PORTABLE ELECTRON RADIOGRAPHY SYSTEM*

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Abstract

The technique of charged particle radiography has been developed and proven with 800 MeV protons at LANSCE and 24 GeV protons at the AGS. Recent work at Los Alamos National Laboratory in collaboration with the Idaho Accelerator Center has extended this diagnostic technique to electron radiography through the development of an inexpensive and portable electron radiography system. This system has been designed to use 30 MeV electrons to radiograph thin static and dynamic systems. The system consists of a 30 MeV electron linear accelerator coupled to a quadrupole lens magnifier constructed from permanent magnet quadrupoles. The design features and operational characteristics of this radiography system are presented as well as the expected radiographic performance parameters.

CHARGED PARTICLE RADIOGRAPHY

The technique of charged particle radiography (CPR) has been developed at LANL to utilize 800 MeV protons as a radiographic probe for the diagnosis of explosively-driven dynamic-events in support of the LANL stockpile stewardship program [1,2]. The beam optics requirements for CPR lens systems are well understood [3] and schematically shown in Fig 1.
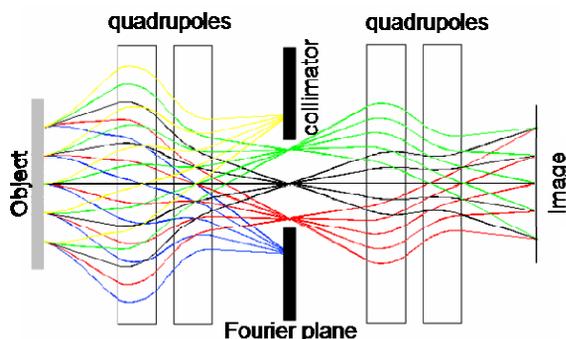
Figure 1: Schematic diagram of a CPR beam-optics system showing the point-to-point focus of particle trajectories (colored lines) from object to image. The colors represent the magnitude of scattering within the object. The Fourier point is located at the midpoint of the lens, where a collimator is positioned. The position-angle correlation at injection determines the location of the Fourier plane as well as partially cancelling second order chromatic aberrations.

There are two primary requirements of any CPR lens system. First, the lens must provide a point-to-point focus from object to image. Second, it must form a Fourier plane, where particles are radially sorted by the magnitude of the scattering within the object. With this correlation, particles that were scattered to large angles can be removed through collimation at the Fourier plane.

The remaining parameters of a CPR lens system design are then determined by the requirements of the radiographic applications. The beam energy must be chosen to penetrate the areal density of the object to be radiographed, and the aperture of the lens system must be chosen to provide sufficient angular acceptance throughout the required field of view.

An additional requirement, which is usually a strong design driver for a CPR lens, is the resolution of the radiography system. This resolution is typically dominated by chromatic aberrations due to energy spread in the injected beam in combination with the spread of energy loss through the object due to areal density variations of the object. Improved resolution is achieved by reducing second order chromatic aberrations [4], T_{126} in TRANSPORT notation. In order to compare the relative resolution of magnifying lens designs it is convenient to define the normalized chromatic aberration coefficient, $C=T_{126}/m$, where m is the magnification factor of the lens.

DESIGN REQUIREMENTS

The electron radiography system described here was designed to provide high radiographic resolution for small, thin objects. The design goals for this radiography system are described below:

- < 0.1 g/cm^2 areal densities.
- > 2 cm field of view.
- > 20 mrad angular acceptance.
- < 0.02 cm RMS resolution.
- > 3 magnification
- < 300 cm long

ELECTRON SOURCE

A Varian Clinac 2500 waveguide was recommissioned with a 5.5 MW CPI peak power klystron, producing a 20 µs S-band microwave pulse of 2.8 GHz. The accelerator and its control system have been constructed at the Idaho Accelerator Center and are portable for eventual deployment at Los Alamos National Laboratory. The accelerator is capable of delivering a pulsed electron beam with energies between 5 MeV and 32 MeV. The present pulse forming network allows electron pulse widths between 200 ns and 2 µs but can be upgraded to allow pulse widths as long as 18 µs. At the waveguide's

optimum energy of 25 MeV, the instantaneous current can be as high as 120 mA. The electron pulses can be supplied as a single shot or repeated at a rate up to120 Hz.

30 MEV IMAGING LENS

Permanent magnet quadrupoles (PMQs) were chosen as the magnetic focusing elements of this lens system because of the high gradients, low cost and simplicity of operation. In order to adjust the focus of the lens system to compensate for energy deviation from the design energy, the PMQs were placed on remotely actuated, linear translation stages. The object-to-first-lens distance, a key parameter in determining angular acceptance and resolution, was required to be large enough to accommodate the installation of static radiographic objects, and the quadrupole spacing, another key parameter in determining resolution, was kept large enough so that the magneto-static forces between neighbouring PMQs were manageable with conventional translation stages.

Fig. 2 shows a schematic diagram of the final lens design along with particle trajectories through the system. A factor of ~5.9 magnification was achievable given the limitations on both the field gradients and the overall length of the radiography system.
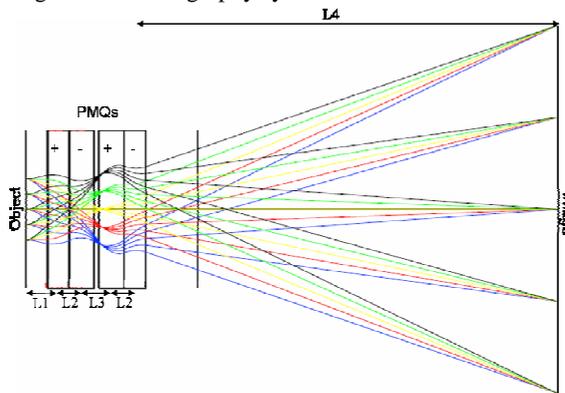
Figure 2: Schematic diagram of the CPR lens design described here showing the x5.9 magnification point-to-point focus of particle trajectories (colored lines) from object to image.

Permanent Magnets

The PMQs are in a Russian quadruplet configuration with alternating quadrupole gradients and the ∫Gdl of the outer magnets are half the ∫Gdl of the inner quadrupoles. This was achieved by doubling the length of the inner quadrupoles.

The permanent magnets are 16-segment Halbach magnets made of NdFeB permanent magnet material with an aperture of 5.08cm. The shorter pair are 1.27 cm long with a ∫Gdl of 0.51 T and the longer pair are 2.54 cm long with a ∫Gdl=1.03 T.

Angular Acceptance

The maximum angular acceptance of the radiography system is predominantly determined by the object-to-first-PMQ standoff distance and the PMQ aperture. Fig. 3 shows the horizontal and vertical angular acceptance as a function of transverse distance from the lens axis. This angular acceptance of the lens allows for a 30 mrad angle collimation cut to be applied uniformly across the field of view, out to ~2 cm radius.
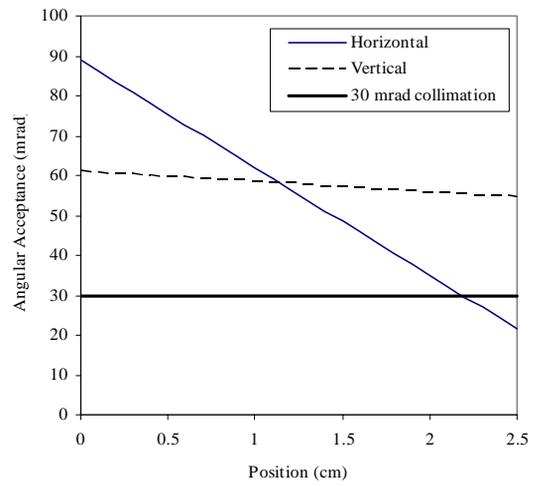
Figure 3: Horizontal and vertical angular acceptance as a function horizontal and vertical offset (respectively) from CPR lens axis.

Imaging System Parameters

The key parameters for the design of this CPR lens system are contained in Table 1. Parameters describing the dimensions of the radiography lens are defined in Fig 2.

Table 1: Key parameters of the CPR lens syst Parameters describing the layout of the lens system lay are defined in Fig. 2.

Parameter	Value	Parameter	Value
L1	12.5 cm	L2	9.0 cm
L3	11.6 cm	L4	162.9 cm
T_{126}	2.82 m	T_{346}	4.48 m
Magnification	5.9	Aperture	5.08 cm
C_n (horiz.)	0.48 m	C_n (vert.)	0.76 m
∫Gdl (short)	0.51 T	∫Gdl (long)	1.03 T
Length	2.05 m	Field of View	± 2 cm

RADIOGRAPHIC PERFORMANCE

Sensitivity

Radiographic contrast is established through collimation of electrons at the Fourier plane of the CPR lens system. The low energy and small rest mass of the electrons results in this radiography system being very sensitive to thin radiographic objects. At 30 MeV the beam-object interactions are dominated by multiple Coulomb scattering (MCS). In Fig. 4 approximate transmission is plotted as a function of radiation lengths for 5, 10, 20 and 30 mrad collimation angles. In this approximation it has been assumed that MCS results in a Gaussian angular scattering distribution and that all electrons scattered to more than the collimation cut angle are removed from the transmitted beam.

Radiographic Resolution
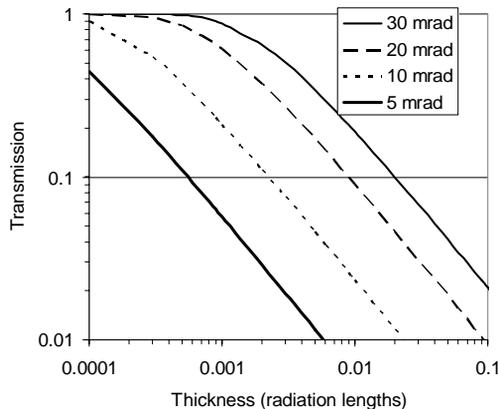
Figure 4: Transmission versus thickness in units of radiation length with a 5, 10, 20 and 30 mrad collimator.

A low resolution prototype electron radiography system, with normalized chromatic aberration coefficient of 1.75 m, was commissioned with 20 MeV electrons in 2002 [5]. On of the first radiographs collected from this system is shown in Fig. 5. An edge transition from this radiograph was used to determine resolution. The edge transition was fit assuming a Gaussian line spread function with a resulting RMS width of 350 µm.

The new CPR lens design is a X5.9 magnifier with a horizontal and vertical chromatic aberration coefficient of 2.82 m and 4.48 m respectively. This results in a horizontal and vertical normalized chromatic aberration coefficient of 0.48 m and 0.76 m respectively. With a 50% increase in beam energy and the same angular acceptance the new radiography system should improve resolution by a factor of 3.5 horizontally and a factor of 5.6 vertically. The ultimate RMS resolution, assuming a Gaussian point spread function, is expected to be 60 µm and 100 µm in the horizontal and vertical planes, respectively.
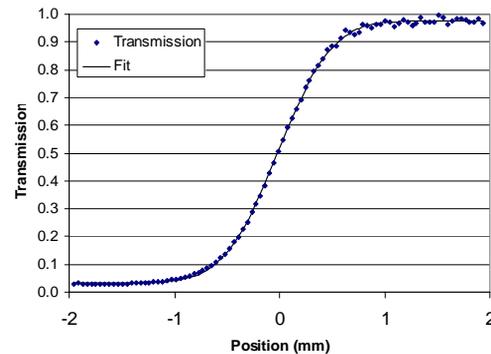
Figure 5: Electron radiograph collected from a prototype system (top). The edge transition as measured from the above radiograph and a fit of the transition expected from a Gaussian line spread function with an RMS width of 350 µm (bottom)

CONCLUSIONS

A portable 30 MeV electron source and radiography system has been designed and built to meet the design requirements described above. This system is scheduled for commissioning in July, 2005. This CPR lens system is expected to provide density measurements for static and dynamic objects with 0.01-1.0 g/cm^2 area densities with an RMS spatial resolution of ~100 µm.

REFERENCES

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