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Magnifying lens for 800 MeV proton radiography

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Abstract

This article describes the design and performance of a magnifying magnetic-lens system designed, built and commissioned at Los Alamos National Laboratory (LANL) for 800 MeV flash proton radiography. The technique of flash proton radiography has been developed at LANL to study material properties under dynamic loading conditions through the analysis of time sequences of proton radiographs. The requirements of this growing experimental program have resulted in the need for improvements in spatial radiographic resolution. To meet these needs a new magnetic lens system, consisting of four permanent magnet quadrupoles, has been developed. This new lens system was designed to reduce the second order chromatic aberrations, the dominant source of image blur in 800 MeV proton radiography, as well as magnifying the image to reduce the blur contribution from the detector and camera systems. The recently commissioned lens system performed as designed, providing nearly a factor of three improvement in radiographic resolution.

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I. Introduction

Flash radiography has been developed at LANL since 1943 for the generation of stop-action or "flash" radiographs of materials driven by high explosives for the study of dynamic material properties (such as equation-of-state, material strength and failure modes) at high pressure, density and strain rate [1]. The early radiographic sources utilized x-rays generated with accelerated electrons interacting with high-Z targets, Bremsstrahlung sources. The ideal x-ray energies for radiographic penetration of thick objects (>10 g/cm²) is ~1-4 MeV, and the generation of these x-rays by a Bremsstrahlung source requires an accelerated electron beam of 2-20 MeV, typically interacting with a converter target. In order to generate stop-action radiographs the electron beam and resulting x-rays must be delivered in a relatively short pulse of <100 ns, requiring very high intensity, short duration electron beams. This requirement results in two difficulties. First, the high intensity beams interacting with the converter target not only generate Bremsstrahlung x-rays, but also lose energy through ionization processes and deposit a significant fraction of the incident electron beam energy as heat, rapidly heating the converter target. This fast energy deposition often destroys the converter target, limiting the flash radiography system to a single radiograph per dynamic event. Second, the high intensity beam is difficult to focus into a small spot size on the target. This typically results in the fundamental limitation of the resolution of the radiography system.

Proton radiography was investigated in the early 1990s at LANL as a radiographic probe that could provide multiple-time, high-resolution radiographs of these dynamic systems [2]. By using the protons as direct radiographic probes, requiring no converter target, the limitation to a
single radiograph was overcome. The major difficulty remained in overcoming the resolution limitations that had been discovered in the very first proton radiography studies in the 1970s [3]. In these studies high energy protons (>100 MeV) were used as direct radiographic probes with images collected on film. From this work it was concluded that multiple Coulomb scattering of the protons within the radiographic object resulted in significant blurring at the image, fundamentally limiting the resolution of this type of radiography. Flash radiography of dynamic systems requires the film to be located a significant distance from the object, exacerbating the degradation in radiographic resolution by converting the angular spread of the protons into spatial spreading as they traveled from the object to the film location.

In 1995 it was discovered at LANL that this degradation of resolution could be mitigated with the introduction of a magnetic imaging lens located between the object being radiographed and the image location [4]. This lens system formed a point-to-point focus of the proton beam, removing the resolution degradation from the angular deflections within the object. This development has been used at proton radiography facilities around the world as well as to applications with electron radiography [5].

With the invention of this new radiographic technique a system designed at LANL was built to utilize the 800 MeV proton beam delivered by the Los Alamos Neutron Science Center (LANSCE) [2]. This identity lens system was built from four quadrupole electromagnets with 30 cm apertures, providing a 120 mm field of view with ~180 μm limiting resolution (RMS of a Gaussian point spread function). The proton beam at LANSCE is generated by a radio frequency accelerator, which typically delivers 12 mA peak proton beams for a maximum duration of 1
ms. A deflector located at the low energy end of the accelerator can turn on and off the proton beam, providing an essentially arbitrary temporal structure. In order to take advantage of this multiple-time capability the film of the radiography system was replaced with fast-gated solid-state cameras, presently providing forty-two radiographs per dynamic experiment. This system has been used to radiograph over 400 dynamic experiments and countless static objects.

Although 180 μm resolution provides significant radiographic detail, some measurements of the dynamic properties of materials required improved resolution. In order to meet these new needs a new magnetic lens system, which is described here, has been designed and commissioned.

II. General description of proton radiography lens systems

While the introduction of a magnetic lens system improves the resolution of the proton radiography system by more than two orders of magnitude, it also introduces the next level of the limiting resolution: chromatic aberrations. Analogous to light optics, magnetic lens systems introduce chromatic aberrations unless properly corrected, which is very difficult and expensive for 800 MeV proton lens systems. Because of the difficulty in correcting these chromatic aberrations in 800 MeV proton lens systems, these aberrations are only partially corrected in the lens systems described here.

In the first order matrix notation for charged particle beam optics, such as Transport notation [6], the definition of a point-to-point focus is provided by the matrix shown in equation 1, where $x_o$ and $\theta_o$ is the proton horizontal position and angle at the object location, $x_i$ and $\theta_i$ are the horizontal position and angle at the image location, $m$ is the magnification of the lens system and
M21 is a constant nearly irrelevant to the radiographic performance of the lens system. An equivalent matrix describes the transport of protons in the vertical plane. The zero in the (1,2) element of the matrix satisfies the point-to-point focus requirement of the lens system, removing the resolution degradation from proton scattering within the object.

\[
\begin{bmatrix}
  x_i \\
  \theta_i \\
\end{bmatrix} =
\begin{bmatrix}
  -m & 0 \\
  M_{21} & -\frac{1}{m} \\
\end{bmatrix}
\begin{bmatrix}
  x_o \\
  \theta_o \\
\end{bmatrix}
\]  \hspace{1cm} (1)

The second order chromatic corrections to the position of the proton at the image location are shown in equation 2, again in Transport notation, where \( \delta \) is the fractional momentum deviation from the central momentum.

\[
x_i = -mx_o + T_{116}x_o \delta + T_{126} \theta_o \delta
\]  \hspace{1cm} (2)

These second order corrections can be cancelled by preparing the proton beam to have a specific position-angle correlation at the entrance to the object. With a perfect position-angle correlation, as defined in Equation 3, the \( T_{116} \) term can be completely cancelled by the \( T_{126} \) term. Preparing the beam to have the proper position angle correlation to cancel the second order chromatics has been termed “matching” of the proton beam to the imaging lens.

\[
x_o = -\frac{T_{126}}{T_{116}} \theta_o
\]  \hspace{1cm} (3)
The finite emittance of the proton beam as well as scattering within the object prohibits achieving a perfect position-angle correlation, resulting in an angular spread away from the matched position-angle correlation. With \( \phi \) being the angular deviation from the ideal position-angle correlation, Equation 3 is modified resulting in Equation 4.

\[
x_o = \frac{-T_{126}}{T_{116}} \theta_o + \phi
\]  

(4)

With this position-angle correlation the deviation due to second order chromatic aberrations of the proton position at the image location relative to the proton position at the object location is shown in Equation 5, where the second order corrections have been translated to the object plane by dividing by the magnification of the system.

\[
\partial x_i = \frac{T_{126} \theta \delta}{m}
\]  

(5)

The resolution degradation from second order chromatic aberrations, therefore, becomes proportional to \( T_{126}/m \) (also called the chromatic length of the lens system), the angular spread of the accepted beam, \( \theta \), and the energy deviation, \( \delta \), away from the central trajectory. For most objects and proton radiography lens systems this becomes the fundamental limit to the resolution of the radiography system. An analogous set of equations apply to the vertical resolution of these lens systems.
As the protons pass through the object they not only undergo multiple Coulomb scattering, but lose energy through ionization. This results in a dependence of the proton energy on object thickness. The magnetic lens systems can be optimized to focus nearly any central energy, but only one proton energy is in focus for a given dynamic experiment. Therefore, the resolution dependence on energy results in a spatial variation of the resolution for an object that is not of uniform thickness as well as a temporal variation of the resolution as the object thickness evolves in time. In order to minimize these effects it is desirable to design magnetic imaging systems with the smallest chromatic length \((T_{126}/m)\) as possible.

III. Magnifying lens design

A new magnetic lens system was designed following a similar philosophy developed for the design of a first generation magnifier lens system [7]. This new system, however, was designed to function with the existing proton radiography system, which imposed some physical constraints on the new imaging system. Dynamic experiments are performed within a confinement vessel, which is \(\sim2\,\text{m}\) in diameter, restricting the minimum distance from the object to first magnet to greater than 1 m. In addition, this system was designed to be interchangeable with the existing magnetic lens system, which is 9.38 m long from object to image location, constraining the length of the new system. Permanent magnet quadrupoles were chosen for the imaging optical elements for operational simplicity and cost considerations.

With these restrictions, design options were studied to minimize the chromatic length of the new lens system. This optimization revealed that the chromatic length of the lens system was minimized at the highest magnification possible. The highest magnification is achieved by
minimizing the object to first magnet distance and maximizing the field gradient in the quadrupole focusing magnets. With 16-segment Halbach [8] permanent magnet quadrupoles, made from the highest remanence permanent magnet material practical: samarium-cobalt, the only option for increasing the field gradient is to reduce the bore of the magnets. Reducing the bore of the magnets resulted in limiting the angular acceptance and the field of view of the radiography lens system. The typical experiment performed with 800 MeV proton radiography at LANL requires ~10 mrad of angular acceptance over a 30 mm field of view. An iterative optimization procedure was performed to maintain an angular acceptance of ~10 mrad over a 30 mm field of view while simultaneously minimizing the horizontal and vertical chromatic lengths of the lens system. The result of this optimization resulted in permanent magnet quadrupoles with a 10.16 cm inner aperture. The resulting angular acceptance as a function of radial position of the optimized lens system is shown in figure 3.

The optimization process described above resulted in the lens configuration described in table 1. Horizontal trajectories of the protons passing through the lens system are shown in figure 1, where the proton trajectories begin at the object location and end at the image location, originating on a regular grid filling the field of view and the angular acceptance around the matched proton trajectories.
Table I: Parameters of the optimized lens system where \( L_1 \text{ to } 4 \) are the magnet separation distances, the integral of \( g \, dl \) is the integral of the quadrupole field gradient along the length of the magnet axis, \( M \) is the magnification factor, \( T_{126} \) and \( T_{346} \) are the second order chromatic terms in TRANSPORT notation, \( m_x \) and \( m_y \) are the matched beam correlation between position and angle of the incident proton beam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_1 )</td>
<td>1.45 m</td>
<td>( M )</td>
<td>2.65</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>0.59 m</td>
<td>( T_{126}/M )</td>
<td>4.55 m</td>
</tr>
<tr>
<td>( L_3 )</td>
<td>0.85 m</td>
<td>( T_{346}/M )</td>
<td>3.54 m</td>
</tr>
<tr>
<td>( L_4 )</td>
<td>5.91 m</td>
<td>( m_x )</td>
<td>-0.29 m/rad</td>
</tr>
<tr>
<td>( \int g , dl )</td>
<td>3.44 T m</td>
<td>( m_y )</td>
<td>-0.43 m/rad</td>
</tr>
</tbody>
</table>

The proton trajectories shown in figure 1 pass through a plane, near the front surface of the third magnet, where the protons are radially sorted by the scattering angle introduced at the object location. A collimator located at this position, fabricated from 10 cm of tungsten, is used to remove protons scattered to large angles at the object location, while letting pass the on-axis protons; generating contrast in the proton radiography images. Although 10 cm of tungsten is not sufficient to stop the protons, the nuclear scattering and the multiple Coulomb scattering within the collimator removes more than 99% of the protons from the angular acceptance of the remaining lens elements. By adjusting the aperture of the tungsten collimator the image contrast can be optimized for each measurement.
In order to form a magnifying imaging lens from four quadrupole magnets in a Russian quadruplet configuration [9], the beam optics requires that the inner two magnets be larger than the first and last quadrupole magnets. In this system the inner magnets where chosen to have twice the integrated field gradient as the outer magnets. This is not the ideal relative length of the inner magnets for optimization of chromatic length, but this is very close to the optimized relative length and provides many practical benefits; such as requiring only one quadrupole magnet design. Through the fabrication of six of these magnet segments the inner two magnets can each be formed from the coupling of two of these magnet sections. This configuration resulted in the field gradient along the magnifier axis shown in figure 2. The quadrupole gradients alternate polarity, as shown in figure 2, and the dip in the inner quadrupole fields is due to a small gap which was required in order to mechanically couple the two magnet segments together to form the inner two magnets.

Objects of various thickness are radiographed with this same magnifier system. Therefore, the lens must be adjusted to focus various energies of protons exiting the object. Lens systems which are fabricated from electromagnetic quadrupoles typically adjust the field gradient of the fixed quadrupole positions. In this case, because permanent magnet quadrupoles are used, the magnetic field gradient is fixed and the positions of the magnets are adjusted to focus the lens. In the system described here the first quadrupole magnet position is fixed and the three downstream magnet positions are adjusted to focus the lens. Beam optics calculations shows that the magnets focus lower energy protons by decreasing the space between each magnet by the same amount (~7 mm per 10 MeV lower than 800 MeV). Therefore, the lens system was designed with a lowest possible focus energy, where the quadrupole magnets begin to collide.
The suite of planned experiments required focusing down to \(~720\) MeV protons as the lowest possible focused energy. This requirement primarily places limits on the integrated field gradient of the quadrupole magnets and results in limiting the resolution of the system.

IV. Results

The limiting resolution of this system was measured through the collection of a radiograph of an edge transition. In this measurement a 3 mm thick tungsten plate was aligned perpendicular to the proton beam in the center of the field of view. The contrast generated by a 10 mrad collimator was used to measure the horizontal and vertical edge transition. A storage phosphor, scanned with a 600 dpi scanner, was used to collect the static image. With the assumption of a Gaussian line spread function, which results in an error functional form for the edge spread function, the edge transition was fit by adjusting the independent horizontal and vertical RMS widths of the edge transition. The results of this fit are shown in figure 3 with the best fit RMS widths of \(\sigma_x=53\ \mu\text{m}\) and \(\sigma_y=63\ \mu\text{m}\) at the object location. With the storage phosphor image scanned with 600 dpi the effective pixel size at the image location is 42 \(\mu\text{m}\). The effective pixel size at the object location is 16 \(\mu\text{m}\), after correcting for the 2.7 magnification factor from the image plane to the object plane. The resolution introduced by the pixel size of the scanned image is therefore an insignificant contribution to the resolution measurement at the image location.

In addition to spatial resolution, the density resolution of the system was studied through transmission measurements through step wedges of known thickness. The radiographs were normalized to transmission images by dividing by an image containing the measured incident
beam distribution. The transmission through each step was measured for comparison to a simple model of 800 MeV proton radiography transmission. In this simple model a two step proton removal process is assumed. In the first step protons are removed through nuclear interactions within the object. In the second removal process multiple Coulomb scattering within the object results in a transverse spread of the protons at the collimator location. Protons scattered to angles larger than the collimator acceptance are removed, while the remainder of the protons are passed to form the image at the focal plane of the magnetic lens system. The removal process due to nuclear interactions can be modeled as an exponential removal process as shown in equation 6, where \( \rho \) is the areal density of the object being radiographed and \( l_i \) is the nuclear interaction length [10].

\[
T_n = e^{-\rho/l_i} \tag{6}
\]

The effect of the second removal process can be estimated from the calculation of the RMS width of the proton angular distribution introduced by multiple Coloumb scattering within the object to be radiographed. The description of this estimate is shown in equation 7 [10], where \( p \) is the proton beam momentum, \( \beta \) is the relativistic velocity and \( X_o \) is the radiation length in the material to be radiographed.

\[
\theta_o = \frac{14.1}{p \beta} \left( \frac{\rho}{X_o} \right)^{1/2} \tag{7}
\]

The imaging lens system is designed such that the angular distribution of scattering within the object is mapped to position at a location upstream of the third magnet in the magnifying lens. A collimator at this location intercepts protons that have been scattered to large angles and allows unscattered protons to pass and form the image at the focal plane of the lens system. The transmission of protons from this process is shown in equation 8, where \( \phi \) is the angular spread.
of the beam at the entrance to the object and $\theta_c$ is the angular cut of the collimator in the imaging lens system.

\[
T_c = 1 - e^{-\frac{1}{2} \left( \frac{\theta^* + \Phi^*}{\theta_c^*} \right)}
\]  \hspace{1cm} (8)

The net transmission through the object and the radiography system is given by the product of the two transmissions described in equation 6 and equation 8 as shown in equation 9.

\[
T_c = e^{-\frac{\theta^*}{\theta_c^*}} \left( 1 - e^{-\frac{1}{2} \left( \frac{\theta^* + \Phi^*}{\theta_c^*} \right)} \right)
\]  \hspace{1cm} (9)

The transmission of an iron step wedge, with wedge thicknesses of 5.53 mm, 10 mm, 30 mm and 50 mm, was measured and compared to the predictions by the simple model described above. The results are shown in Figure 5. The agreement between the measured and predicted transmission demonstrate that this magnifying lens system is functioning as designed, providing density measurements with an accuracy of a few percent.

V. Conclusions

The results of commissioning the magnifier system described here has demonstrated significant improvement in radiographic resolution with no degradation in density resolution and this system is now being used as to radiograph more than half of the experiments performed in the LANL proton radiography program. The new imaging lens system has demonstrated a factor of three improvement in limiting radiographic resolution as well as a factor of three reduction in chromatic length, reducing the artifacts introduced through second order chromatic aberrations.

Acknowledgments

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dedication ensures the productivity of the proton radiography project and LANSCE. LANL is operated by LANS, LLC, under DOE/NNSA contract DE-AC52-06NA25396.
VI. References


Figure 1: Horizontal trajectories of protons traveling through the magnifier system. The vertical scale has been expanded by a factor of 22 for display purposes. The lengths shown here are provided in Table I along with the other key design parameters of the imaging system.
Figure 2: Pole tip field strength along the axis of the magnifier system. The magnet polarities alternate between magnets and the inner two magnets are made by combining two magnet segments. A small gap between magnet segments, which is required to couple the two segments, results in the slight drop in the magnetic field.
Figure 3: The horizontal and vertical angular acceptance of the lens system was required to provide 10 mrad of angular acceptance to a radius of 30 mm. This figure shows the horizontal and vertical angular acceptance as a function of position.
Figure 4: Error function fits to the horizontal (a) and vertical (b) edge spread functions resulting in a Gaussian line spread function with an RMS width of $\sigma_x=53$ $\mu$m and $\sigma_y=63$ $\mu$m.
Figure 5: Measured transmission as a function of areal density of iron with a curve overlaid, which was generated from the model shown in equation 9.