioisotope target station, TATTOOS (Targeted Alpha Tumour Therapy and Other Oncological Solutions) will allow the production of terbium radionuclides for therapeutic and diagnostic purposes. The proposed TATTOOS beamline and target will be located near the UCN (Ultra Cold Neutron source) target area, branching off from the main UCN beamline. In particular, the beamline is intended to operate at a beam intensity of 100 μA, requiring a continuous splitting of the main beam via an electrostatic splitter. Realistic beam loss simulations to verify safe operation have been performed and optimised using Beam Delivery Simulation (BDSIM), a Geant4 based tool enabling the simulation of beam transportation through magnets and particle passage through the accelerator. In this study, beam profiles, beam transmission and power deposits are generated and studied.

1. Introduction

The High Intensity Proton Accelerator (HIPA) at the Paul Scherrer Institute (PSI) is at the forefront of the high intensity frontier of particle accelerators delivering a 590 MeV continuous wave proton beam with currents of up to 2.4 mA (1.4 MW beam power) [1].

IMPACT (Isotope and Muon Production using Advanced Cyclotron and Target technologies) is a proposed initiative envisaged for HIPA [2]. As part of IMPACT, a radioisotope target station, TATTOOS (Targeted Alpha Tumour Therapy and Other Oncological Solutions) will allow the production of unprecedented quantities of terbium radionuclides for therapeutic and diagnostic purposes. The TATTOOS beamline is intended to operate at a beam intensity of 100 μA (60 kW beam power), requiring a continuous splitting of the high-powered beam via an electrostatic splitter [3].

A realistic model of the complete TATTOOS beamline from splitter to target was established for the first time in Beam Delivery Simulation (BDSIM) [4], a Geant4 [5] based tool enabling simulation of beam transportation through magnets and particle tracking in electromagnetic fields. BDSIM allows electromagnetic fields to be attached to user-built elements such as the splitter.

The splitter has to withstand significant power deposition and the beam losses due to scattering are a major aspect of the concept that must be evaluated. Indeed, in both the design and operational phases of high intensity accelerators it is critical to minimise beam losses to avoid damage and activation of components, while at the same time maintaining high transmission. In this paper, beam profiles, beam transmission to the target and power deposits are simulated and studied.

2. Proton beamline

2.1. Overview of the HIPA facility

An overview of the HIPA facility with the TATTOOS installation is illustrated in figure 1 [2].

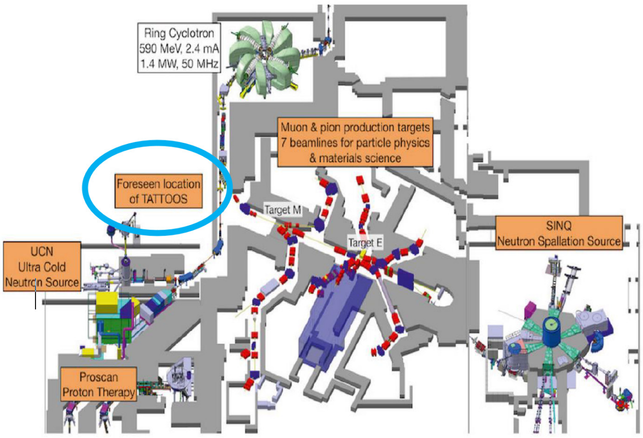

Figure 1. PSI's proton accelerator facility HIPA and the proposed TATTOOS installation circled in blue.

The proton beam is extracted from the Ring Cyclotron and transported to two target stations, Target M (TgM) and Target E (TgE) where secondary particles are produced for user experiments.

The proton beam also feeds two spallation sources, Swiss Spallation Neutron Source (SINQ) [6] and Ultra Cold Neutron source (UCN) [7], the latter running concurrently to the targets. A fast kicker magnet diverts the full intensity beam towards UCN via macro-pulsed kicks. Finally, the splitter located downstream from the kicker magnet can peel off a small portion of the main beam and send it to the UCN target. The elements of the TATTOOS beamline are described in detail in the following section.

2.2. TATTOOS beamline description

The simplest way of including the proposed TATTOOS beamline within the present framework is to split off part of the proton beam needed for TATTOOS by means of the splitter, use the existing magnetic septum magnet (ABS) to divert the peeled beam to the UCN beamline and finally steer it out of UCN and towards TATTOOS via a new bending magnet, specifically ramped up during TATTOOS operation.

In order to peel off such a high-power beam, the splitter possesses a distinct geometry (figure 2) consisting of 179 electrically grounded tungsten alloy strips with each strip tensioned by a pair of springs (all the strips have the same dimension and are 50 µm thick and 3 mm wide).

In total, the splitter amounts to a length of 1107 mm. Furthermore, the includes two cathodes, both at a negative voltage of -172 kV creating two electric fields on every side of the strips. The protons are thus pulled away from the strips at the end of the splitter for each beam [8]. A detailed electric field map has been obtained with ANSYS. Previous simulation studies [2] have demonstrated the viability of the splitter. In particular, the splitter can withstand the power deposition, with around 20 W being deposited on the first strip.

Figure 2. Splitter geometry implemented in BDSIM.

The proposed "alternating beam operation" consists in running TATTOOS between two UCN pulses (one UCN pulse lasts 8 s and the time between two pulses is 300 s). A dipole magnet, ABT (located downstream of the ABS), could be used to divert the beam from the UCN line into the new proposed TATTOOS beamline.

The combined effect of ABS and ABT would be a 13-degree bend. Furthermore, an additional dipole magnet, ADA will bend the beam a further 32 degrees for a total of 45 degrees towards the TATTOOS beamline. To make place for ADA, the existing QBB1 and QBB2 quadrupoles in the UCN beamline will be moved downstream by a few metres without having a detrimental effect on the UCN operation. Figure 3 illustrates the complete simulated BDSIM model from the beam splitter (left) to the target (right).

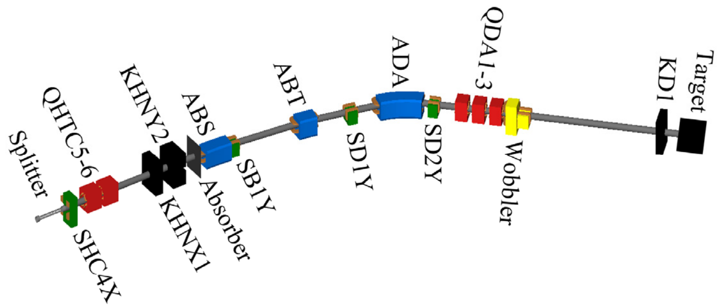

Figure 3. Complete TATTOOS beamline.

Several other components are required for the TATTOOS beamline. A quadrupole triplet (QDA1-3) will be used to shape the beam on target. A so-called "Wobbler" is used to flatten the beam footprint and achieve uniform target temperature. The Wobbler consists of two fast dipole magnets driven by AC current with a frequency of around 30 Hz [9].

Three dipole steering magnets (SB1Y, SD1Y and SD2Y) will be used to steer the beam in the vertical plane while steering in the horizontal plane is performed by the bending magnets.

In BDSIM, a fictious element called "Absorber" [10] was used to artificially remove the protons going into the SINQ line before the ABS septum, leaving only the TATTOOS protons.

A collimation system is also foreseen for TATTOOS. Existing collimators KHNX1 and KHNY2 are represented as jaw collimators in BDSIM, acting in the transverse x-y plane and cutting the beam in these two directions respectively. A last collimator, KD1 is placed at the end of the beamline to protect the target.

A comprehensive overview of all the elements in the TATTOOS beamline is given in ref. [2].

3. Simulations

3.1. Beamline optics validation

During the design of a beamline, it is of crucial importance to benchmark simulations against standard calculations or other dedicated simulation tools. The beamline lattice was designed in TRANSPORT [11] and the beam optics from BDSIM was benchmarked with MAD-X [12]. Proton tracking started 1.0054 m upstream of the upstream-end of the ABS for both codes and excludes the splitter since its implementation in conventional beam optics program such as MAD-X is complex. The TATTOOS line from the starting point to the target measures 21.479 m. Figure 4 illustrates the comparison of the beta-function between BDSIM and MAD-X. An excellent agreement is found between the two codes.

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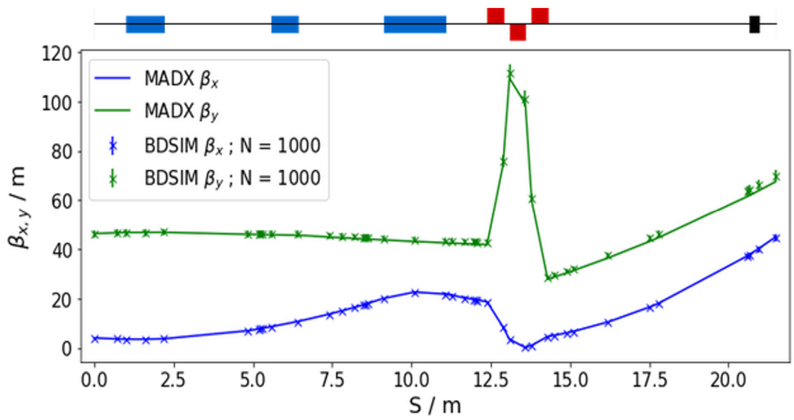

Figure 4. Benchmarking between BDSIM and MAD-X – beta-function validation.

3.2. Input file and horizontal beam profile

The initial beam is considered a six-dimensional Gaussian distribution representing a proton bunch in phase space. Protons are first tracked from splitter to target and an input file is then used to record the phase space coordinates after the splitter (at QHTC6) for each proton. By using the input file, CPU time is saved as the splitter field map does not have to be loaded for each simulation run. At the same time the properties of the split beam are preserved in the analysis. The horizontal beam profile is simulated with one million primary protons at QHTC6 as shown in figure 5.

A wide range of physics processes, including electromagnetic, hadronic and radioactive decay, are activated for the BDSIM simulation using the physics list physicsList=em ftfp_bert decay muon hadronic_elastic em_extra [10].

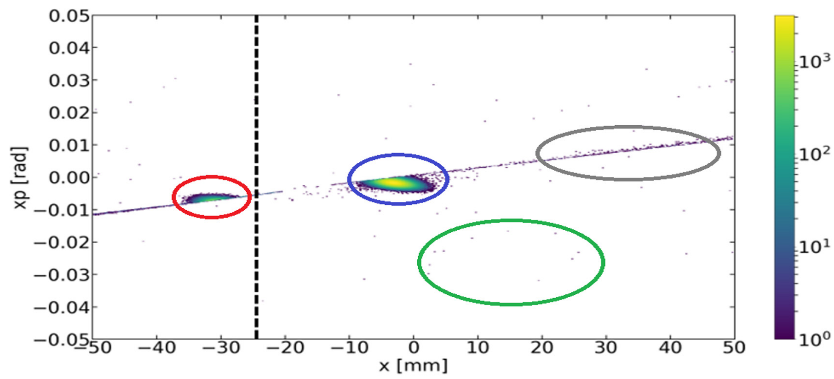

Figure 5. Horizontal phase space at QHTC6 approximately 1 m from the splitter.

From figure 5, the split and main beams can be clearly distinguished (red and blue circles respectively). Assuming a 2 mA beam, 100 µA is split. Off-momentum protons resulting from inelastic scattering with the splitter strips may be visible (green circle). Finally, a line of scattered protons due to the non-uniformity of the electric field acting on the strips may be noticed (grey circle).

3.3. Power deposition and transmission studies

The initial number of protons for the tracking simulations is taken from the split beam distribution before the collimators. From figure 5, only the protons with x < -25 mm (dashed line) are selected. These protons are then tracked along the beamline to the TATTOOS target. For transmission studies only the primary protons from this split beam are tracked, whereas for the power deposition studies, the entire beam (main and split) is tracked including the secondary particles.

In order to determine the collimator requirements for the TATTOOS beamline, the influence of the two collimators KHNX1 and KHNY2 is studied. The aim is to infer the aperture sizes suitable for minimising the energy losses. Parametric studies are performed whereby the aperture sizes of each collimator in x and y are varied. Several aperture settings are considered and compared to the case where there are no collimators. Figure 6 shows the power deposition from splitter to target for each KHNX1 aperture (KHNY2 is kept fixed at 0.080 m).

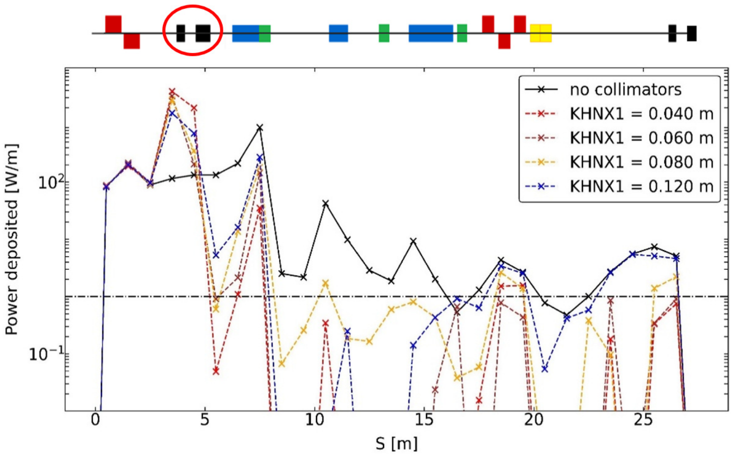

Figure 6. Power deposition from splitter to target.

From figure 6, the power deposited is highest at the collimators (red circle) but after the collimators, the power deposited is always lower when the collimators are present compared to when there are none. In general, the power deposited when the collimators are present is less than 1 W/m (dashed line in figure 6) which is a reference value for acceptable losses in high energy hadron accelerators [13].

Figure 7 illustrates the total power deposited after KHNY2 as a function of KHNY2 aperture (left) as well as transmission to the target (right).

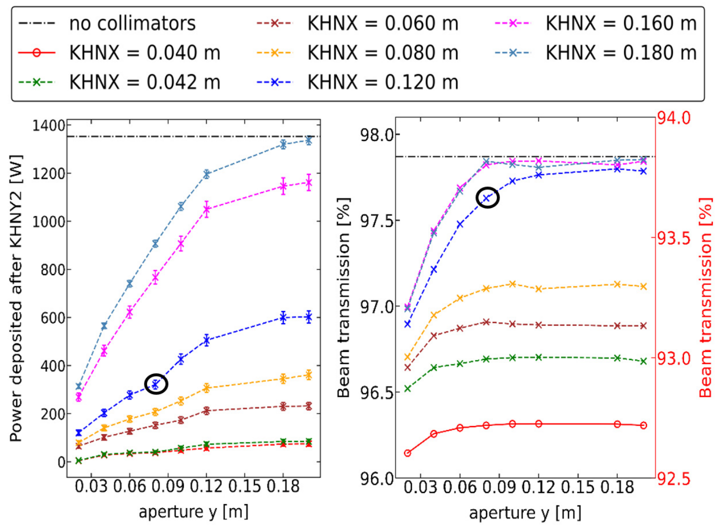

Figure 7. Power deposited and transmission to target as a function of KHNY2 aperture size for several KHNX1 aperture sizes.

As expected, the losses and transmission increase as the aperture size of the collimators is increased. The larger the aperture size, the more one approximates the case without collimators. Furthermore, as the KHNX1 aperture size is decreased to 0.040 m, the transmission is decreased by approximately 4%. This is because the edges of the collimator are cutting the core of the split beam, reducing the protons arriving at the target. Indeed, for a small aperture size, the beam is more sensitive to changes in position. An optimal collimator aperture could then be KHNX1 = 0.120 m, KHNY2 = 0.080 m (circled in figure 7) as the transmission here is high and the losses much lower than the case where there are no collimators.

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4. Conclusion

In this paper, the TATTOOS lattice design was presented including the first realistic simulations of the beamline using BDSIM. With the current optimised collimator system, the simulation results show that the TATTOOS beamline may safely operate to produce radionuclides using a high-power beam that is split by a unique beam splitter without significant losses and with a high transmission. Furthermore, the splitter can withstand the power deposition and can hence be used as a viable component for TATTOOS. These simulation results will serve as model predictions for future TATTOOS beamline measurements.

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