Optimal Design of Diffuser and Matching Lens in Proton Radiography

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Abstract—**In this paper, we study the optimal design of diffuser and matching magnetic lens in high-energy proton radiography. The constraints related to the limitation of overall length, maximum magnetic lens intensities, cross-sectional size of magnetic lens and the size of object are all addressed using the genetic algorithm. The parameters of the diffuser and the matching lens are obtained to be suitable for the proton beam of 20 GeV. The Monte Carlo code Geant4 is applied to verify the diffuser performance and to improve it.**

Keywords-proton radiography; multiple Coulomb scattering; diffuser; matching lens.

I. INTRODUCTION

Compared to X-ray, high-energy protons perform better as a radiographic probe for dense objects in hydrotest experiments because of their extremely penetrating power [1]. The three most important effects on the protons as they go through an object are absorption, Multiple Coulomb Scattering (MCS), and energy loss. The MCS effect will seriously blur the radiographic image of the object. To suppress this kind of blurring, a magnetic structure called Zumbro lens was developed by Mottershead and Zumbro [2].

The protons that are not scattered or absorbed in the object emerge from the object with a reduced energy spread due to collision with atomic electrons. The energy spread, together with chromatic aberration in the lens, causes image blurring. Chromatic aberrations in the magnetic lens can be minimized by making the lens system as short as possible and by using an illuminating beam with a special correlation between transverse position and angle. The protons must have an “angle-position correlation”, which means that the angle of the illuminating rays is a linear function of the distance from the axis, as if it comes from a (virtual) point source a distance upstream of the entry plane of the lens. Before entering the imaging lens that forms the radiographic images, the proton beam passes through a thin tantalum sheet, which spreads the beam so it can illuminate the entire test object. The beam passes through a set of quadrupole electromagnets that gives the protons the angle-position correlation. The matching lens may give the protons the necessary correlation [3].

To the best of our knowledge, there is no report on how to design both the diffuser and the matching lens. Some references [4-6] focus on optimal design of Zumbro lens (downstream of matching lens). These designs are mainly based on an analytic method with thin-lens approximation. With all constraints such as Fourier points and Field-of-View (FOV) [4], the allowed parameter sets can produce the inverting identity (-I) magnetic optics. Beam physics packages such as MARTLIE [5] and COSY [6] are employed to compute the chromatics for each parameter set. Regarding the design of the diffuser and the matching lens, several constraints such as the position-angle correlation required by Zumbro lens, FOV size and drifting length are limiting the searching of best solutions with less chromatic aberration. This kind of chromatic aberration is produced when the proton attenuates the diffuser. So, the design of both the diffuser and the matching lens is expected to be a multi-objective optimization with many constraints. Therefore, we employ genetic algorithm (GA) as the optimization method because it is recognized as the best globally well-adapted optimization algorithm [7]. The Monte Carlo code Geant4 is applied to verify the diffuser performance [8].

This paper is organized as follows. The principles of the diffuser and the matching lens are presented in Section II. In Section III, the numerical results are obtained with the GA. Finally, the conclusion is given in Section IV.

II. PRINCIPLES OF DIFFUSER AND MATCHING LENS

The designed matching lens should have two functions. The first function is to provide proton beam with the desired angle-position correlation at the object plane. The second function is to expand the beam size to fully illuminate the object. In addition, the design should consider the upstream diffuser. The diffuser works together with the matching lens. Once the lens is designed, the thickness of the diffuser is obtained. To get a lower chromatic aberration, a thinner diffuser should be used. However, if the diffuser is too thin, it may not provide the required position-angle correlation for the matching lens. Therefore, the diffuser thickness should also be taken into the matching lens optimization.

The transfer of a proton in matching lens of x plane has the form:

$$\begin{pmatrix} Ax_0 \\ wAx_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ w_0 x_0 + \varphi_{\text{diffuser}} \end{pmatrix} \tag{1}$$

Here, A is the amplification factor of matching lens; w is the required correlation at the object plane; w_0 is the correlation when the proton is at the entrance of the matching section;

φ_{diffusr} represents all deviations from the correlation line due to both MCS in the diffuser and non-zero emittance in the illuminating beam; M is the x plane transfer matrix of the matching lens. The value of w_0 is not only involved in the matching lens, but it also closely relates to the diffuser.

Compared to the distance from matching lens to the diffuser, the beam size is small. The proton beam is approximated as a point source. Therefore, w_0 equals to the reciprocal of the draft from the diffuser to the matching lens D_1. Then, w_0 is expected to have a positive correlation with the diffuser thickness:

$$w_0 = {}^{1}\!/_{D_1} \propto T_{\text{diffusr}} \tag{2}$$

To decrease the chromatic aberration caused by the diffuser, a thin diffuser should be used. However, it results in a large distance between the matching lens and the diffuser. Therefore, apart from the correlation and amplification, a reasonable value of w_0 should be carefully selected in the optimization of the matching lens.

If the φ_{diffusr} is close to zero, then (1) can be expressed as

$$\begin{cases} M_{11} + w_0 M_{12} = -A \\ M_{21} + w_0 M_{22} = -wA \end{cases} \tag{3}$$

The equation for y plane is similar to (3). If w is positive in the x plane, it is equal in magnitude and negative in the y plane. Equation (3) acts as the constraints in the optimization.

The design of the diffuser and matching lens is expected to be a multi-objective optimization. The traditional method is based on thin-lens approximation. It takes the size of field of view (FOV) as a posterior limitation on the parameters. However, this may not provide the best solution. The constraints should be taken as object functions to guarantee a reasonable result. The GA is recognized as the best globally well-adapted optimization algorithm and this is why we decided to use it in our approach.

III. Optimization for Proton Radiography

The basic structure of both the diffuser and the matching lens can be found in Figure 1 (trajectories are simulated by Geant4 code [8]). The matching lens consists of three quadrupoles combined with four drifts. The proton beam starts from the right side and it is scattered by a diffuser. Then, the beam with angular divergence drifts (with length of D_1) to the matching lens with position X_0 and direction vector $w_0{*}X_0$ in x-axis. When the proton transport to the end of matching lens has position $A{*}X_0$ and direction vector $A{*}w_0{*}X_0$ in x-axis, then the beam will cover the object.

The goal of the optimization is to obtain a higher amplification factor of the matching lens. The parameters to optimize are drifts: D_1, D_2, D_3, D_4, the magnetic lens thicknesses: T_1, T_2, T_3 , magnetic lens strength G_1, G_2, G_3 and diffuser thickness. The constraints are related to the limitations of overall length, maximum magnetic lens intensities, cross-sectional size of magnetic lens and the size of object. Because w_0 can be calculated by drift length D_1, the domain of w_0 is set to be from 0.1 to 0.13 to ensure an available drift length. The GA is employed to obtain a matching lens with larger amplification.

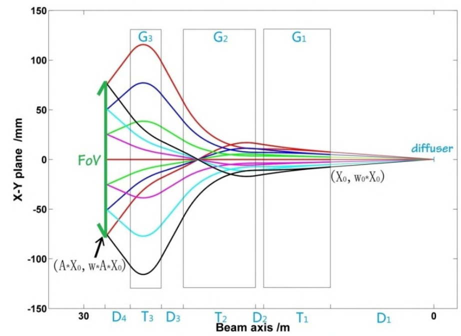

Figure 1. Simulated proton trajectories in matching lens.

All the constraints can be written as:

$$\begin{cases} \sum_{i=1}^{4} D_i + \sum_{j=1}^{3} T_i \le 27 \\ G_i \le 10,\, i = 1,2,3,4 \\ \left| X_{\text{pos}} \right| < \min(R_{\text{quadrupoles}}, R_{\text{drift\_tube}}) \\ R_{\text{FOV}} > R_{\text{object}} \end{cases} \tag{4}$$

in which the $R_{\text{quadrupoles}}$ and $R_{\text{drift\_tube}}$ are the inner radius of quadrupoles and drift tubes, X_{pos} is the proton position value on the designed trajectories. This constraint means the proton should not bombard the magnet. The R_{FOV} is a function of A and diffuser thickness.

The matching lens should provide the proton beam with the necessary correlation for Zumrbo lens, which means the vaule of w in (3) is fixed. With constraints shown in (3) and (4), the object is to minimize the difference between the obtained w and the desired Zumbro lens. All the constraints could be written as a penalty term which is part of the object fuction. The contribution of each constraint can not be expressed by a formula. Therefore the optimizer may use intelligent optimization algorithms.

For the proton beam of 20 GeV , we use GA and found the best results are obtained when: the drifts D_1=7.95m, D_2=0.70m, D_3=1.90m, D_4=2.00m; the magnet length T_1=5.72m, T_2= 6.17m, T_3=2.65m; the field gradient G_1=1.00T·m^{-1}, G_2=9.93 T·m^{-1}, G_3=8.79T·m^{-1}; diffuser thickness T_{diffuser}= 1.50mm.

Two issues should be noted for the parameters. (2) is obtained by using the assumption which the initial beam comes from a point source. Therefore, $1/w_0$ is just an initial value of D_1. Geant4 is employed to obtain the exact value of D_1 by repetition simulations. The secondary issue is relevant to the thickness of the diffuser.

If the parameters of the required proton beam are obtained, the diffuser thickness can be calculated. To use the proton beam efficiently, the proton intensity at the center of illuminating beam should be higher than that at the edge of FOV. The root mean square (RMS) angular deviation θ_0 induced by the expected diffuser can be calculated by:

$$\varphi_{\text{diffusr}} = \sqrt{\theta_0^2 + \varphi_0^2} = \sqrt{\frac{\theta^2}{-2\ln[I(\theta)/I(0)]}} \quad (4)$$

where φ_0 is the angular deviation of the beam generated by the accelerator. θ_0 is the MCS angle given approximately by

$$\theta_0 \approx \frac{14.1\,\text{MeV}}{pc\beta}\sqrt{\frac{T_{\text{diffusr}}}{X}} \quad (5)$$

Here, p is the beam momentum, $\beta = v/c$ where v is the beam velocity and c is the speed of light, and X is the radiation length for the material of the diffuser.

Combining (4) with (5), the thickness of tantalum diffuser can be obtained.

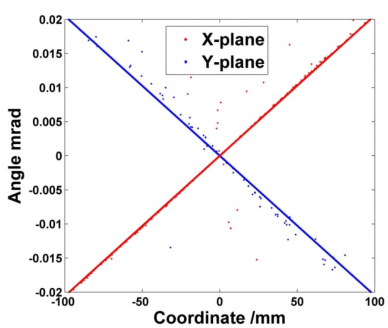

Figure 2. The angle-positon correlations at object plane.

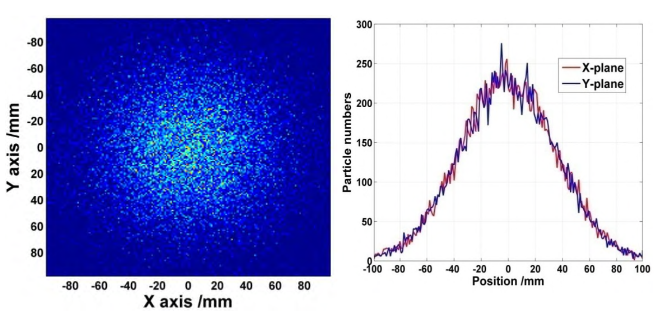

Figure 3. The planar distribution and cross-sectional distribution profile at the object plane.

The designed diffuser, matching lens and Zumbro lens were assembled as a whole system and simulated by Geant4. The obtained angle-position correlations for both x and y planes at the object plane are given in Figure 2. The simulated correlations coincide with the design. The simulation also shows that over 95% of protons can pass through this whole system, and finally reach the detector.

Figure 3 shows the beam distribution at the object plane. The result shows that the proton flux at the edge of FOV is about 20% of the maximum value. The beam distribution is also consistent with our design. Both the diffuser and the matching lens work as expected.

IV. CONCLUSIONS

The diffuser and matching lens are key components in high-energy proton radiography. In order to minimize chromatic aberration, the optimal design of the diffuser and matching lens should provide the proton beam with the necessary correlation for Zumrbo lens imaging system. The domains of parameters, magnification, target size and the thickness of diffuser are all considered by the genetic algorithm. The parameters of diffuser and matching lens are obtained for the proton beam of 20 GeV. The beam distribution is consistent with our design by use of the Monte Carlo code Geant4. Thus, the study is beneficial for the design of the magnetic lens in high-energy proton radiography.

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