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Author(s): Frank Merrill

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Form 836 (7/06)

PRIOR Magnifier Design

Introduction

The primary constraints which drive the design of the imaging lens system are the performance goals for the field of view, spatial resolution, density range and density resolution in combination with the proton beam energy to be used for the radiography. The design described here has been developed to utilize 4500 MeV protons delivered by the SIS-18 synchrotron. This proton radiography system will be imaging objects with areal density of 1-20 g/cm^2 and capable of better than 10 μm resolution over a 15 mm field of view. A confinement vessel will be utilized to confine the products of dynamic experiments. The space required by this vessel system imposes additional requirements on the lens system as well as the available floor space in the HHT experimental area.

Quadrupole Magnets

Proton radiography systems are designed utilizing quadrupole magnets as focusing elements. The most cost effective quadrupole technology for both fabrication and operation costs are permanent magnet quadrupoles. Therefore, this design is based on quadrupoles constructed from rare earth permanent magnet material. In this baseline design we have assumed the traditional 16-segmented permanent magnet quadrupole design shown in figure 1. In this design each segment is magnetized along a different axis and when assembled generate a quadrupole field essentially free of higher order multipoles. The magnet shown in figure 1 has an inner aperture of 30 mm, an outer aperture of 100 mm and is 165 mm long. The field distribution from this magnet is shown in figure 2.

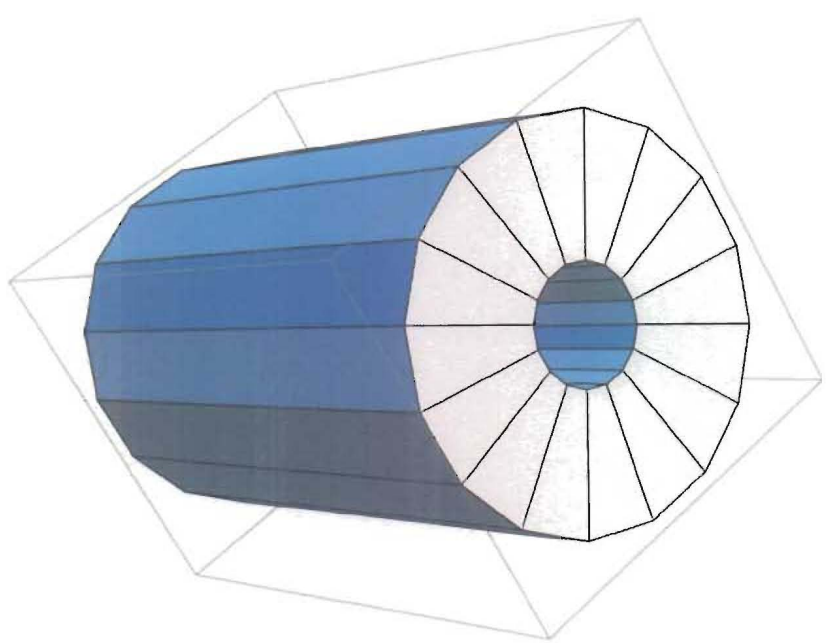

Figure 1: Schematic layout of permanent magnet material to form a 16-segment permanent magnet quadrupole.

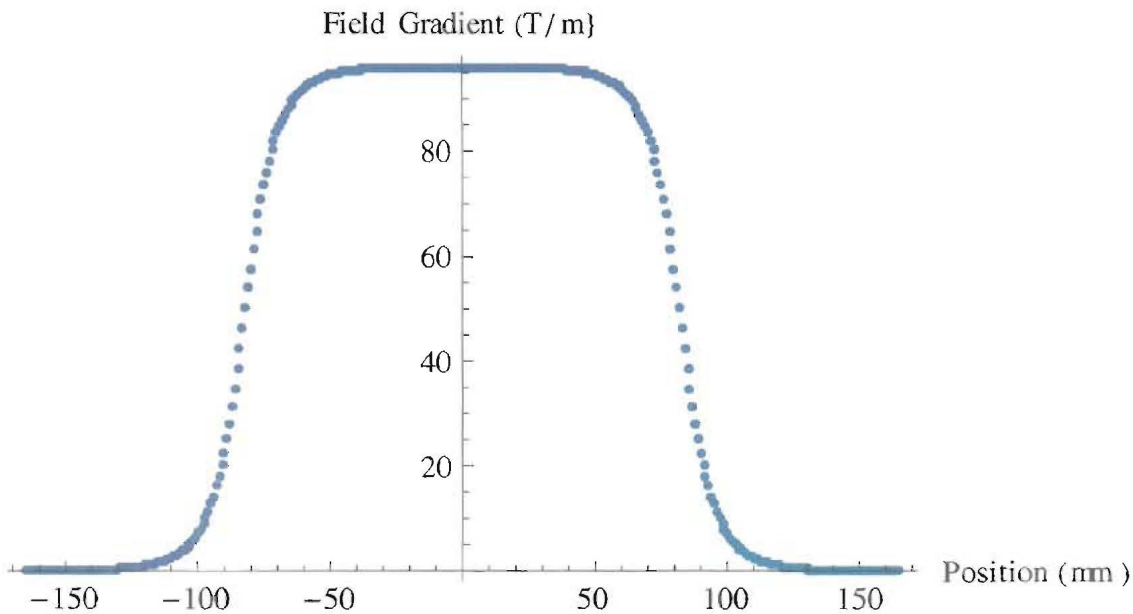

Figure 2: Field gradient (T/m) as a function of axial position inside the quadrupole shown in figure 1.

Since the magnets will need to operate in a potentially high radiation fields, the most radiation resistant rare earth permanent magnet material, samarium cobalt, was assumed in this design. Sumarium cobalt permanent magnet material has a maximum achievable remnant field of 1.1 Tesla. For a given aperture this remnant field determines the maximum field gradient achievable in a 16-segment quadrupole, described above. This maximum remnant field was assumed in the calculation of field gradient shown in figure 2 and this maximum field gradient was assumed in all design calculations described below.

These magnets have significant fringe fields and in the design calculations described below the magnets were forced to be separated by twice the aperture diameter to minimize the fringe field cancellation of neighboring opposite polarity quadrupoles as well as minimizing the foces between neighboring quads. Figure 3 shows the resulting magnetic field distribution in the baseline design.

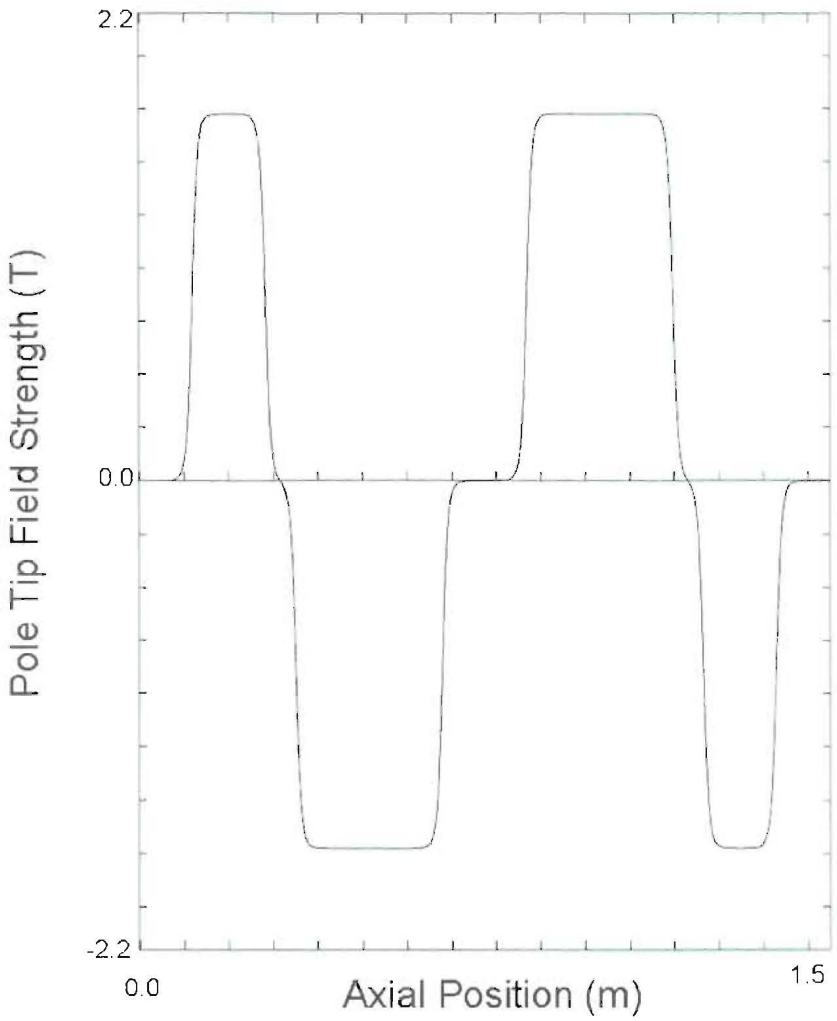

Figure 3: Bole tip field strength along the axis of the magnifier system. The magnet separation was fixed to minimize fringe field cancellation as well as minimizing forces between neighboring magnets.

Optical Layout

Given the field gradients achievable with the magnet design shown above, the magnets must be positioned to form an imaging system in the floor space available for the lens design. In HHT the maximum length of the magnifier system is ~10 m. Since all performance characteristics improve with the length of the lens system all design studies were performed assuming the maximum available length of 10 m. The magnets must then be placed to form and image in the 10 meters between the object location and the image location. The COSY Infinity beam dynamics simulation code was used to adjust the position of the quads to form this imaging lens.

In practice, when imaging thick objects, the proton beam will lose energy as it passes through the object and the magnets will need to be moved closer together in order to form this imaging lens. Therefore, the maximum energy loss or maximum object

thickness is an important design constraint. Very thick objects will not be properly focused because the magnets will not be able to be moved close enough to focus at the very low energies.

In this design we choose a maximum energy loss of 100 MeV. This is anticipated to be a much larger energy loss than expected through the maximum thickness object to be imaged. Therefore, the length of the quadrupoles were chosen to focus the 4400 MeV protons on 10 meters. The length of the quadrupoles were then fixed and their positions were allowed to vary in order to focus 4500 MeV protons in the same 10 meters. Since the magnets must be separated further to focus at higher energies, this ensures that the lens system can be focused for objects ranging in energy loss of 0-100 MeV.

Table 1 shows the key parameters determined in this design process. Figure 3 defines the parameters which are given in table 1.

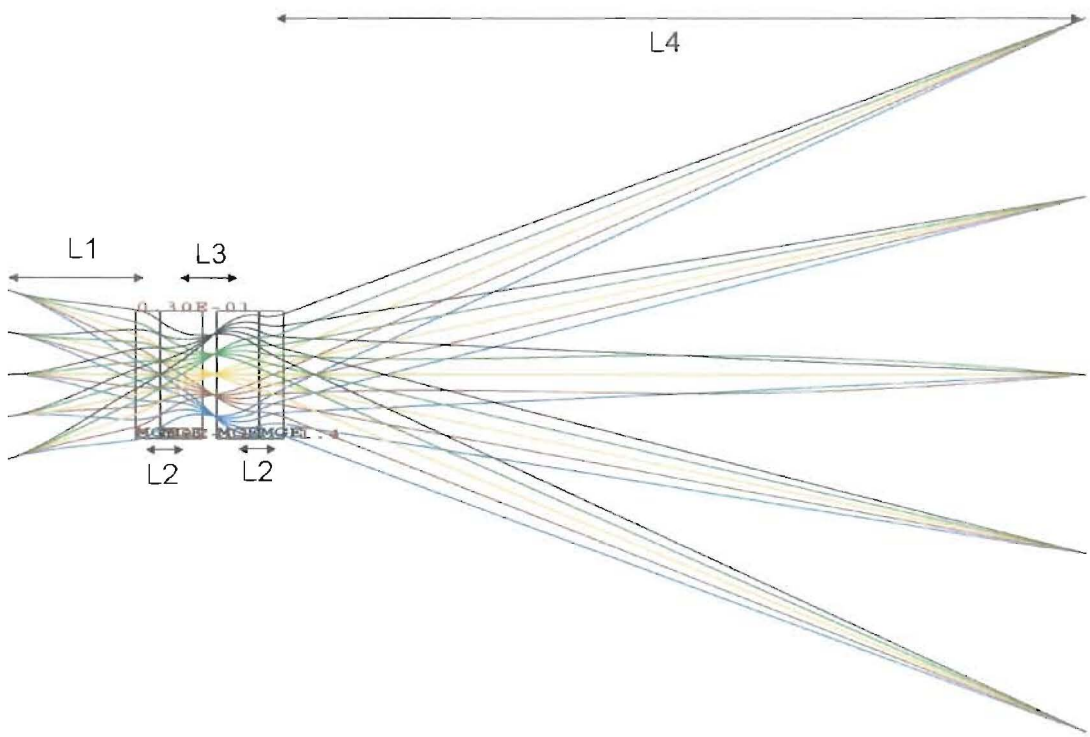

Figure 4: Magnet layout which defines the parameters in Table 1. The colored lines are the proton trajectories through the magnifier system.

Performance

The performance characteristics are summarized in table 2. The main performance characteristics, described in the introduction, are the field of view, the spatial resolution, the maximum object thickness and the density resolution. These performance characteristics are critically dependent on the lens parameters.

Parameter	Value
Beam energy	4.5 GeV/c^2
Inner aperture D_i	30 mm
Out aperture D_o	100 m
B_p "pole tip" field	1.1 T
Gradient	115 T/m
"short" quad length	165 mm
"Long" quad length	330 mm
L_1 (object to first quad)	1.3 m
L_2 (first to second)	0.307 m
L3 (second to third)	0.515 m
L4 (last quad to image)	7.576 m
Total length	10.000 m

Table 1: Parameters of baseline PRIOR magnifier design.

Angular Acceptance

The angular acceptance of the lens system is determined by the aperture of the quadrupoles. In the design presented here the horizontal limit is at the entrance to the first quadrupole while the vertical limit is at the exit of the fourth quadrupole. Of course, the angular acceptance of the magnifier is dependent on transverse position at the object location. Figure 4 shows this dependence in the horizontal and vertical planes.

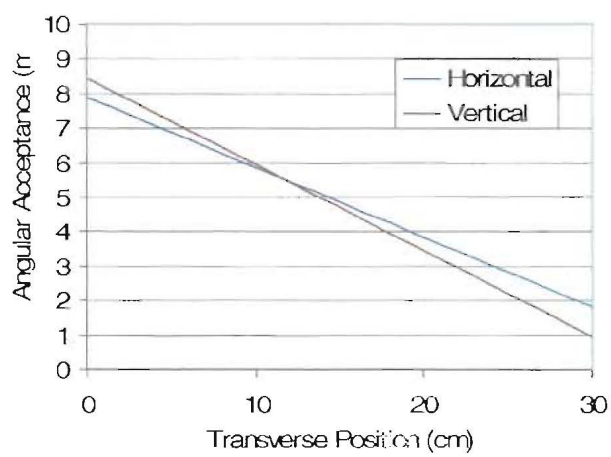

Figure 5: Angular acceptance of the magnifier system as a function of transverse position at the object location for both the horizontal and vertical direction.

Spatial Resolution

The limiting resolution for properly matched beam can be determined from the chromatic length of the lens system, the energy spread of the SIS-18 beam and the angular acceptance of the lens system. This chromatic length couples the energy spread of the beam to the spatial

Parameter	Value
Magnification	4.1
C_x horizontal Chromatic length	3.99 m
C_y vertical chromatic length	3.41 m
Angular Acceptance	5 mrad
M_x Horizontal Matching Correlation	-0.45 mrad/mm
M_y Horizontal Matching Correlation	-0.55 mrad/mm

Table 2: Performance parameters for the baseline PRIOR magnifier design.

resolution through the following relationship $\sigma = \delta\theta C$, where σ is the RMS of a Gaussian blur function, δ=∂E/E is the fractional energy deviation from the central trajectory, θ is the scattering angle of the proton beam in the object and C is the chromatic length. If we assume δ=∂E/E =5x10^{-4} and the angular acceptance of the lens is θ=0.005 radians, with a horizontal chromatic length of 4.0 m we would expect a Gaussian line spread function with an RMS of 10 microns. With a vertical chromatic length of 3.6 m we would expect a Guassian line spread function with an RMS width of 9 microns.

Density Reconstruction

When discussing the density reconstruction it is useful to define a figure of merit which is proportional to the statistical sensitivity of density measurement that has been inferred from a transmission measurement. The easiest figure of merit to form is essentially the signal to noise ratio per fractional change in object thickness. The signal is the reduction in transmission intensity and the noise is the statistical fluctuations in the transmitted beam. This figure of merit is shown in equation 1, where T is the transmission through the object, l is the object thickness and N_0 is the number of incident beam particles. In this formulation the figure of merit (FOM) provides the signal to noise ratio per fractional change in object thickness. For example, the curves shown in figure 6 show the FOM for 1 cm of tungsten (19 g/cm^2) and 0.1 cm of tungsten (1.9 g/cm^2) as a function of collimator cut angle. These two graphs show that given the magnifier angular acceptance of 5 mrad results in a density range of 0 to ~20 g/cm^2.

Equation 1

$$FOM = \frac{\Delta N / \sqrt{N_o}}{\Delta l / l} = l\sqrt{N_o}\,\frac{dT}{dl}$$

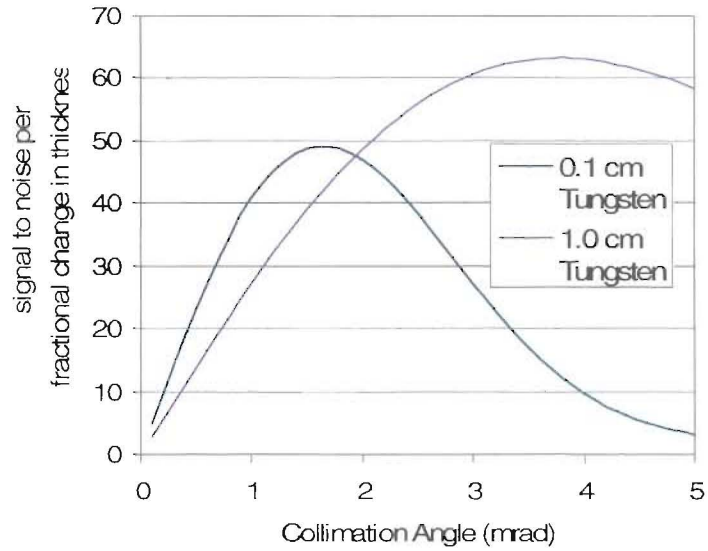

Figure 6: Figure of merit as a function of angular acceptance for 0.1 cm and 1.0 cm of tungsten.

Matching Condition

To cancel second order chromatic aberrations the beam must enter the object plane with a specified position-angle correlation, which are different in the horizontal and vertical planes. This position-angle correlation is given by $\theta_x = M_x x$ and $\theta_y = M_y y$ in the horizontal and vertical planes respectively. Where x and y are the horizontal and vertical position at the entrance to the object and θ_x and θ_y are the horizontal and vertical angle at the object location. M_x and M_y specify the correlation required for matching. This correlation, which cancels the first order chromatic aberrations, results in a Fourier plane, where the protons are radially sorted by scattering angle, just upstream of the third collimator, as can be seen in figure 4.