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GSI pRad Strawman Radiography Design and Showstopper Analysis

4/22/2009

Introduction

A straw man design has been developed for a proton radiography lens system to be fielded at GSI. This straw man design is intended to be starting point for the development of a real design, providing estimated performance characteristics as well as a basis for schedule and cost estimates. It is very likely that this design evolves substantially from this initial concept.

Magnets

I have assumed that the magnets will be fabricated from permanent magnet material. This is primarily a cost savings measure (a factor of 5-10 cost savings), but for small aperture quadrupoles permanent magnets are likely to provide a higher field gradient. The design and fabrication of custom electromagnets would most likely provide a more robust and easier operation at the expense of requiring cooling, power supplies and substantially more space.

Previous experience with building magnifier systems shows that the field of view is typically slightly larger than the half the diameter of the quadrupole aperture. Therefore, in order to meet the requirement of a 1 cm field of view we have chosen a quadrupole aperture of 1.6 cm diameter. Unfortunately, the resolution of the system is strongly driven by the quadrupole field gradient and, therefore, we trade field of view for resolution.

The "pole-tip" field of a permanent magnet is approximately $2*B_r*(1/R_i-1/R_o)/R_i$, where R_i is the inner radius of the permanent magnet material and R_o is the outer radius of the magnet materials and B_r is the remnant field of the magnet material. Based on existing permanent magnet quads that have been built, an inner radius of 0.8 cm with an outer radius of 2 cm seems like a reasonable quadrupole. With a remnant field of 1.2 T this magnet would provide a field of 1.4 T at the aperture, resulting in a 200 T/m quadrupole. This is a very high gradient quad and these approximations have not been vetted by experts. However, some magnets with these gradients have been built as an R&D effort for the PLEIADES inverse Compton X-ray source at UCLA and LLNL.

Physical Layout

With the quadrupole characteristics described above and the requirement that the first magnet be located ~ 1 m downstream of the object location, the remaining physical layout is established through the requirement that the magnets form an imaging lens. In addition the system has been optimized to provide the shortest imaging lens possible to fit in the HHT cave. With these constraints the magnifier parameters are shown in table 1.

Because of the fixed field nature of permanent magnet quadrupoles, the magnets will need to be moved in order to focus the lens system. This will require a motion control system with performance specifications that are easily achieved with commercial components.

A conceptual layout of the system is shown in the figures below. In this conceptual layout, we only show the region of the permanent magnet quadrupoles. A vacuum beam pipe would extend from what you see below to an image location located a ~7 meters downstream of the last quadrupole.

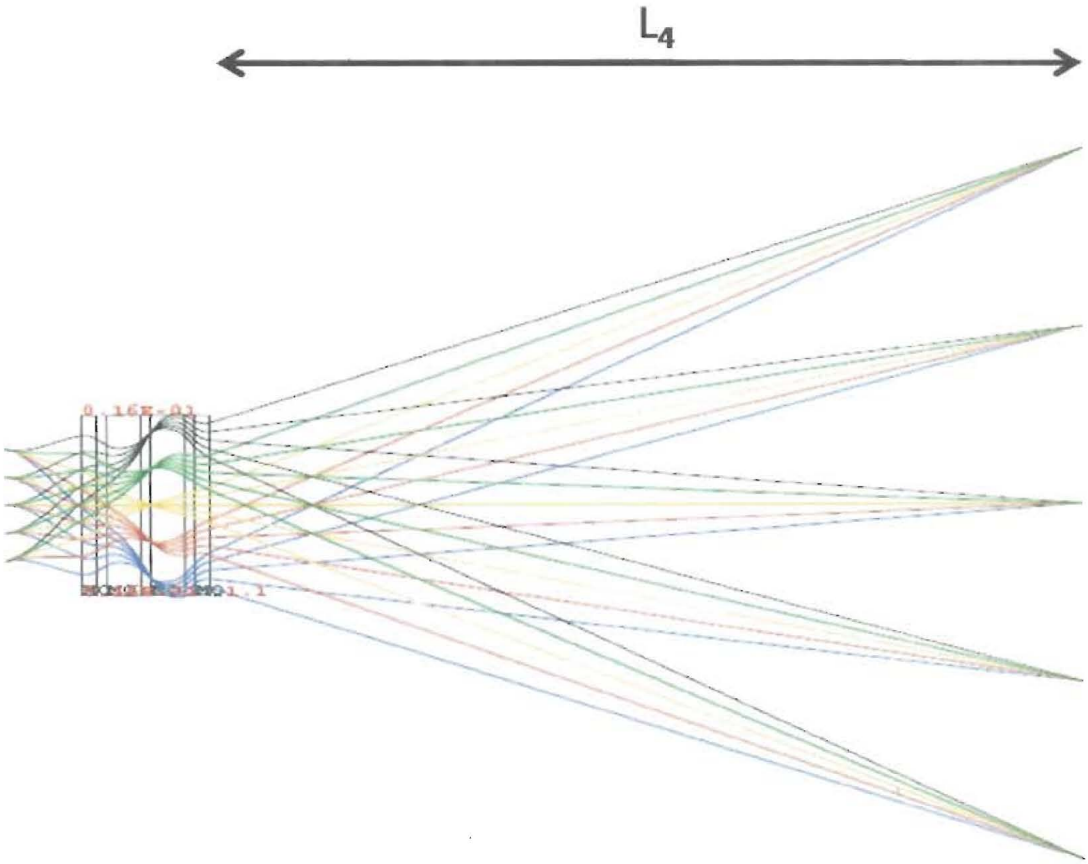
Also shown below are proton trajectories tracked through this straw man design.

Resolution

With the parameters described in table 1 this system has a chromatic length of 2.43 m and 1.89 m in the horizontal and vertical planes, respectively. This chromatic length couples the energy spread of the beam to spatial resolution through the following relationship $\sigma = \frac{\delta P}{P}\theta C$, where σ is the RMS of a Gaussian blur function, δP/P is the 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 $\delta P/P=5\times10^{-4}$ and the angular acceptance of the lens is θ=0.005 radians, with a horizontal chromatic length of 2.43 m we would expect a Gaussian line spread function with an RMS of 6 microns. With a vertical chromatic length of 1.89 we would expect a Guassian line spread function of 5 microns.

Camera Systems

With a 1 cm field of view and 5 micron RMS resolution the camera system will need 2kx2k pixels (4 megapixels) . This is available with conventional CCD cameras. In order to collect 2-4 frames, multiple CCD cameras will be required, and these cameras will need to be fast shuttered cameras. Typically the fast-gating scheme needs to be designed to not limit the radiographic resolution.


L_4

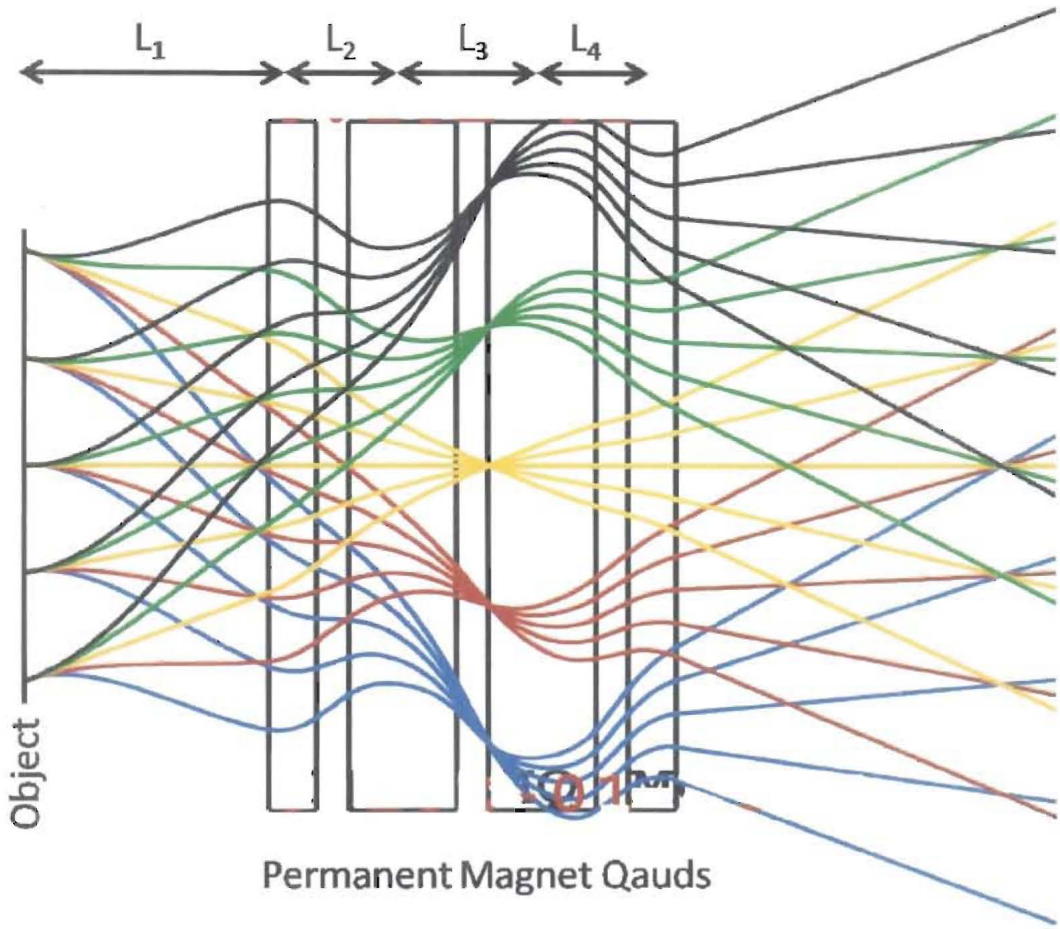
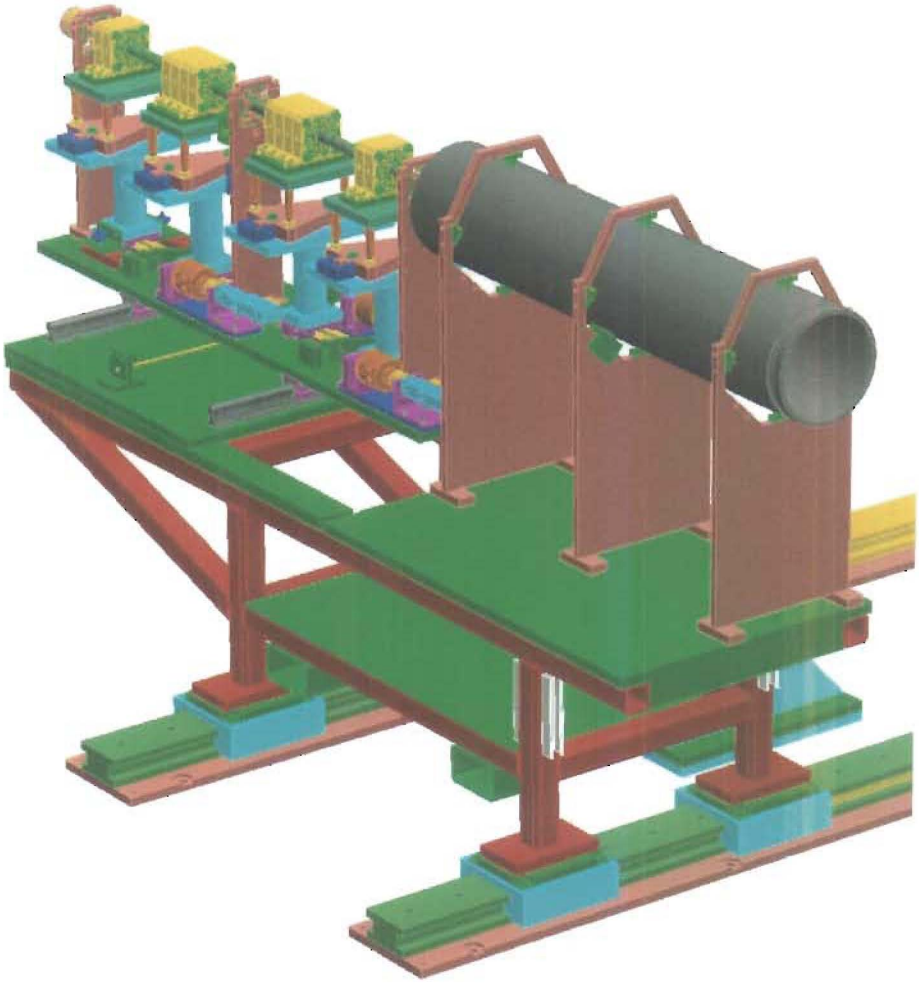

L1
L2
L3
L4
Object
Permanent Magnet Qauds

Table 1: parameters of straw man GSI magnifier design.

Parameter	Value
Beam energy	4.5 GeV/c^2
Inner aperture R_i	0.008 m
Out aperture R_o	0.020 m
B_p "pole tip" field	1.4 T
Gradient	200 T/m
"short" quad length	0.12 m
"Long" quad length	0.27 m
L_1 Object to first Qaud	0.7 m
L_2 (first to second and third to fourth quad spacing)	0.28 m
L3 (second to third quad spacing)	0.36 m
L4 (last quad to image)	7.38 m
Total length	9 m
Magnification	6.5
C_x horizontal Chromatic length	2.43 m
C_y vertical chromatic length	1.89 m
Angular Acceptance	5 mrad



Cost Estimate

Final design of the magnifier will take 4 months of a beam line physicist, 2 months of an engineer and 3 months of a designer . The stand, vacuum, alignment components and motion control system would be ~$75k at Los Alamos. It will take two technicians a month to assemble, install and align.

The magnets discussed here are very simple and small. Therefore the cost of magnet material is minimal. The major cost will lie in the design and tuning of these small quadrupoles. Also, this system could gain substantially through the development of very high gradient quadrupoles. There are some designs that exist that could be adopted for this effort. This would be an additional cost for procurement of these magnets. A rough guess for the cost of these magnets, designed and fabricated at a US company would be $100k.

A single fast gated camera system, similar to what we use with 800 MeV proton radiography, would cost $150k. Four frames will require four cameras mounted around a single scintillator for a total camera cost of $600k. A 7x7 cm LSO scintillator will be $5-10k and the mounting and optics will cost $15k.

Collimator

How short can a tungsten collimator for 4.5 GeV proton radiography? The proposal is for a 15 cm tungsten collimator. Back of the envelope estimates have been made of the extinction ratio for this length of a collimator. There are two contributors to the extinction ratio. First, nuclear interactions within the collimator can result in large angle scattering which remove the protons from the angular acceptance of the lens system. Second, small angle multiple Coulomb scattering coupled with energy loss can result in protons remaining in the angular acceptance of the lens system but being focuses severely (because of the lower energy), resulting in a trajectory which misses the scintillator at the image plane.

To accurately predict the extinction due to the nuclear interactions one should use a Monte Carlo such as GEANT which accurately track particles modeling the nuclear interactions. However, an estimate of the removal process can be made using the nuclear collision length. The nuclear collision length is the mean free path between any nuclear reaction of a high energy proton traversing the material. For tungsten the collision length is 110.4 g/cm^2. 15 cm of tungsten, which has a density of 19 g/cm^3, has a total areal density of 285 g/cm^2 will provide a removal of ~93% of the protons. This estimate assumes all nuclear interactions results in proton removal. A more conservative estimate would use the nuclear interaction length rather than the collision length. In this calculation the assumption becomes all inelastic nuclear interactions results in proton removal. The nuclear interaction length in tungsten is 185 g/cm^2, resulting in an estimate of 88% proton removal.

The removal process due to MCS and the magnetic lens system is a bit more difficult. 4.5 GeV protons traversing 15 cm of tungsten will lose approximately 350 MeV and will suffer 18 mrad of angular scatter due to multiple Coulomb interactions. Assuming a centered pencil beam impinging on a collimator located at the front edge of the third magnet in the magnifier, this scattering results in a Gaussian beam distribution at the image location with a width of 15 cm horizontally and 11 cm vertically (a simple Monte Carlo simulation which also keeps track of position shows a Gaussian width of 17 cm horizontally and 12 cm vertically) . If the scintillator is 6.5*0.5cm=3.25cm to cover the field of view, the total amount of beam reaching the scintillator is 4% or 96% removal process.

The combination of the two removal processes results in an estimate extinction ratio of <0.5% extinction ratio (0.04*0.07=0.003 to 0.04*0.12=.005). This 0.5% of the beam the would ideally be removed from the radiography will be uniformly distributed across the entire image. This is probably not a significant problem and 15 cm of tungsten is a reasonable collimator length.

In the strawman design the fourier plane for chromatically matched beam is located at 0.0969 m downstream of the second quadrupole. The relevant matrix elements from the object location to the collimator location is M12=1.30 m and M34=0.94 m. This means that a 5 mrad angular acceptance requires a collimator aperture with a horizontal aperture with a radius of 6.5 mm and a vertical aperture with a radius of 4.7 mm.

Rotational Alignment

Experience from commissioning our x3 magnifier highlighted the importance of rotational alignment. If we assume the leading distortion comes from the vertical angular coupling into the horizontal position the relationship becomes xi=M14y'. If I assume the maximum angular acceptance of the lens system if 5 mrad, then m14<<xres/0.005. If the resolution of the system is at the 5 micron level than M14<<1e-6m/.005=.0002 m. Atlernately, if I assume that the dominant term is from the vertical position coupling into the horizontal position, then xi=M13y or M13<<1e-6m/.005m=.0002 at the edge of the field of view. This will set the align specification for the rotational tolerance of the magnets. This requires M13 to be ~.01 mrad or 0.5 degrees.

We have generated an algorithm to empirically correct any rotational misalignment of the magnets. This requires that rotational adjustment be built into the alignment fixture for these magnets.