IMAGING SYSTEMS FOR 800 MeV PROTON RADIOGRAPHY

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Abstract

Los Alamos National Laboratory (LANL) has developed several "flash" proton radiography systems that use 800 MeV protons generated by the LANSCE linear accelerator for the study of dynamic materials science. These systems have been optimized to measure the fundamental properties of dynamic materials such as the equation of state, strength, and phase transitions, as well as the physical processes important in predicting the hydrodynamic flow of these materials at high velocity, pressure, and density. To meet the requirements of these measurements, three radiography systems have been developed: an identity lens, a ×3 magnifier and a ×7 microscope. These systems have been optimized for 800 MeV proton radiography, but future radiographic improvements can be achieved by increasing the proton energy, as has been demonstrated at higher energy proton radiography facilities around the world.

INTRODUCTION

Modern "flash" proton radiography was invented at Los Alamos in the 1990's [1,2,3] and has become a mainstay of LANL's dynamic materials research by providing high-resolution radiographic movies of more than 500 fast dynamic systems. For these measurements, protons from the LANSCE accelerator pass through the dynamically evolving material and then enter into a magnetic imaging lens. The magnetic field of this lens re-images the proton beam onto a scintillator plate at an image plane, mitigating the effects of scattering within the object. The flexible pulse timing structure of the linac-generated proton beam provides a series of short exposure times to sequentially "freeze" the motion of the fast dynamic events. Light from the scintillator plate is recorded by a series of fast cameras capable of collecting multiple images to form the radiographic movies [4].

The majority of the performance characteristics of a proton radiography system are determined by the proton imaging lens. Early in the development of proton radiography a reflective-symmetric quadruplet lens configuration was adopted [5] to ensure co-located focal planes in both the horizontal and vertical. Although the introduction of the magnetic lens system removed most of the blurring due to multiple Coulomb scattering within the object, the lens also introduced the next level limitation in resolution: chromatic aberrations. However, a clever scheme of preparing the transverse beam phase space, called matching, was identified to remove the most destructive second order chromatic aberrations [5]. The remaining blur from chromatic aberrations is described in equation 1, where σ_x and σ_y are the horizontal and vertical resolution, T_{126} and T_{346} are the second order tensor elements of the lens in TRANSPORT notation, θ_x and θ_y are the angular widths of the proton beam within the acceptance of the lens, δ is the fractional momentum spread of the proton beam and m is the magnification of the lens. Equation 1 also defines the chromatic lengths of an imaging lens, C_x and C_y, which provides a useful way to compare systems of various magnifications.

$$\sigma_x = \frac{T_{126}\theta_x\delta}{m} = C_x\theta_x\delta$$
$$\sigma_x = \frac{T_{134}\theta_y\delta}{m} = C_y\theta_y\delta \qquad (1)$$

Figure 1 shows proton trajectories through the identity lens that is commonly used for 800 MeV proton radiography at LANSCE. Protons are injected into the object with a position-angle correlation, called the matching condition, which cancels chromatic aberrations but also forms a Fourier plane at the center of the lens, where the protons are radially sorted by scattering introduced in the object. A collimator at the Fourier location removes protons scattered to large angles and passes the unscattered protons to form the radiographic image.

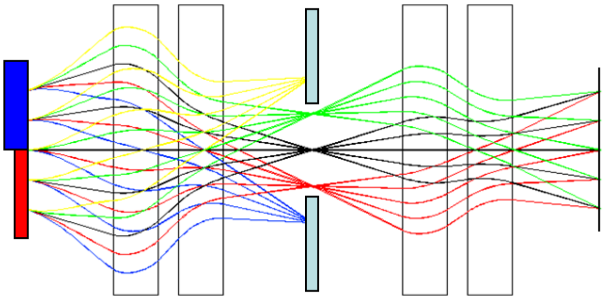

Figure 1: Protons traveling from left to right follow these horizontal trajectories through identity lens system. The matching condition results in the position-angle correlation seen at the object. This same matching condition results in a Fourier plane at the center of the lens.

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Four identical quadrupole magnets of the identity lens (-I lens) have an aperture diameter of 30.48 cm, an

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effective length of 73.5 cm and operate at 0.9 Tesla pole tip field. They are configured for an object-to-image length of 9.4 m, with the first magnet positioned 1.447 m downstream of the object location. In this configuration the identity lens system provides a "bare resolution" of 180 µm over a field of view of 120 mm. Here we define bare resolution as the RMS width of a Gaussian point spread function through a thin (<1 g/cm^2) object. Thicker objects will degrade the resolution by scattering within the object and by energy loss in the object coupled to chromatic aberrations.

At the LANL pRad facility, two identical back-to-back identity lenses provide two image locations, doubling the number of cameras that can be fielded on each experiment. The resolution of this second image location is degraded twice by chromatic aberrations and we will refer to this lens system as the -I^2 lens.

For intermediate-size objects requiring higher resolution, the identity lens discussed above is replaced with a ×3 magnifier system [6]. This lens has the same object to image distance as the identity lens, with the first magnet 1.45 m downstream of the object. The quadrupole magnets of this lens are Hallbach style permanent magnets, the first having a length of 21.4 cm, an aperture of 4.5 cm and an integrated field gradient strength of 3.44 T. The lengths of the second and third quadrupoles are double the lengths of the first and fourth. The bare resolution of this imaging lens is 60 µm over a 42 mm field of view.

The third lens system is a ×7 microscope [7], used for small objects requiring the best spatial resolution. It can also replace the identity lens system with the same object-to-image distance. The first Hallbach style permanent magnet quadrupole is 0.4 m downstream of the object location and is 7.62 cm long, with an aperture 25.4 mm in diameter and integrated gradient length of 5.64 T. Again, the inner two magnets are double the length of the outer two.

Table 1 summarizes the parameters of the four lens systems that are presently being used to perform 800 MeV proton radiography experiments at LANSCE.

Table 1: Summary of Proton Imaging Lens Parameters

Lens	Mag	Cx (m)	Cy (m)	σ_x (µm)	σ_y (µm)	FoV (mm)
-I	1	12.2	12.2	180	180	120
-I^2	1	24.3	24.3	280	280	120
×3	2.65	6.8	5.4	53	63	42
×7	6.92	1.8	3.0	17	17	15

The strong correlation between the resolution and the field of view means that the number of resolution elements across the field of view is fixed, at ~1000×1000, limiting the radiography to megapixel images. This correlation between resolution and field of view is due to the connection between the magnetic field gradient and the radius of the conventional magnets that have been used in the existing lenses, whose pole-tip fields are approximately constant near ~1 Tesla. In order to achieve the field gradient required for these magnifier systems, the radius of the poles has been reduced, which also reduces the field of view of the lens system.

HIGH ENERGY PROTON MICROSCOPY

To date the majority of the effort to improve resolution with 800 MeV protons has been focused on reducing the chromatic lengths of these magnet systems. With conventional magnets, iron electro-magnets or permanent magnet quadrupoles, reductions in chromatic length come with a reduction in field of view. Equation 1, however, does show an alternate approach to improving resolution by reducing the fractional momentum spread of the beam, δ. The absolute momentum spread of the protons is difficult to reduce because it is typically set by dE/dx interactions within objects or in vacuum windows for very thin objects. The easiest way to improve resolution, therefore, is to increase the incoming beam energy so that the fractional momentum spread is reduced. This conclusion has been tested by experiments conducted with 7-20 GeV proton radiography data at the Brookhaven National Laboratory Alternating Gradient Synchrotron [8,9], where resolutions of 200 µm were observed through thick objects (214 g/cm^2).

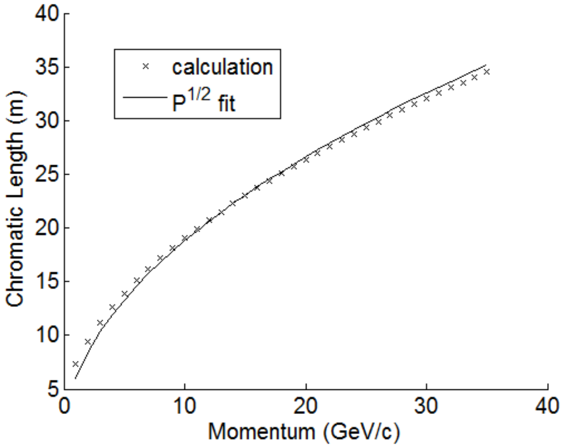

Figure 2: Points are the chromatic length calculated for an identity lens at energies from 1 GeV/c through 35 Gev/c and the solid line is a fit of P$^{1/2}$, showing that chromatic length scales with the square root of momentum.

The improvement in resolution for higher proton beam momentum is determined by the product of the chromatic length, C, of the imaging lenses, the angular width, θ, of the proton beam, and the fractional momentum spread δ. Figure 2 shows how the chromatic length scales with momentum. Scattering processes determine the value of θ, which scales inversely with momentum, as does δ. The resolution, therefore, scales as the product of these three terms: 1/P$^{3/2}$. This means that resolution should improve

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with increasing proton energy until processes other than chromatic aberrations begin to determine the resolution, such as multiple scattering within the object or geometric aberrations in the lens system. Since LANL initially demonstrated the performance gain of high-energy proton radiography for large, thick (~214 g/cm^2) objects [8,9], a team of Russian scientists have commissioned a new 50 GeV proton radiography facility at the Institute for High Energy Physics in Protvino, Russia [10]. This system again demonstrated the resolution improvements (~100 μm) gained by high energy protons through relatively thick objects (~300 g/cm^2).

More recently, an international collaboration of scientists bringing together expertise from each of the proton radiography facilities around the world, have commissioned a high-energy proton microscope system at GSI in Darmstadt, Germany [11]. This system combines the resolution improvements gained by higher energies (4.5 GeV) with the improved resolution of a microscope imaging system. Commissioning activities are underway, with preliminary measurements of bare resolution reaching 30 μm, consistent with the predictions from these scaling laws at this stage in the commissioning. This system should be capable of reaching the 10 μm level once commissioning is complete. Similar systems are being designed for use at proton accelerator facilities in China [12].

An alternate approach to improving resolution would be the use of an achromatic imaging lens system. This has been previously studied [13], but requires ~20 magnetic elements to form the chromatically corrected magnetic imaging lens. In practice this number of elements is expensive and impractical to tune at the precision required to achieve significant advantages over four element imaging lens systems. Achromatic systems which cancel the most important chromatic aberrations, while minimizing the effects of geometric aberrations, may exist and are an area for future investigations. To date, the preferred solution to improving resolution of proton radiography is to increase the energy of the proton beam [14].

CONCLUSIONS

High energy proton accelerators are being re-purposed around the world to serve as proton sources for proton radiography applications, providing new windows for the study of dynamic materials properties. Research in the development of this technique is leading to improved spatial resolution, similar to the improvements gained in the early days of electron microscopy. The application of high energy protons for radiography have generated significant improvements and future improvements will most likely come from the development of imaging systems with reduced chromatic aberrations.

REFERENCES

[1] N. S. P. King, et al., “An 800 MeV Proton Radiography facility for dynamic experiments”, Nucl. Instrum. Meth. Phys. Res. A, 424, 1, 84-91.

[2] G.E. Hogan, et al., “Proton Radiography,” PAC’99, New York, NY, USA, p. 579

[3] H.-J. Ziock, et al., "The Proton Radiography Concept," Proceeding of the Third International Symposium on Development and Application of Semiconductor Tracking Detectors (The Hiroshima Symposium) at Melbourne, December 9-12, 199.

[4] K. Kwiatkowski J.-F. Beche, M. T. Burks, G. Hart, G. E. Hogan and F. Manfredi et al., “Development of multiframe detectors for ultrafast radiography with 800 MeV protons,” IEEE Trans. Nucl. Sci., pt. 2, vol. 49, pp 293-296, (2002)

[5] C.T. Mottershead and J. D. Zumbro, "Magnetic Optics for Proton Radiography", Proceedings of the 1997 Particle Accelerator Conference, Vancouver, B. C., Canada

[6] F. E. Merrill, et al., “Magnifying Lens for 800 MeV Proton Radiography”, Rev. Sci. Instrum. **82**, 103709 (2011)

[7] Mottershead, T., et al. "Design and operation of a proton microscope for radiography at 800 MeV." *Particle Accelerator Conference, 2003. PAC 2003. Proceedings of the*. Vol. 1. IEEE, 2003.

[8] Morris, C. L., et al. "Flash radiography with 24 GeV/c protons." *Journal of Applied Physics* 109.10 (2011): 104905.

[9] Morris, C. L., et al. "Charged particle radiography." *Reports on progress in physics. Physical Society (Great Britain)* 76.4 (2013): 046301-046301.

[10] Antipov, Yu M., et al. "A radiographic facility for the 70-GeV proton accelerator of the Institute for High Energy Physics." *Instruments and Experimental Techniques* 53.3 (2010): 319-326.

[11] Merrill, F. E., et al. "Proton microscopy at FAIR." *SHOCK COMPRESSION OF CONDENSED MATTER 2009: Proceedings of the American Physical Society Topical Group on Shock Compression of Condensed Matter*. Vol. 1195. No. 1. AIP Publishing, 2010.

[12] Guo-Jun, Yang, et al. "A design study of a magnifying magnetic lens for proton radiography." *Chinese Physics C* 36.3 (2012): 247.

[13] Blind, Barbara, and Andrew J. Jason. "Chromatically Corrected Imaging Systems for Charged-Particle Radiography." *Particle Accelerator Conference, 2005. PAC 2005. Proceedings of the*. IEEE, 2005.

[14] Garnett, R. W., Merrill, F. E., O’Hara, J. F., Rees, D. E., Rybarcyk, L. J., Tajima, T., & Walstrom, P. L. A CONCEPTUAL 3-GEV LANSCE LINAC UPGRADE FOR ENHANCED PROTON RADIOGRAPHY. Proceedings of the 2012 International Particle Accelerator Conference.