Measurement of spatial resolution of 11 MeV proton radiography postprint

Authors: ZHANG Xiao-Ding, LI Yi-Ding, YANG Guo-Jun, WEI Tao, Xiao-Zhong He, LONG Ji-Dong, JIANG Xiao-Guo, MA Chao-Fan, ZHAO Liang-Chao, YANG Xing-Lin, ZHANG Zhuo, WANG Yuan, Wei-Feng Li, SHI Jin-Shui

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

Abstract

Proton radiography experiment with a Zumbro lens system was carried out on an 11 MeV proton cyclotron. The experimental results show that the image blurring is improved markedly. Clear images and good spatial resolution of the density step edges are obtained, which is important for hydrotest experiments, and the spatial resolution can achieve 100 m.

Full Text

Preamble

Measurement of Spatial Resolution of 11 MeV Proton Radiography

ZHANG Xiao-Ding,1,† LI Yi-Ding,1 YANG Guo-Jun,1 WEI Tao,1 HE Xiao-Zhong,1 LONG Ji-Dong,1 JIANG Xiao-Guo,1 MA Chao-Fan,1 ZHAO Liang-Chao,1 YANG Xing-Lin,1 ZHANG Zhuo,1 WANG Yuan,1 LI Wei-Feng,1 and SHI Jin-Shui1

1Institute of Fluid Physics, China Academy of Engineering Physics, P.O. Box 919-106, Mianyang 621900, China

(Received January 21, 2014; accepted in revised form May 24, 2014; published online December 15, 2014)

Proton radiography experiments with a Zumbro lens system were carried out on an 11 MeV proton cyclotron. The experimental results show that image blurring is improved markedly, with clear images and good spatial resolution of density step edges obtained—an important outcome for hydrotest experiments. The spatial resolution achieved is approximately 100 μm.

Keywords: Proton radiography, Zumbro lens system, Spatial resolution

DOI: 10.13538/j.1001-8042/nst.25.060204

Introduction

Proton radiography (PRAD) is an advantageous method for hydrotests, offering high penetrating power, high detection efficiency, low scattered background, inherent multi-pulse capability, and large standoff distances between the object and detector [**?**]. Proton-material interactions enable PRAD to resolve higher-density objects than flash x-ray radiography and to identify materials. PRAD images can be used to evaluate interfaces, determine the position and velocity of shock fronts, and measure density transformations in test samples. The spatial resolution and areal density resolution for static objects serve as benchmarks of the imaging system’ s working status.

When protons penetrate materials, they interact with electrons, the nuclear Coulomb field, and the nucleus, producing three primary effects: energy loss, multiple Coulomb scattering (MCS), and nuclear scattering. The MCS effect is the main cause of image blurring with low-energy incident proton beams. To eliminate this limitation, Zumbro and Thomas proposed a simple yet elegant magnetic lens system to focus scattered protons. Subsequent magnetic lens systems were designed for proton radiography experiments on the 800 MeV accelerator at Los Alamos Neutron Scattering Center (LANSCE) [**?**] and on the Alternating Gradient Synchrotron (AGS, 24 GeV proton beams) at Brookhaven National Laboratory [**?**]. These experimental results proved that such lens systems could reduce image blurring remarkably, achieving spatial resolutions of about 100 µm.

Protons in the tens of MeV range can penetrate samples hundreds of microns thick, making them proper tools for imaging sub-millimeter samples. PRAD may also be used for imaging medical and biological samples. However, for low-energy PRAD, spatial resolution is a key parameter for obtaining sample information. In this paper, we report proton radiography using a unit-magnification Zumbro magnetic lens system on an 11 MeV cyclotron. By analyzing radiographed images of static objects, we demonstrate that the spatial resolution of the magnetic lens system is approximately 100 µm—an encouraging result for developing this technique for hydrotesting experiments.

II. Methods

A. Chromatic Cancellation of Zumbro Lens System

The Zumbro lens system is a point-to-point imaging system with unit magnification [**?**, **?**]. Along the x and y directions, the transport transfer matrices are $-I$’ s. The system comprises two identical quadrupole doublets arranged with reflection symmetry.

B. Blurring Analysis

In radiography, the Zumbro lens system, the radiographed objects, the scintillator, and the optical recording system all contribute to image blurring. The blurring contributions from each component are considered as follows.

For the Zumbro lens system, position-dependent chromatic aberrations and blurring from proton beam transport can be eliminated because the lens operates in point-to-point radiography mode. However, chromatic aberration cannot be eliminated for different sample positions. The chromatic aberration blurring at different sample positions is calculated as [**?**]

$$B_{lens} = T_{126}\theta_0\delta,$$

where θ_0 is the deviation angle from MCS, $\delta = \Delta p/p_0$ is the momentum deviation, and T_{126} is an element of the transport matrix in TRANSPORT notation representing second-order chromatic aberration.

Before exiting the object, protons undergo millions of Coulomb scatterings, and the angular distribution of penetrating protons can be approximated as Gaussian. The root-mean-square (rms) width of the MCS exit cone, in milliradians, is

$$\theta_0 = \frac{13.6}{p\beta c}\left(\frac{L}{L_R}\right)^{1/2}\left\{1+\frac{\log(L/L_R)}{9}\right\},$$

where p is the beam momentum in GeV/c, βc is the proton velocity, L is the object thickness, and $L_R \propto Z^2/A$ is the radiation length of the material [**?**]. The blurring from the object can therefore be expressed as [**?**]

$$B_{obj} = 3^{-1/2}L\theta_0.$$

The blurring from the detection system (scintillator and downstream optical imaging system including the optical lens and CCD camera) is denoted as B_{det}. The total blurring can then be calculated as

$$B_{tot,FWHM} = 2.36\left(B_{obj}^2 + B_{lens}^2 + B_{det}^2\right)^{1/2},$$

where the coefficient 2.36 derives from the Gaussian distribution. This total blurring represents the theoretical FWHM (Full Width at Half Maximum) of the edge differential image.

C. Experimental Setup

The PRAD experiment for measuring spatial resolution of the Zumbro lens system with static objects was conducted on an 11 MeV compact proton cyclotron [**?**], providing an average beam current of 50 µA. The collimated proton beam on the scintillator detectors integrated thousands of micro-pulses over ten seconds or longer.

Figure 1 [Figure 1: see original paper] shows the layout of the low-energy PRAD imaging beamline [?]. It consists of a matching section, the magnetic lens system, and the recording system. The matching section includes two correction magnets and two quadrupoles to match the beam to the magnetic lens system. The recording system comprises an LSO scintillator at the image plane and a high-resolution CCD camera positioned about 15 cm downstream of the LSO scintillator.

The object was assembled from aluminum foils of different thicknesses and a charcoal layer coated by a laser printer. The charcoal layer thickness was determined as follows: a 50 mm × 50 mm × 6 µm Al foil of known weight was coated with charcoal of known density and weighed using an electric balance with 10 µg precision, yielding an average charcoal thickness of 4 µm.

A $ $6 mm collimator was fixed on the Fourier plane to select the scattering angle of protons, with a maximum acceptance angle of 4.06 mrad in our experiment. The field of view (FOV) is larger than $ $30 mm. The scintillator is a $ $38mmLSO(Lu\_2SiO\_4$) screen, and the camera is a high-quality industrial CCD camera.

III. Experimental Data

Parameters of the imaging system are known or calculated. For example, $T_{126} = 2929$ mm is determined by the design of the Zumbro magnetic lens system. The total blurring of the imaging beamline with a 16 µm thick Al foil object is estimated as follows: because the object is too thin to affect momentum deviation, δ_{rms} should equal the momentum deviation of the cyclotron, which is about 0.003 (half from the cyclotron and half from the diffuser). From Eq. (2), the MCS angle is $\theta_0 \sim 5.6$ mrad without collimators. Therefore, the blurring from the lens system is $B_{lens} = 82$ µm. With the collimator, the rms MCS angle changes. After the first doublet, exiting protons are focused to a spot on the Fourier plane, and the collimator cuts off protons beyond its diameter, changing the maximum angle to the collimated angle. On the scintillator, the angle θ becomes 3.38 mrad and the blurring is $B_{lens} = 29.73$ µm. For a 9 µm thick Al foil, the blurring with collimator can be estimated as $B_{lens} = 29.70$ µm.

According to Eq. (3), the body blurring (B_{obj}) values are 0.064 µm and 0.04 µm for the 16 µm and 9 µm thick Al foils, respectively. From SRIM calculations, the lateral straggling for 11 MeV protons traveling through a 0.5 mm thick LSO scintillator is about 36 µm, giving $B_{det} \approx 36.9$ µm. Therefore, from Eq. (4), the total blurring (FWHM) for 16 µm and 9 µm thick Al foils is $B_{tot,FWHM} \approx 112$ µm.

Figure 2 [Figure 2: see original paper] shows the transmission image and edge position image of the stepped sample with a $ $6 mm collimator on the Fourier plane. Density step positions in Fig. 2(b) are identified as points where the image gradient is maximum. To obtain more precise edge positions, we analyzed the red region in Fig. 2(a). By averaging along the Y direction and differentiating along the X direction, we obtained Fig. 2(c). Gaussian fitting of the differential peaks yielded the maxima and FWHM values. Compared with the edge image, the peak occurs at the same position, with a FWHM of about 100 µm, indicating that the spatial resolution of the total imaging system is approximately 100 µm. The distance between two edges is 5,320 mm in Fig. 2(b) and 5,308 mm in Fig. 2(c). For this simple configuration, searching for interface positions using the MatLab toolbox can provide approximate edge locations.

To obtain more direct information about spatial resolution, verify the spatial resolving power, and confirm the feasibility of the interface position detection method, reticle samples were radiographed. Figure 3 [Figure 3: see original paper] shows transmission images of reticles with 0.5, 1.0, 2.5, and 5.0 lp/mm prepared with a laser printer on a 50 mm × 50 mm × 6 µm Al foil. We analyzed the intensity distribution and its derivative along rectangular regions.

In Fig. 3, the 2.5 lp/mm reticle can be clearly distinguished, and the 5 lp/mm reticle is also distinguishable by eye, confirming that 100 µm spatial resolution for the entire system can be achieved.

Comparing these results reveals some inconsistency between experimental data and theoretical image blurring estimates, likely arising from complex environmental factors such as vacuum pump vibrations and proton beam jitter. To obtain clearer radiographs, further efforts are needed to better understand the principles and working status of the Zumbro lens system.

IV. Conclusion

We have performed spatial resolution measurements of proton radiography on an 11 MeV cyclotron with a unit-magnification Zumbro lens system. Analysis of transmission images of reticles and edge images of Al foils demonstrates that the imaging system can achieve a resolving power of 100 µm. These results are encouraging and prove that static radiography on a low-current cyclotron is feasible. However, substantial work remains to improve the system' s spatial resolution. For example, under bombardment by 11 MeV protons, scintillation occurs not at a point but over a spot in the scintillator, so the response characteristics of the scintillator require further study. Similar efforts are needed for collimator design, cyclotron beam diagnosis, and precise beam matching to the magnetic lens system. These improvements will greatly enhance system performance.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 11205144 and No. 11176001). The corresponding author can be reached at zhangxiaod@163.com.

References

[1] Burtsev V V, Lebedev A I, Mikhailov A L, et al. Combust Explo Shock+, 2011, 47: 627-638.
[2] Shiberin I V, Batkov Y V, Burstev V V. XI Kharitonov Thematic Scientific Readings, Sarov, 2009, 304-309.
[3] Smilowitz L, Henson B F, Romero J J, et al. J Appl Phys, 2012, 111: 103515.
[4] Morris C L, Hopson J W, Goldstone P. Los Alamos Science, 2006, 32: 32-39.
[5] King N S P, Ables E, Adams K, et al. Nucl Instrum Meth A, 1999, 424: 84-87.
[6] Morris C L, Ables E, Alrick K R, et al. J Appl Phys, 2011, 109: 104904.
[7] Mottershead C T and Zumbro J D. Proceedings of the 1997 Particle Accelerator Conference, Vancouver, Canada, 1997, 1397-1399.
[8] He X, Yang G, Liu C. High Power Laser Part Beam, 2008, 20: 297-300. (in Chinese)
[9] Wei T, Yang G J, Long J D. Chinese Phys C, 2013, 37: 068201.
[10] He X, Yang G, Long J, et al. Nucl Tech, 2014, 37: 010201. (in Chinese)
[11] Wei T, Yang G, Long J, et al. Chinese Phys C, 2012, 36: 792-796.

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