Imaging Principle and Experimental Results of an 11 MeV Low-Energy Proton Radiography System Postprint

Authors: LI Yi-Ding, ZHANG Xiao-Ding, WEI Tao, ZHAO Liang-Chao, HE Xiao-Zhong, MA Chao-Fan, YANG Guo-Jun, JIANG Xiao-Guo

Date: 2023-06-18T00:00:00+00:00

Abstract

Differing from radiography without lens system, the high-energy proton radiography (PRAD) uses Zumbro lens system to focus the penetrating protons. Since the Zumbro lens system is able to limit the range of multiple Coulomb scattering angles of the protons, the low-energy PRAD with Zumbro lens system is also feasible, although the attenuation of probing protons in the object is negligible. Low-energy PRAD is superior to the high-energy PRAD for diagnosing the objects of small thicknesses. To verify the imaging principle of Zumbro lens system, 11 MeV PRAD experiments were performed at the China Academy of Engineering Physics (CAEP) recently. The experiment results demonstrated that this 11 MeV PRAD was able to radiograph objects of area density less than 2.710-2 g/cm2 and the area density discrepancy less than 2.3% could be distinguished.

Full Text

Preamble

Imaging Principle and Experiment Results of an 11 MeV Low-Energy Proton Radiography System

LI Yi-Ding,[1],† ZHANG Xiao-Ding,[1] WEI Tao,[1] ZHAO Liang-Chao,[1] HE Xiao-Zhong,[1] MA Chao-Fan,[1] YANG Guo-Jun,[1] and JIANG Xiao-Guo[1]

[1]Institute of Fluid Physics, CAEP, P.O. Box 919-106, Mianyang 621900, China

(Received January 2, 2014; accepted in revised form June 19, 2014; published online December 9, 2014)

Abstract: Unlike lensless radiography, high-energy proton radiography (PRAD) employs a Zumbro lens system to focus penetrating protons. Since the Zumbro lens system can limit the range of multiple Coulomb scattering angles of protons, low-energy PRAD with a Zumbro lens system is also feasible, despite negligible attenuation of probing protons in the object. Low-energy PRAD is superior to high-energy PRAD for diagnosing objects of small thickness. To verify the imaging principle of the Zumbro lens system, 11 MeV PRAD experiments were recently performed at the China Academy of Engineering Physics (CAEP). The experimental results demonstrated that this 11 MeV PRAD system could radiograph objects with area density less than 2.7 $\times$ 10^{-2} g/cm^2 and distinguish area density discrepancies of less than 2.3%.

Keywords: Proton radiography, Multiple Coulomb scattering, Zumbro lens system, Radiation length, Fourier plane

DOI: 10.13538/j.1001-8042/nst.25.060203

Introduction

Radiography is an imaging technique that uses radiation to diagnose the internal structure of an object under study. A classical radiography system employs X-rays that transmit through an object to a detector plane, producing a shadowgraph of the object. The concept of using protons for radiography was first investigated in the 1960s [1]. However, unlike X-rays, probing protons undergo multiple Coulomb scattering (MCS) while passing through an object, causing radiographic images to blur since protons do not travel in straight lines through the material. To minimize this effect, the detector must be placed immediately downstream of the object to reduce transverse displacement as protons travel from the object to the detector.

In the 1990s, scientists at Los Alamos National Laboratory (LANL) investigated high-energy proton radiography (PRAD) as a new tool for advanced hydrotesting. Due to the long attenuation length of high-energy protons, this technique is well-suited for diagnosing thick objects. To compensate for MCS angles, a magnetic lens system known as the Zumbro lens system [2] was employed in high-energy PRAD to focus protons exiting the object onto a distant image plane. This significantly improved spatial resolution by eliminating image blur caused by MCS.

Experiments conducted at 800 MeV and 24 GeV using the Zumbro lens system at the Los Alamos Neutron Scattering Center (LANSCE) and the Alternating Gradient Synchrotron (AGS) in the USA [3, 4] demonstrated that PRAD can provide multiple detailed radiographs (with spatial resolution better than 1 mm) in rapid succession (200 ns between frames) for thick systems, proving superior to X-ray radiography for advanced hydrotesting [5]. In Russia, a 70 GeV PRAD beamline was constructed on the U-70 accelerator at the Institute of High Energy Physics (IHEP) [6].

To develop high-energy PRAD capabilities in China, we built a PRAD beamline with a Zumbro lens system at CAEP to verify the imaging technique [7], utilizing 11 MeV proton beams from a cyclotron [8], as high-energy proton accelerators were not available in China. At such low energies, energy loss of protons traversing a thick object introduces considerable energy dispersion and chromatic aberration. Therefore, the thickness of objects to be radiographed must be limited to reduce energy loss. The objects are orders of magnitude thinner than the proton attenuation length, making attenuation of traversing protons negligible. Theoretical analysis shows that 11 MeV low-energy PRAD can provide images with contrast based on different object thicknesses. PRAD experiments on aluminum foil verified two primary features of the Zumbro lens system: point-to-point focus from object to image and the formation of a Fourier plane where protons are sorted by the magnitude of scattering in the object.

II. High-Energy PRAD Using Zumbro Lens System

A PRAD system is shown schematically in Fig. 1 [Figure 1: see original paper]. Proton beams extracted from the accelerator are transferred to the object through a matching section, where the beams are diffused and modulated. Protons penetrating the object are focused by the Zumbro lens system onto a scintillator plate, which collects the protons and produces scintillation light. A CCD camera captures images of the scintillator to obtain the radiographic image.

The Zumbro lens system consists of four magnetic quadrupoles. The object to be radiographed and the scintillator plate are placed at the object and image planes of this lens system, respectively. The transverse transfer matrix of the Zumbro lens system is minus-identity (−I), meaning protons exiting each point of the object are focused onto corresponding points on the scintillator plate (Fig. 2 [Figure 2: see original paper]). Owing to this point-to-point focus, the transverse distribution of protons exiting the object is reproduced at the image plane, allowing a 1:1 inverted image of the object to be recorded by the CCD camera. Transverse positions of protons arriving at the image plane are independent of their initial scattering angles at the object plane, so angular dispersion caused by MCS does not blur the radiographic image.

The Zumbro lens system has another important feature: at the Fourier plane, located in the gap between the two middle quadrupoles, protons are sorted by their MCS scattering angles in the object, regardless of their origin point in the object plane. MCS changes the transverse angle of a proton passing through the object by a deviation angle (Fig. 3 [Figure 3: see original paper]), which determines the radial distance of the proton when it arrives at the Fourier plane. Placing a collimator at this plane can selectively filter protons based on their MCS deviation angles (Fig. 2).

In high-energy PRAD with a Zumbro lens system, the proton transmission rate through the object depends on both attenuation and scattering. The attenuation of protons traversing the object is given by tλ = N/N$_0$ = e$^-$ /λ, where N$_0$ is the number of incident protons, N is the number of transmitted protons, l is the area density of the object, and λ is the attenuation length. This dependence of attenuation on area density allows radiography to produce a shadowgraph of the object' s area density distribution, which also forms the basis of lensless radiography.

The transmission rate of the Zumbro lens system is primarily determined by the collimator at the Fourier plane and thus depends on proton scattering angles. The distribution of deviation angles caused by MCS is well described by Molière theory and is approximately Gaussian for small angles:

$$f(\theta) = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\theta^2/2\theta_0^2}$$

The width of this Gaussian distribution from a fit to Molière theory is given by [9]:

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta pc}\sqrt{\frac{l}{X_0}}\left[1 + 0.038\ln\left(\frac{l}{X_0}\right)\right]$$

where pc and β are the proton momentum (in MeV) and relative velocity to light velocity c, respectively, and X$_0$ is the radiation length of the object, parameterized as:

$$X_0 = \frac{716.4\,A}{Z(Z+1)\ln(287/\sqrt{Z})}\ \mathrm{g/cm}^2$$

where Z and A are the atomic number and atomic weight of the material, respectively.

By integrating the angular distribution over the lens acceptance, the transmission rate of the Zumbro lens system with collimator angle c is:

$$t_X = 2\pi \int_0^{\theta_c} f(\theta)\sin(\theta)d\theta \approx 1 - e^{-\theta_c^2/2\theta_0^2}$$

From these equations, $_0$ depends on the atomic number Z, so the transmission rate tX of the Zumbro lens system correlates with the object material. The total proton transmission rate is t = tλtX.

In high-energy PRAD, radiographing an object with a collimator of sufficiently large c such that tX   1 provides the attenuation rate tλ as in lensless radiography. By radiographing again with a collimator angle c that cuts into the MCS distribution and comparing this radiograph to the first one, the transmission rate tX for that collimator angle can be obtained. Since tλ and tX depend on l/λ and l/X_0, respectively, and the attenuation length λ and radiation length X_0 have different dependencies on atomic number, this provides material identification capability.

III. Low-Energy PRAD Using Zumbro Lens System

The energy dispersion of protons leaving the object increases with object thickness. In low-energy PRAD using a Zumbro lens system, to minimize chromatic aberration caused by energy dispersion, the object thickness must be limited. According to numerical simulations using G4beamline [10], the aluminum foil to be radiographed on the 11 MeV PRAD system should be less than 2.7×10^{-2} g/cm^2 to keep chromatic blur smaller than 1 mm. This is about three orders of magnitude smaller than the proton attenuation length in aluminum, so attenuation of protons passing through the foil is negligible and the total transmission rate t approximately equals the transmission rate tX of the Zumbro lens system.

The transmission rate of the Zumbro lens system depends on MCS angles of protons. From Eq. (3), the width of the MCS deviation angle distribution increases with object area density l. Therefore, under a fixed collimator angle c, the transmission rate tX in Eq. (5) decreases with increasing area density. If the collimator angle c cuts into the MCS angular distribution, the transmission rate tX becomes sensitive to changes in area density. This correlation between the Zumbro lens system transmission rate and object area density allows low-energy PRAD to provide image contrast, even though nearly all probing protons pass through the object.

Based on this analysis, low-energy PRAD using 11 MeV proton beams is feasible. It can verify the Zumbro lens system' s ability for point-to-point focus and the Fourier plane' s ability to select the MCS angular range of protons passing to the image plane.

Compared to high-energy PRAD, low-energy PRAD offers advantages for diagnosing thin objects. From Eq. (3), the width of the scattering angle distribution is smaller for high-energy protons. For example, the RMS deviation angle $_0$ caused by MCS is only 0.23 mrad for 1 GeV protons transmitted through an aluminum foil of area density 2.7×10^{-2} g/cm^2. This deviation angle distribution is so narrow that protons are hardly blocked by the collimator (typically with collimator angle c of several mrad according to Zumbro lens system design). Both transmission rates tX and tλ are approximately one, so high-energy PRAD cannot provide sufficient contrast for such thin objects.

For 11 MeV protons transmitting through the same aluminum foil, the RMS deviation angle $_0$ is about 15 mrad, and the scattering angular distribution can be cut by a collimator angle c of several mrad, enabling low-energy PRAD to provide adequate contrast for minor discrepancies in small area densities.

However, since low-energy PRAD imaging is independent of proton attenuation in the object and $t\lambda$ 1, the ratio l/λ cannot be determined by low-energy PRAD, nor can material identification be performed.

IV. Results and Discussion

To verify the Zumbro lens system technique, a PRAD beamline was constructed on the 11 MeV proton cyclotron at the Institute of Fluid Physics, CAEP. The system provides 11 MeV proton beams with an average current of 50 µA. As shown in Fig. 1, the proton beams pass through a Φ1 mm pinhole and a 20 µm thick Al foil diffuser to increase angular divergence. Magnets in the matching section modulate the positions and angles of protons [7]. The beams arriving at the end of the matching section uniformly illuminate a Φ30 mm area at the object plane, with transverse angles linearly correlated to transverse position. At the object plane, protons undergo MCS in Al foils. The Zumbro lens system transports protons to the image plane, where a scintillator plate and CCD camera record the transverse proton distribution as a shadowgraph.

An object made of aluminum foils was radiographed on the PRAD beamline. As shown in Fig. 4 [Figure 4: see original paper], it has nine regions: a central square hole and eight surrounding regions with aluminum foils of different thicknesses. Table 1 lists the area densities of each region and the corresponding RMS scattering angles of transmitted protons calculated using Eq. (3). The measured transmission rate images with collimator angles c of 26.2, 4.14, 2.76, and 1.38 mrad are shown in Fig. 5 [Figure 5: see original paper].

To measure the transmission rate tX with the object, the transverse distribution of the incident beam was first measured. The object was removed so that the transverse distribution of the incident beam at the object plane could be 1:1 transferred by the Zumbro lens system to the image plane and recorded by the CCD camera. According to measurement data, proton number fluctuation was less than 2% over tens of hours.

Each time an object was radiographed, the transverse distribution of the incident beam was measured again immediately without the object. The transmission rate image was obtained by dividing the radiographic image of the object by the incident beam image pixel-by-pixel.

Figure 5 demonstrates the effects of decreasing collimator angle. Contrast between foils of different thicknesses was only achieved when the collimator angle cut into part of the RMS scattering angles $_0$ listed in Table 1. This verified that the Fourier plane can effectively select the MCS angular range of imaging protons.

Transmission rates with a collimator angle of 4.14 mrad, which provided good contrast (Fig. 5(b)), were obtained by averaging measured transmission over a flat region (11 × 11 pixels) for each region in Fig. 5(b). The results are listed in the last column of Table 1 .

By fitting the measured transmission rates and thicknesses from Table 1 using

Eq. (5), the radiation length X_0 of aluminum was determined to be 21.3 g/cm^2, which is less than the value of 24.3 g/cm^2 calculated from Eq. (4). The measured transmission rates generally agree with calculated values, showing significant differences only when the aluminum foil is thinner than 4×10^{-3} g/cm^2. This discrepancy may be due to contributions from nuclear scattering not included in the Gaussian approximation of Eq. (2). Fringe fields of the quadrupoles and nonlinear response of the CCD camera may also affect measurements.

An aluminum foil covered with charcoal bands was also radiographed. The foil had an area density of 2.7×10^{-2} g/cm^2 and was covered by eight charcoal bands of 1 mm or 2 mm width (four each). The area density of the charcoal bands was 6.21×10^{-4} g/cm^2, creating a density discrepancy of about 2.3%. For an Al foil with area density 2.7×10^{-2} g/cm^2, the RMS deviation angle $_0$ of traversing protons is about 15 mrad. By setting the collimator angle c to 12.4 mrad, which cuts into the angular distribution, the 2.3% area density discrepancy could be resolved in the radiographic image (Fig. 6 [Figure 6: see original paper]).

V. Conclusion

Our analysis demonstrates that low-energy PRAD using 11 MeV proton beams can produce shadowgraphs of objects, despite negligible proton attenuation in the object. The imaging contrast in low-energy PRAD is based on the relationship between the MCS angular dispersion of transmitted protons and object thickness.

Experiments on the imaging beamline verified the point-to-point focus from object to image and the angular sorting capability of the Fourier plane. Measured transmission rates of aluminum foils agree with values calculated from the Gaussian scattering angle distribution for area densities above 4×10^{-3} g/cm^2.

The 11 MeV PRAD system can radiograph objects with area density less than 2.7 $\times$ 10^{-2} g/cm^2. By setting the collimator angle to cut into the RMS deviation angle $_0$ of traversing protons, this low-energy PRAD system can distinguish area density discrepancies of less than 2.3%.

References

[1] Koehler A. Science, 1968, 160: 303-304.
[2] Mottershead C T and Zumbro J D. Magnet optics for proton radiography (PAC' 97), Vancouver, B. C., Canada, May 12-16, 1997.
[3] King N S P, Ables E, Adams K J, et al. Nucl Instrum Meth A, 1999, 424: 84-91.
[4] Morris C L, Ables E, Alrick K R, et al. J Appl Phys, 2011, 109: 010201.
[5] Ziock H J, Adams K J, Alrick K R, et al. The proton radiography concept. Los Alamos National Laboratory, LA-UR-98-1368, 1998.
[6] Burtsev V V, Lebedev A I, Mikhailov A L, et al. Combust Explo Shock+, 2011, 47: 627-638.

[7] Wei T, Yang G J, Li Y D, et al. arXiv:1310.5528v1.
[8] He X Z, Yang G J, Long J D, et al. Nucl Tech, 2014, 37: (in Chinese).
[9] Nakamura K, Hagiwara K, Hikasa K, et al. J Phys G Nucl Partic, 2010, 37: 075021.
[10] http://g4beamline.muonsinc.com.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.