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Proton Microscopy at GSI and FAIR

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Abstract. Proton radiography was invented in the 1990's at Los Alamos National Laboratory (LANL) as a diagnostic to study dynamic material properties under extreme pressures, strain and strain rate. Since this time hundreds of dynamic proton radiography experiments have been performed at LANL and facilities have been commissioned at the Institute for Theoretical and Experimental Physics (ITEP) in Russia for similar applications in dynamic material studies. Recently an international collaboration was formed to develop a new proton radiography capability for the study of dynamic material properties at the Facility for Anti-proton and Ion Research (FAIR) located at Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany. This new Proton microscope for FAIR (PRIOR) will provide radiographic imaging of dynamic systems with unprecedented spatial, temporal and density resolution, resulting in a window for understanding dynamic material properties at new length scales. These dynamic experiments will be driven with many energy sources including heavy ions, high explosives and lasers. The design of the proton microscope and expected radiographic performance is presented.

Keywords: proton radiography, flash radiography, dynamic imaging.
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INTRODUCTION

Using high energy protons for radiography was first considered in 1946 [1] with the advent of high energy proton accelerators. The first proton radiograph was not published until 1968 [2], concluding that protons were a nice radiographic probe for relatively thick objects, but that multiple Coulomb scattering within the object limited the spatial resolution of the radiographs. Studies of proton radiography continued at high energy proton accelerators around the world in the 1970's [3]. However, because of the electric charge of the protons multiple Coulomb scattering (MCS) within the object continued to result in substantial resolution degradation and the technique was slowly dropped by the community.

In the 1990s LANL initiated an effort to use 800 MeV protons as probes for flash radiography to study fast dynamically evolving objects for material science research [4]. The breakthrough which overcame the previous resolution limitations of proton radiography was the introduction of a magnetic focusing lens downstream of the object. This magnetic focusing lens collects the protons at the exit of the object and transports them to an image location located many meters downstream. This lens system was designed to form the proton image independent of the scattering of the protons within the object being radiographed, overcoming the MCS blur limmitation.

Since 1990 LANL has developed the technique of proton radiography, using 800 MeV protons at LANSCE to study the evolution of hundreds of dynamic systems. In the course of this development multiple magnetic imaging lens systems have been studied to improve radiographic resolution. More recently the ITEP has commissioned an 800 MeV proton radiography capability in Moscow, using a proton beam from the terawatt accumulator synchrotron, also for applications in dynamic materials science.

In collaboration with GSI scientists, teams from LANL and ITEP have designed a proton microscope to use 4500 MeV protons from the SIS-18 synchrotron at GSI. The goal for this new system is to provide a high resolution flash radiography capability for the study of dynamic materials science.

IMAGING LENS DESIGN

Proton radiography uses a magnetic lens system to form an image where a scintillator converts the proton distribution to a light distribution. This light is then collected with fast gated cameras. The performance of the magnetic lens system plays a significant role in the fundamental performance of the radiography system.

TRANSPORT notation [5] can be used to describe the propagation of protons through the magnetic lens system. In this matrix formalism the first order beam optics for motion in the horizontal plane can be written as shown in Eq. 1, where the index i denotes proton position and angle, x and x', at the image location and the index o denotes the position and angle at the object location. A similar equation can be written for the vertical plane.

$$\begin{bmatrix} x_i \\ x_i' \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} x_o \\ x_o' \end{bmatrix} \qquad (1)$$

The requirement for this lens to form a point-to-point image, independent of the scattering angle within the object, the R_{12} matrix element must be zero. Since all transport matrices must have a determinant of 1, the R matrix for a proton radiography imaging lens must be in the form shown in equation 2, where M is the magnification factor of the imaging lens system. Again, a similar relation exists in the vertical plane.

$$\begin{bmatrix} x_i \\ x_i' \end{bmatrix} = \begin{bmatrix} M & 0 \\ R_{21} & \frac{1}{M} \end{bmatrix} \begin{bmatrix} x_o \\ x_o' \end{bmatrix} \qquad (2)$$

Because the proton trajectory through the magnetic field of the imaging lens is dependent on the proton momentum, the R_{12} matrix element can only be zero for one proton momentum.

Deviations from this "focused" proton momentum result in chromatic effects, which require second order beam optics to quantify. The second order corrections due to chromatic beam optics is shown in eq. 3, where T is the tensor description in TRANSPORT notation and δ is the fractional deviation of the proton momentum from the focused momentum.

$$\begin{aligned} x_i &= M x_o + T_{116} x_o \delta + T_{126} x_o' \delta \\ T_{116} &= \frac{\partial R_{11}}{\partial \delta} \\ T_{126} &= \frac{\partial R_{12}}{\partial \delta} \end{aligned} \qquad (3)$$

Chromatic Matching

Chromatic aberrations typically limit the resolution of proton radiography systems. Therefore, the beam is prepared to cancel as much of the second order chromatic aberrations as possible [6]. To this end the beam is "matched" into the radiography. For proper matching the protons are prepared with a position-angle correlation designed to maximally cancel the chromatic aberrations. The position angle correlation at the object location can be written as shown in eq. 4.

$$x_o' = m_x x_o \qquad (4)$$

Substituting this into the equation for the proton position at the image location, we can determine the correlation parameter, or matching condition, which results in maximal cancelation. This is shown in eq. 5, where ϕ is the proton scattering angle away from the initial trajectory from interactions of the proton within the object.

$$x_i = Mx_o + (T_{116} + m_x T_{126})x_o\delta + T_{126}\phi\delta \quad (5)$$

By choosing the matching correlation to be $m_x=-T_{116}/T_{126}$, the first second-order correction in eq. 5 can be cancelled leaving only the $T_{126}\phi\delta$ term. This remaining second order correction to the beam optics results in symmetric image blur.

Eq. 7 shows the second order chromatic blur to a purely magnified image for properly matched beam. This equation can be used to estimate the resolution of a radiography system with angular acceptance θ_A.

$$x_i - \frac{x_o}{M} = \frac{T_{126}\theta_A\delta}{M} \quad (7)$$

The proton beam must also be matched in the vertical plane resulting in a nearly identical set of equations. With a matching correlation in the vertical plane of $m_y=-T_{336}/T_{346}$ the vertical resolution can then be estimated using eq. 8.

$$y_i - \frac{y_o}{M} = \frac{T_{346}\theta_A\delta}{M} \quad (8)$$

Parameters of the Proton Microscope

A 4.5 GeV proton microscope designed for applications at GSI and FAIR must meet some physical requirements: the objects to be radiographed will require a 15 mm x 15 mm field of view, the total length of the system must fit within the 10 m length of an existing experimental hall and the first magnet must be more than one meter downstream of the object location to accommodate a confinement vessel.

Previous lens design has demonstrated that resolution improves with increasing magnification [7]. With the 10 m length limitation the magnification is then limited by the field strength of the quadrupole magnets. Higher quadrupole gradients provide larger magnification, resulting in a higher resolution imaging lens system. Halbach style permanent magnet quadrupoles (PMQs) were chosen to provide the highest quadrupole gradient, g, achievable with non-superconducting magnets.

With these constraints the proton microscope lens system was designed to minimize T_{126}/M and T_{346}/M, the values which determine the resolution degradation from second order chromatic effects.

Table 1 shows the resulting parameters of the proton microscope which has been designed to meet these criteria. Fig. 1 shows the proton trajectories in the horizontal plane through the proton microscope design.

TABLE 1. Parameters of the proton microscope design.

Parameter	Value	Parameter	Value
L_1	1.300 m	M	4.1
L_2	0.307 m	T_{126}/M	4.68 m
L_3	0.515 m	T_{346}/M	4.00 m
L_4	7.576 m	m_x	-0.45 rad/m
Aperture	3.00 cm	m_y	-0.55 rad/m
g (gradient)	115 T/m	θ_A	0.005 rad

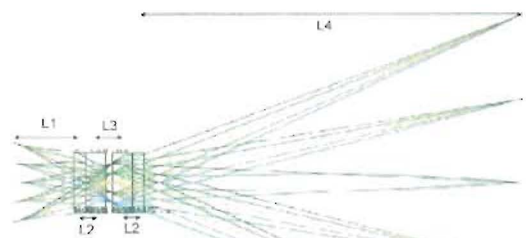

Figure 1. Proton trajectories through the proton microscope designed for applications at GSI and FAIR. Protons trajectories are started at the object location, with the ideal matching correlation, pass through the four PMQs to form an image at the image location, where the protor trajectories end. The nomenclature for the distances described in table 1 are shown.

Spatial Resolution Performance

From Eq. 7 and 8, the values shown in table 1 and the fractional energy spread of the SIS-18 proton beam, δ=0.05%, the resolution can be estimated for this microscope This estimate results in 12 μm in the horizontal plane and 10 μm in the vertical plane.

Temporal Resolution Performance

The temporal resolution of the radiography system is dominated by the time structure of the SIS-18 beam as well as the camera systems that will be used to collect the radiographic images. The SIS-18 synchrotron has a ~1 μs transit time around the ring for 4.5 GeV beam. Four evenly spaced bunches, each containing ~2.5×10^9 protons are stored in the ring. Each bunch has a ~100 ns RMS width and these bunches are sequentially extracted to provide four radiographs per dynamic event, each separated by 250 ns.

To study very fast processes exposure times may be reduced. This will be accomplished with fast gated cameras capable of ~10ns exposures, at the expense of proton statistics.

Transmission Estimates

The proton transmission through the object and imaging lens is also an important characteristic. From estimates of transmission as a function of object thickness one can estimate image contrast for features of interest within the object. This relationship is easily estimated through Eq. 9, where T is the fractional transmission of the protons, x is the thickness of the object, λ_c is the nuclear collision length [8] and θ_0 is the MCS within the object.

$$T = e^{-\frac{x}{\lambda_c}}\left(1 - e^{-\frac{\theta^2_A}{2\theta^2_o}}\right) \qquad (9)$$

The MCS within the object can be estimate by equation 10 [8], where X_o is the radiation length [8] of the object materials.

$$\theta_o = 0.0258\sqrt{\frac{x}{X_o}}\left[1 + 0.038\ln\left(\frac{x}{X_o}\right)\right] \qquad (10)$$

The best density resolution is achieved when the proton transmission is at ~30%, (e.g. 4.8 cm of iron). Objects with transmission less that 10% or greater than 90% will result in radiographs more difficult to extract densities. The angular acceptance of the lens system can be adjusted to increase contrast for thinner objects.

CONCLUSIONS

A proton microscope has been designed to use 4.5 GeV protons for dynamic materials science at GSI and FAIR. This proton microscope should provide ~10 μm resolution over a 15 mm field of view through objects <50 g/cm^2. Each dynamic event will be viewed at four times with 250 ns between frames.

This new window into dynamic materials science will be used to investigate the dynamic properties of materials driven by high explosives, lasers, pulsed power as well as heavy ions delivered by the new heavy ion synchrotron that is being built as part of the FAIR project.

The high resolution radiography combined with the multiple drivers will provide a unique facility for the study of dynamic material science in the areas of material strength, equation of state, phase transitions and warm dense matter.

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