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PROTON BEAMLINE SIMULATIONS FOR THE HIGH INTENSITY MUON BEAMLINE AT PSI

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Abstract

The High Intensity Proton Accelerator (HIPA) cyclotron at the Paul Scherrer Institut (PSI) delivers 590 MeV CW proton beam with a maximum power of 1.42 MW. After extraction, the beam is transferred in a 120 m long channel towards two target stations (TgM and TgE) before depositing its remaining power at the spallation target SINQ for neutron production. As part of the High Intensity Muon Beamline (HIMB) feasibility study, which belongs to the IMPACT (Isotope and Muon Production using Advanced Cyclotron and Target technologies) initiative, the first of these targets will be replaced with a thicker one and its geometry optimized thereby specifically boosting the emission of surface muons. In order to assess the impact of the changes on the proton beamline, BDSIM/GEANT4 simulations were performed with the realistic technical design of the target insert, the collimation system was redesigned and the power depositions were benchmarked with MCNP6. In this paper, we discuss the major changes and challenges for HIMB as well as the key considerations in redesigning the optics of the high power beam in the vicinity of the target stations.

INTRODUCTION

The High Intensity Proton Accelerator (HIPA) complex at PSI is in operation since 1974, with several major upgrades enabling a maximum beam power of 1.42 MW [1]. To keep HIPA at the forefront of intensity frontier research, the IMPACT project [2] was recently proposed by the Paul Scherrer Institut (PSI), the University of Zurich (UZH), and the University hospital of Zurich (USZ). The project aims to construct two new target stations and beamlines at PSI. One of these target stations, the focus of the present paper, aims to increase the rate of surface muons by two orders of magnitude ($\sim 10^{10}\mu^+/s$), hence the name High Intensity Muon Beams (HIMB).

To achieve the goals for HIMB, the 5 mm Target M (TgM) [3] will be replaced with a newly designed Target H (TgH) such that the effective thickness of the target is increased to 20 mm, and its geometry as well as the connected beamlines optimized to enable two orders of magnitude increase in the rate of transmitted surface muons ($\sim 10^{10}\mu^+/s$) [2, 4]. As a consequence, the larger divergence induced by the thicker TgH shall lead to increased primary beam losses. Thus, the present paper discusses the main changes and challenges of replacing TgM with the thicker TgH from the point of view of the primary proton beamline.

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DESIGN CONSIDERATIONS

Owing to the complicated nature of the problem, which requires particle tracking simulations in electromagnetic fields, as well as the accurate simulation of the interaction processes between the high power beam and the beamline components, benchmarking the optics is a crucial task. For this reason, the Beam Delivery Simulation (BDSIM) is chosen as the reference program for all calculations [5]: BDSIM combines particle accelerator tracking routines with the standard high energy physics code GEANT4 [6]. The optics shall be benchmarked against TRANSPORT [7], MAD-X [8] and ZGOUBI [9] while the interaction processes shall be benchmarked against MCNP6 [10]. The latter will be discussed in the present paper. However, the interested reader is referred to the IMPACT Conceptual Design Report for further details [2]. Furthermore, to establish the validity of the developed simulation tools, an experimental campaign was performed to benchmark the existing MW-class beamline with various measurements [11].

The purpose of the transport channels is to transport the high power beam with minimum losses towards each target and to produce optimum matching conditions suitable for both the primary and the secondary beamlines.

Upstream of TgH the optics shall not experience any important change with the beam maintaining the same properties. The only exception to this is the addition of one vertical steerer magnet and the replacement of the existing one as illustrated in Fig. 1. This is justified as follows: TgH is surrounded by two capture solenoids producing a non negligible fringing field in the transverse X-direction. Such field component, if uncorrected, will alter the beam trajectory in the vertical plane. For flexibility reasons, the worst case scenario is treated in which both solenoids have the same polarity so that their stray fields add-up at TgH. In order to limit and compensate for the impact of the capture solenoids' stray fields on the proton beam, we proceed as follows:

1. Placing mirror plates adjacently to the solenoid entrances (from the viewpoint of the target) allows to reduce the fringing field extent, i.e., the field integral seen by the primary beam, by 30%. A mirror plate thickness of 40 mm is chosen to achieve this as a trade-off between the space constraint in the target region and the effectiveness of the plates to reduce the stray fields while being cooled.

2. A full cancellation of the impact that the remaining fringing field will have on the primary proton beam trajectory after the target, is possible by means of two vertical steering magnets. These are placed upstream of

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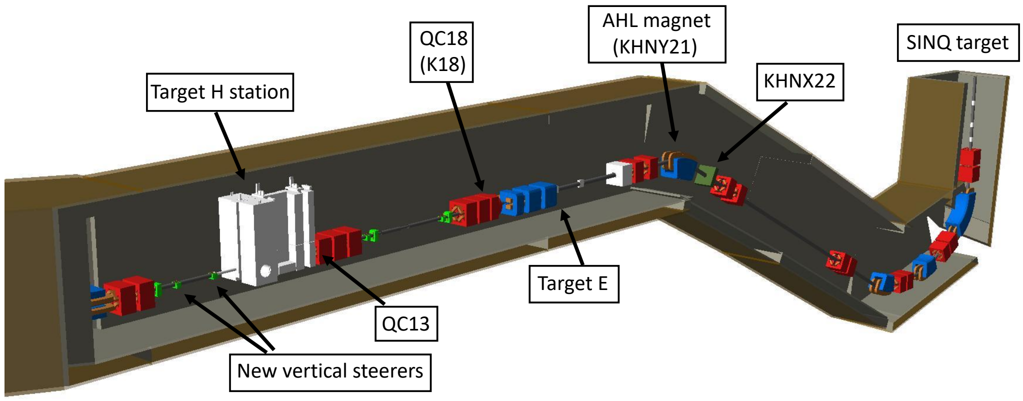

Figure 1: Optical layout of the SINQ beamline displaying the quadrupoles (red), bending magnets (blue), steerers (green) and TgH station (white). The collimator K18 is partially placed inside the QC18 quadrupole. The tunnel is implemented to guide the eye only.

TgH given the need to center the beam trajectory before cleaning its tails with the subsequent collimators.

Downstream of TgH, the losses will be substantially different and the divergence of the exiting beam will substantially increase. The collimation system, of the utmost importance for a high power beamline, shall thus be replaced with a newly designed one. The subsequent elements, starting at QC13 quadrupole (see Fig. 1), all remain at their original location. In addition, with the anticipated beam intensity upgrade of the cyclotron complex in the years to come, the new collimators shall withstand the power deposited by a 3 mA beam. The collimators, acting both as local shielding and as absorbers, should not be very sensitive to beam misalignment errors of sub-millimeter level in order not to trigger frequent interlocks of the machine. The outer width of the collimator (chosen to be 20 cm in diameter) is yet another important parameter in the optimization process. As a general rule of thumb, two third of the power deposition shall go into it and one third to the surrounding shielding. The next step in the optimization process is to devise an adequate scheme to ensure the largest beam transmission while reducing the beam halo that might deposit its energy in the critical parts of the beamline which are not sufficiently protected against high radiation levels. To achieve this, two steps are necessary:

1. First, the optics between TgH and TgE is adjusted by changing the gradients of all six quadrupoles in between, namely QC13 to QC18. The objective is to reduce the transverse beam sizes at the location of the limiting apertures, specifically QC13 and K18 collimator while achieving the matching conditions at TgH where the beam shall be focused to a waist with typical spot sizes $\sigma_x = \sigma_y = 1$ mm.

2. The second step is to perform parametric scans of the collimators' aperture in order to determine the region with the lowest power deposition on triplets 1 & 2 (located between the two target stations). Furthermore, the positioning of the collimators along with their outer widths are crucial parameters of the optimization process. Last but not least, due to the proximity of the beamline elements to TgH, it is important to perform the parametric studies of the beam deposited power with the shielding in place. With the envisaged HIPA upgrade from 2.2 mA to 3 mA nominal current [12], the actively-cooled collimators shall be designed to withstand the power depositions from a 3 mA beam.

Given the limited available space (2.9 m) to place the collimators, the diagnostic elements as well as the shielding between TgH and and QC13, the choice was to opt for three tightly packed collimators as illustrated in Fig. 2: the first one, denoted KHM0, acts as a shielding for the wide angle scattered particles from the target. The next collimators KHM1 and KHM2, placed together in the same vacuum

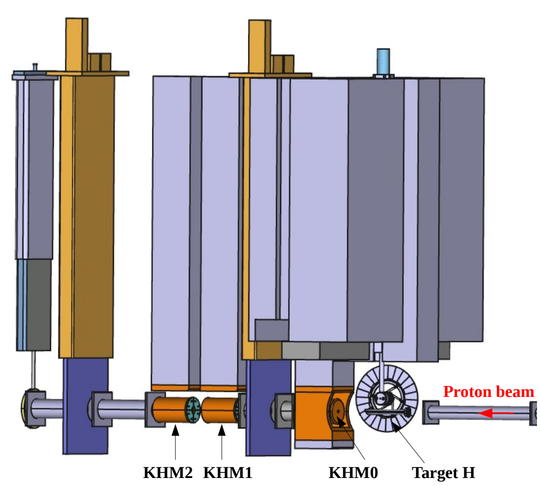

Figure 2: Layout of the TgH station with view of the beam components. TgH is rotating at 1 Hz. The collimators, made of copper, are displayed in orange, while the two profile monitors are in violet.

chamber, were optimized by having an elliptical shape that cuts a larger fraction of the beam in the horizontal plane than in the vertical one. This is justified by the fact that the next optical element in the beamline, QC13, is a defocusing quadrupole that will increase the divergence of the already divergent beam in the horizontal plane. The optimized shape, illustrated in Fig. 3, allows to reduce the losses on subsequent elements and achieve the highest possible transmission to target E which is around 93%. A comparison of the transverse beam envelopes obtained with the standard TgM and with the slanted TgH is finally shown in Fig. 4.

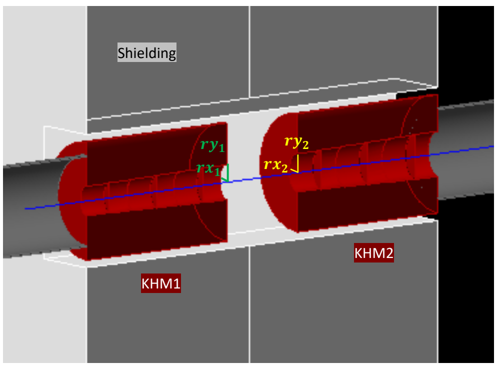

Figure 3: Cross section of the collimators 3D models with labels.

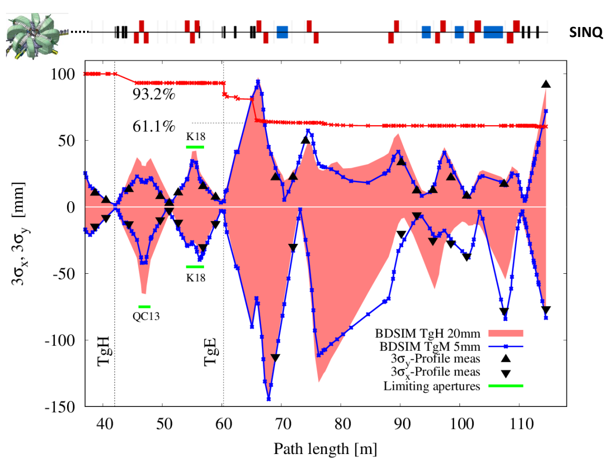

Figure 4: Comparison of the transverse beam envelopes obtained with the standard TgM and with the slanted TgH. The upper part displays the vertical plane while the lower one corresponds to the horizontal one. The beam transmission is displayed in red.

BENCHMARKING BDSIM/MCNP6 SIMULATIONS

Benchmarking the power deposition calculations in BDSIM and MCNP6 is crucial to validate the Monte Carlo simulations. To this end, both simulations shall be performed by relying on the same geometry, the same beam parameters and last but not least the same material composition. To facilitate the task, both codes start from the same Computer-Aided Design (CAD) model which is converted by means of appropriate tools: using the SuperMC software developed by the FDS team [13, 14], the geometry of the MCNP6 model is created. In BDSIM, the recently developed python library Pyg4ometry [15] allows the conversion of the CAD files to tesselated solids based on the Geometry Description Markup Language (GDML) [16]. Furthermore, a 2 mA pencil beam impinging on target is assumed for both cases to avoid uncertainties from beam generation methods. In summary, the power depositions are compared in Table 1 for the newly designed elements. Although the overall agreement is better than 1%, the local differences shall be explained by the difference in the physics models: In the MCNP6 simulation, the CEM 03.03 model [17] was used for the interactions of nucleons, photons and pions and the LAQGSM model [18] for the interactions of ions at all energies. In BDSIM, one resorts to the recommended modular physics lists in which the Bertini cascade model is used to describe the hadron-nucleus interactions of interest [19].

Table 1: Power Deposition

Beamline Element	BDSIM (kW)	MCNP6 (kW)
Target H	17.9	18.7
KHM0	22.9	20.3
KHM1	7.8	8.8
KHM2	0.9	1.3
Total	49.5	49.1

Last but not least, the present beamline optics is benchmarked with the profile measurements as shown in Fig. 4 to accurately simulate the beam conditions. The latter play a crucial role to explain the distributed losses of the MW-class beam [11].

CONCLUSION AND OUTLOOK

For the newly designed TgH station at PSI, a collimation system aiming to protect the beamline from the losses induced by the 1.4 MW beam was designed and benchmarked in BDSIM and MCNP6. The adjusted optics demonstrated that the fraction of the beam reaching TgE shall be 5% lower than with the existing TgM. The subsequent losses on TgE and its set of collimators will thus be lower [2]. Nevertheless, due to the increased energy spread of the beam, a careful assessment of the losses after the AHL magnet is in order. In particular, due to the intensity-dependent effects, the beam properties originating from the cyclotron shall change with the current. This will be investigated in detail in the near future, including for the envisaged uprade of HIPA to 3 mA nominal beam current.

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