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HIGH-FIDELITY MODELING AND TRANSMISSION OPTIMIZATION FOR THE BEAMLINE OF HUST-PTF *

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Abstract

A superconducting cyclotron-based proton therapy facility is under construction at Huazhong University of Science and Technology (HUST-PTF). In previous works, the vacuum chamber's shape and the tail effect of the energy spectrum are not considered when calculating the transmission efficiency of the beamline. This study proposes a high-fidelity modeling and optimization method for the HUST-PTF beamline based on Monte Carlo simulation using BDSIM. The modeling procedure of the beamline based on BDSIM is briefly introduced. Then verification of the optical parameters are performed on the gantry sections, and the transmission efficiency of the gantry is optimized by analyzing the unexpected beam loss. After optimization, the transmission efficiency at each energy setting point is calculated. The simulation results show that (1) the proposed optimization method improves the gantry's transmission efficiency from 92.4% to 95.6%; (2) the transmission efficiency calculated by high-fidelity modeling is more accurate than previous simulations because the beam-matter interaction and practical vacuum chamber geometry are considered.

INTRODUCTION

Huazhong University of Science and Technology is building a superconducting cyclotron-based proton therapy facility, and all magnet designs and installations have now been completed. Previous works have focused on the beamline's design [1], but evaluating the beamline's working state still using separated codes used in the design process may be unsuitable. The more realistic conditions should be considered. For beam tuning, it is of engineering significance to build a high-fidelity model to evaluate the operating state of the beamline and as a surrogate model.

The Refs. [2, 3] use beam delivery simulation software (BDSIM) to conduct seamless simulation on proton therapy systems for radiation protection. Their works consider the beam-matter interaction and practical vacuum chamber geometry. Inspired by their works, this study proposes a high-fidelity modeling and transmission optimization method with the HUST-PTF Beamline as a case study.

The remainder of this study is organized as follows: the model setup and the methodology are briefly introduced in Section II; the results are presented in Section III; and Section VI provides the study's conclusion.

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THE MODEL SETUP AND METHODOLOGY

The HUST-PTF beamline is built and validated using BDSIM, a Geant4-based Monte Carlo program that simulates the dynamic motion of beam transport considering the particle–matter interaction and the vacuum chamber geometry [4]. As shown in Fig. 1, the HUST-PTF beamline includes three sections: (i). The energy selection section (ESS) modulates the beam energy and quality. (ii). The periodic transport section transmits the particles to each coupling point efficiently. (iii). The gantry section is to achieve multi-angle treatment. In addition, the physics list "g4qbbc", which includes pure hadronic parts consisting of elastic, inelastic, and capture processes, is used to simulate the physical process during the treatment.

The primary idea behind optimizing transmission efficiency is to analyze the beam loss process and use the gained insights to guide the constraints of the Transport code [5]. This approach achieves the desired results without resorting to complex algorithms. In the next section, this study will present a detailed account of how this study optimized the transmission efficiency of the gantry in the HUST-PTF beamline using this method.

THE RESULTS

To illustrate the consistency of the high-fidelity model constructed by BDSIM with the present design, the optical parameters need to be verified. Because the optical design does not include the energy modulation process, the beamline is divided into three segments for optical parameters verification according to the collimators' position (line1: from the start to Col#2, line2: from Col#2 to the coupling point; Gantry: from coupling point to iso center).

The optical parameters of line1 and line2 based on BDSIM-model bear almost no difference from the previous optical design, and the transmission efficiency (line1: 100%, line2: 95.8%) satisfy the design requirements of ≥ 95%. However, the optical parameters of the gantry section, whose transmission efficiency is 92.4% (≤ 95%) and isn't capable of meeting expectations, exhibit some dissimilarities from the previous design, as illustrated in Fig. 2.

From Fig. 2, it can be seen that after the beam enters the first dipole, its x-direction envelope is too large, causing its peripheral particles to hit the beam pipe, thus leading to beam loss, which is the reason why the β_x calculated by BDSIM is small than that calculated by MAD-X codes [6].

Therefore, it is necessary to optimize the transmission efficiency of the gantry section. Based on the above analysis,

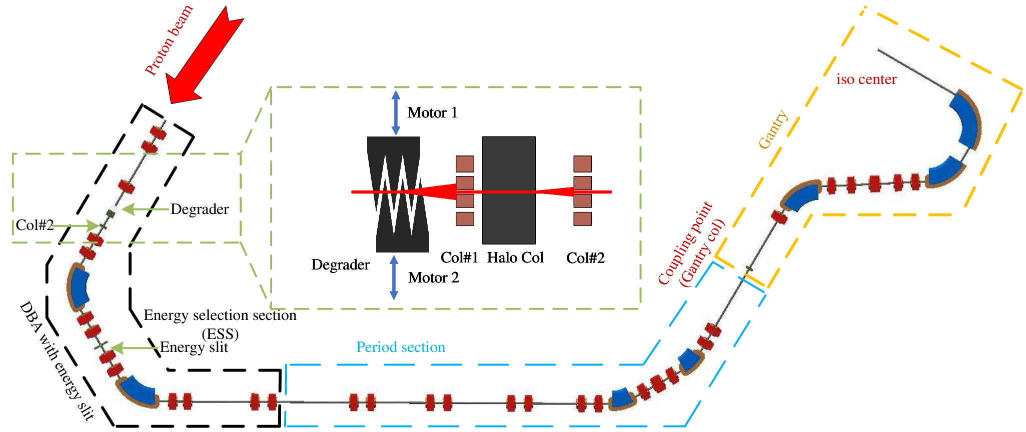


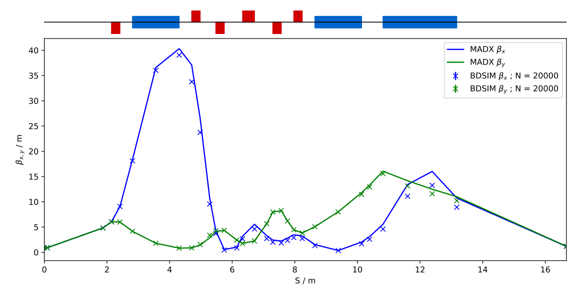
Figure 1: The overall layout of the HUST-PTF beamline based on BDSIM. The ESS is from the beginning to the double-bend achromatic (DBA) entrance. The Period section is from the entrance of DBA to the coupling point. The remaining part is the gantry section. In addition, there are names of typical elements in the figure, which is convenient for evaluating the beam quality after the beam passes through these elements.

Table 1: Transmission Efficiency Under Different Conditions

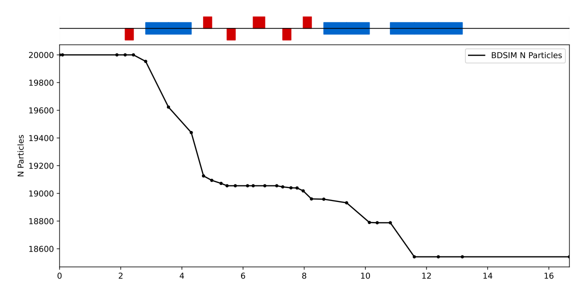
Type	Conditions	Transmission efficiency
Previous restrictions	=18mm	92.4%
Option 1	=15mm	94.2%
Option 2	=14.5mm	94.6%
Option 3	=14.42mm	95.6%
Option 4	=14.41mm	93.4%

a new set of magnets' parameters consisting of six normal quadrupole coefficients can be attained by adjusting envelope conditions, specifically within the x-direction, at the exit of the first magnet. This shall be achieved by employing Transport code matching while ensuring adherence to the established image optics conditions in the previous works [7]. The transmission efficiency under different conditions is shown in Table 1. As shown in Table 1, the highest transmission efficiency is obtained by option 3, which will be adopted to replace the previous magnets' parameters. The optical parameters under the optimized magnets' parameters are shown in Fig. 3. From Fig. 3, it can be concluded that compared with the result in Fig. 2a, the β_x calculated by BDSIM in Fig. 3a is closer to the result of MAD-X code, indicating that the collision at the first dipole has been mitigated after optimization.

After optimization, this study estimates the transmission efficiency of the HUST-PTF beamline under the new magnets' parameters based on the constructed high-fidelity model and the specific settings (lengths of graphite wedge at each energy point and the distance of energy slit at $\frac{\Delta P}{P} = 0.3\%(1\sigma)$), and compares the results with the previous works [8], as shown in Fig. 4. From Fig. 4, it can be concluded that the current results are consistent with the results of the previous work in the high-energy range, but the



(a) β_x and β_y



(b) beam transport loss process

Figure 2: Comparison results of optical parameters and beam transport loss process of the Gantry before optimization.

discrepancy becomes larger as the energy setting decreases. This is due to the fact that as the energy setting decreases, the tail effect of the energy spectrum in the energy modulation process becomes more severe, while the previous work assumes beam energy distribution after the degrader as a Gaussian distribution when using Turtle code [9] for calculating transmission efficiency. In addition, the effect of the vacuum chamber's shape on the beam transport is not considered.

To further verify the correctness of the above analysis, Table 2 lists the particle transmission efficiency at typical

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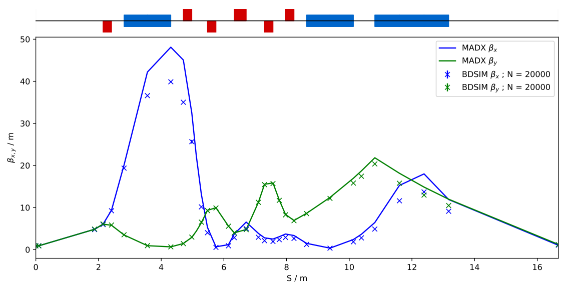
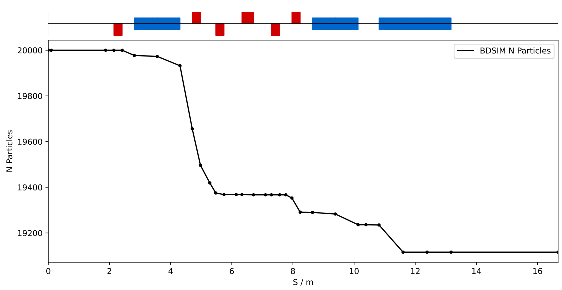
Table 2: Transmission Efficiency of Beam Transport Satisfying the Condition $\frac{\Delta P}{P} < 0.6\%$

	70 MeV		230 MeV	
Element	Transmission efficiency ($\frac{\Delta P}{P}$ <0.6%)	Transmission efficiency	Transmission efficiency ($\frac{\Delta P}{P} < 0.6\%$)	Transmission efficiency
Deg	8.2513%	66.4667%	82.5043%	94.2335%
Col#2	0.0546%	0.4571%	14.3113%	20.3937%
Energy slit	0.0481%	0.0495%	13.4451%	13.9387%
Coupling point	0.0472%	0.0478%	13.3852%	13.4515%
iso center	0.0446%	0.0456%	13.2052%	13.2715%



(a) β_x and β_y



(b) beam transport loss process

Figure 3: Comparison results of optical parameters and beam transport loss process of the Gantry after optimization.

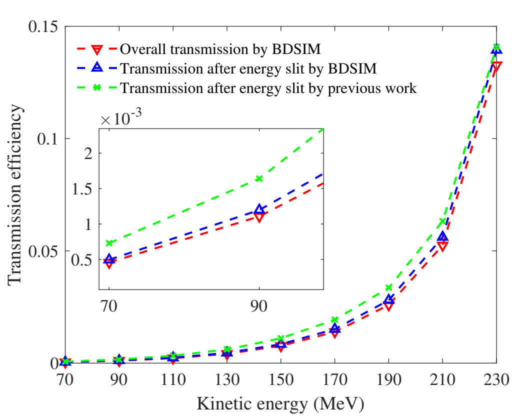


Figure 4: The transmission efficiency at each energy setting

elements under the condition ($\frac{\Delta P}{P} < 0.6\%\ 2\sigma$). From Table 2, it can be seen that: (i). The transmission efficiency (0.0546%) at 70 MeV that meets the condition after passing through Col#2 is already lower than that (0.0729%) previously calculated by Turtle code. (ii). With the premise that downstream beamline transmission efficiency is high (>95%), the beamline actually transports particles that meet the $\frac{\Delta P}{P} < 0.6\%$ after passing through Col#2.

THE CONCLUSION AND FUTURE WORK

In summary, this study proposes high-fidelity modeling and transmission optimization method with the HUST-PTF beamline as a case study. This study utilized a high-fidelity model, considering the vacuum chamber's shape and the tail effect of the energy spectrum, to achieve start-to-end simulation and calculate the transmission efficiency of the beamline at each energy setting. In addition, this study modifies the constraints of Transport code and improves transmission efficiency by analyzing the beam loss process, which is simple and efficient. Our next step is to verify the model's realism through experiments and use the built model data to get a surrogate model to accelerate calculations.

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