Optimum Angle-Cut of Collimator for Dense Objects in High-Energy Proton Radiography

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***Abstract*—The use of minus identity lenses with an angle-cut collimator can achieve high contrast images in high-energy proton radiography. This article presents the principles of choosing the angle-cut aperture of the collimator for different energies and objects. Numerical simulation using the Monte Carlo code Geant4 has been implemented to investigate the entire radiography for the French test object. The optimum angle-cut apertures of the collimators are also obtained for different energies.**

Keywords-proton radiography; multiple Coulomb scattering; angualr collimator; Geant4.

I. INTRODUCTION

High-energy proton radiography could provide a new, quantitative, and much more capable diagnostic technique to analyze the aspects for hydrotest experiments [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 key technology that led to the development of proton radiography is a magnetic imaging lens system located between the object and the image, which forms a point-to-point focus of the proton beam and provides good position resolution over the entire field of view required for radiography.

The lens is a minus identity lens. Mottershead and Zumbro [2] demonstrated that it is possible to sort the scattered beam in terms of how it has been scattered. This always occurs in the mid-plane (Fourier plane) of a chromatically matched identity lens, where the trajectory position depends only on the MCS angle, independent of the initial position. If one places an angular collimator at this intermediate Fourier plane where the rays are completely sorted by MCS angle, it is possible to apply an angle-cut to the proton beam, removing part of the scattered beam.

It is a very important to improve the diagnostic technique. By using a single magnetic lens with just an angle-cut, one can achieve high contrast images in proton radiography. The angle-cut must be different for different proton energies and objects. In order to obtain the best image, it is desirable to choose the matching angular collimator and give an optimum angle-cut for that collimator [3].

This paper is organized as follows. The basic principles of proton radiography and choosing collimator angle-cut aperture are presented in Sections II and III, respectively. In Section IV, the numerical results are obtained with the Geant4 toolkit. Finally, the conclusion is given in Section V.

II. BASIC PRINCIPLES OF PROTON RADIOGRAPHY

The processes of proton radiography can be described by assuming a simple exponential formula for nuclear attenuation and the angular distribution of scattering as Gaussian MCS [4]. In this approximation, the transmission of protons through the magnetic lens and angle-cut collimators has the following form:

$$T(L) = \exp\left(-\sum_i \frac{L_i}{\lambda_i}\right)\left[1 - \exp\left(-\frac{\theta_{\text{cut}}^2}{2\theta_0^2}\right)\right] \tag{1}$$

Here, L is the sum of the areal densities of all materials of the object, and L_i is the areal density of the *i'th* material and λ_i is the nuclear attenuation factor for the *i'th* material. θ_{cut} is the angle-cut imposed by the angular collimator and θ_0 is the MCS angle given approximately by

$$\theta_0 \approx \frac{14.1\,\text{MeV}}{pc\beta}\sqrt{\sum_i^n \frac{L_i}{X_{0i}}} \tag{2}$$

Here, p is the beam momentum, $\beta = v/c$ where v is the beam velocity and c is the speed of light, and X_{0i} is the radiation length for the *i'th* material given by

$$X_{0i} = \frac{716.4 A_i}{Z_i(Z_i+1)\ln\left(287/\sqrt{Z_i}\right)} \tag{3}$$

The first term of (1) in the attenuation is the nuclear attenuation and is analogous to X-ray attenuation processes, but the second term is due to angular attenuation and makes proton radiography unique. Angular attenuation provides another way of distinguishing material properties.

III. PRINCIPLES OF CHOOSING COLLIMATOR ANGLE-CUT APERTURE

Different collimator apertures will permit the obtaining of different radiographs per proton pulse in the image plane. In order to obtain the best image, which can produce an intensified effect between the special points or structures in transmission; it is desirable to choose a matching angular

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collimator. The MCS θ_0 is proportional to the beam energy, so that the angle-cut θ_{cut} must be different for different proton energies. By placing an aperture restriction at the Fourier plane that removes scattered beam with large angles, the image contrast can be enhanced to give optimal images.

The transmission along ray *j* can be expressed by

$$T(L_j) = \exp\left(-\sum_i \frac{L_{ij}}{\lambda_i}\right)\left[1-\exp\left(-\frac{\theta_{\text{cut}}^2}{2\theta_{0j}^2}\right)\right] \tag{4}$$

Suppose that *a* and *b* are two important pixels needed for observation in the image plane, and the contrast between them is correlated with the quality in proton radiography; the difference of transmission between them can be written as

$$\Delta T = \exp\left(-\sum_i \frac{L_{ia}}{\lambda_i}\right)\left[1-\exp\left(-\frac{\theta_{\text{cut}}^2}{2\theta_{0a}^2}\right)\right] - \exp\left(-\sum_i \frac{L_{ib}}{\lambda_i}\right)\left[1-\exp\left(-\frac{\theta_{\text{cut}}^2}{2\theta_{0b}^2}\right)\right] \tag{5}$$

The value of the optimal cut angle can be determined by Eq. 5. At high energies where the mean free path λ_i for the *i'th* material is approximately constant, by setting the derivative of ΔT with respect to θ_{cut} to zero, the optimum angle-cut can be obtained.

IV. GEANT4 SIMULATION

The simulations of the transport of protons have been implemented with the Geant4 toolkit [5] in proton radiography. The central part of the collimator designed in the simulation was the same as that in the experimental setup used at Brookhaven National Laboratory. In experiment 955 [6], the protons were provided by the Alternating Gradient Synchrotron, and the momentum of the protons was 24 GeV/c. The collimators approximated multiple-scattering angle acceptance cuts of 6.68 mrad. We have taken data on a thick test object, the so-called French Test Object (FTO), which was designed to allow French and U.S. experimenters to collaborate on high-energy X-ray radiography methods and analysis, and their detection [7]. The FTO consisted of three concentric spherical shells. The inner shell was uranium with an inside radius of 1 cm and an outside radius of 4.5 cm. This was surrounded by a copper shell of outside radius of 6.5 cm, and this was surrounded by a shell of foam plastic with an outside radius of 22.5 cm.

The transmissions for the FTO are taken with different angle-cut apertures of the collimators. The transmission versus angle-cut aperture for 10 GeV, 23 GeV and 50 GeV proton radiography are plotted in Fig. 1. The highest points of the curves are the optimum angle-cut apertures. From Fig. 1, we can see that the optimum angle-cut apertures of the collimators are 13.09 mrad for 10 GeV, 6.68 mrad for 23 GeV and 2.56 mrad for 50 GeV for the FTO.

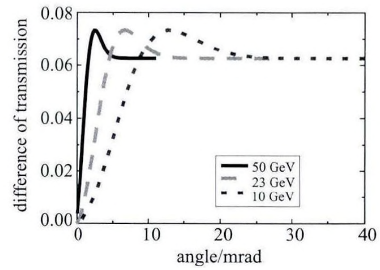

Figure 1. The difference in transmission between central point and the inner shell of uranium as a function of angle-cut aperture.

The simulation results of the proton radiograph image plane of the FTO are shown in Fig. 2. The image in Fig. 2(a) corresponds to the normal angle-cut apertures of the 6.68 mrad collimator, and the image in Fig. 2(b) corresponds to the optimum angle-cut apertures of the 13.09 mrad collimator for 10 GeV, respectively. Fig. 2(c) is the radial distribution for the FTO radiograph where the highest outer dosage is 1.

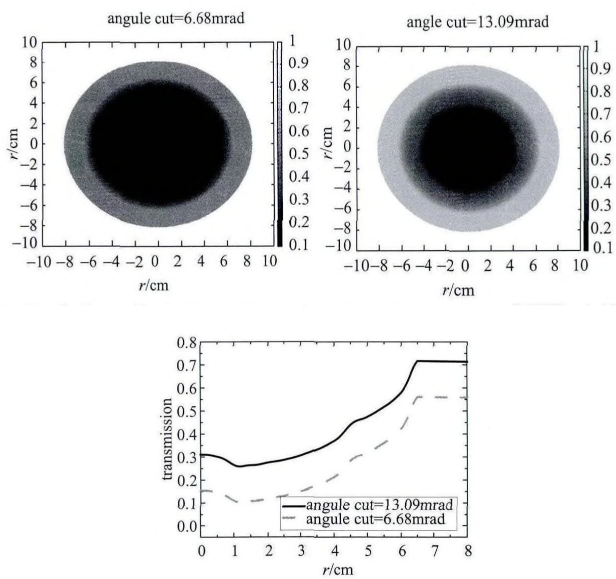

Figure 2. Simulation results from image plane of FTO at 10 GeV protons with angle-cut.

It can be seen that with the increase of angle-cut, there are more protons received in the image plane, and the image becomes lighter. It is obvious that the whole structure of the object can be seen from the image of angle-cut at 13.09 mrad but the core of the object cannot be distinguished if the angle-cut is at 6.68 mrad. This conclusion is consistent with Fig. 1.

V. CONCLUSIONS

The ability of proton radiography to adjust the image contrast by adjusting the angle-cut aperture of the collimator has been demonstrated. There is an optimum angle-cut aperture of the collimator for a given object and a given energy. The angle-cut aperture of the collimator is chosen according to the optical thickness of the object. In this article, using the Monte Carlo code Geant4, the optimum angle-cut apertures of the collimators are obtained as 13.09 mrad for 10 GeV, 6.68 mrad for 23 GeV and 2.56 mrad for 50 GeV respectively for the FTO. The numerical results indicate that the image resolution can be improved by choosing the optimum angle-cut apertures of collimators. Thus, the study is beneficial for the design of the magnetic imaging lens in high-energy proton radiography.

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