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11 MeV low-energy magnifying pRad at CAEP ☆

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ABSTRACT

To make a further improvement of resolution, the 11 MeV low-energy pRad beamline at CAEP was rebuilt into a 1:3 magnifying imaging beamline recently. The principle of low-energy pRad and the design of magnifying pRad line are described in detail. By using magnetic imaging lens of magnification three, images are spread over larger area at image plane and the effect of optical system on spatial resolution limitation is weakened. According to the radiographing results, for 10 μm thick aluminum object, spatial resolution less than 30 μm is achieved on the new magnifying pRad beamline.

1. Introduction

Lens focused proton radiography (pRad), which was first proposed by Los Alamos National Laboratory (LANL) in 1990s [1,2], is a new kind of radiography technique. Unlike classical radiography, such as X-ray radiography, magnetic imaging lens is utilized in pRad system to achieve point-to-point focus from object to scintillator screen (see Fig. 1) in order to eliminate the blur caused by scattering angular divergence of penetrating protons. The advantages in penetrability, resolution, scatter background and detection efficiency make pRad an alternative to X-ray flash radiography [2,3].

There are two kinds of magnetic imaging lens utilized in pRad: identity imaging lens and magnifying imaging lens. pRad utilizing identity imaging lens was first presented by Mottershead and Zumbro [4]. The 800 MeV and 24 GeV identity pRad experiments at Los Alamos Neutron Scattering Center (LANSCE) and Alternating Gradient Synchrotron (AGS) validated its ability of advanced hydrotesting [5,6]. Russian researchers also built a 70 GeV identity pRad beamline on the U-70 accelerator at Institute of High Energy Physics (IHEP) to obtain multiple detailed radiographs of hydrokinetics processes [7].

A few years after the invention of identity pRad, the idea of magnifying imaging lens was also proposed by LANL researchers to furtherly improve the pRad resolution and the validating experiment was carried out at LANSCE in 2003 [8]. A 1:2.7 magnifying pRad beamline was also commissioned at LANL since then, and significant improvement in resolution was observed. By 2011, more than half of the LANL pRad experiments were performed on this magnifying pRad beamline [9].

The electron radiography (eRad) technique was under development almost at the same time. A 30 MeV eRad system of magnification 5.6 demonstrated this technique in 2007 [10]. In the Matter-Radiation Interaction in Extremes (MaRIE) experimental facility presented by LANL, a 12 GeV high-energy eRad system with high-magnification of 50 is included and submicron spatial involution is expected [11]. Though the weak penetrability hinders high-energy eRad from thick object flash radiography, it is able to provide good resolution for thin objects at less expense.

To study pRad technique, China Academy of Engineering Physics (CAEP) had built an 11 MeV low-energy pRad beamline utilizing identity imaging lens in 2013 [12]. Theoretical analysis and experiment results validated the feasibility of low-energy pRad and spatial resolution of 100 μm was achieved [13,14]. According to the analysis on the radiographing result, the major limitation on spatial resolution was the resolving power of optical system.

Recently, this 11 MeV low-energy pRad beamline at CAEP was rebuilt into a pRad beamline of magnification three to make a further improvement on spatial resolution. Some aluminum objects were radiographed on this new magnifying pRad beamline to evaluate its spatial resolution. By using magnifying magnetic imaging lens, the spatial resolution limitation imposed by optical system is effectively weakened and the spatial resolution of the pRad beamline is significantly improved.

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2. Magnetic imaging lens

The crucial element of pRad system is the magnetic imaging lens composed by quadrupoles. The test object and the scintillator screen are placed at the object plane and the image plane of magnetic imaging lens respectively. The transverse transfer matrix R of magnetic imaging lens satisfies the condition $R_{12}=R_{34}=0$, so that the transverse position of each proton arriving the imaging plane does not depend on its initial scattering angle. Since all protons exiting from the same point of object join in a single point of image plane (see Fig. 2), the blur caused by angular divergence of penetrating protons is eliminated.

Because of the initial energy dispersion brought by the probe source (proton accelerator) and the energy-loss in test object, the momentum of penetrating proton may differ from design momentum. To first order of relative momentum deviation $\Delta=\delta p/p_0$, probing proton's final position on the image plane is

$$
\begin{aligned}
(x_f, y_f) &= (R_{11}\times x_0 + R_{12}\times x_0', R_{33}y_0 + R_{34}y_0') \\
&\quad + (T_{116}\times x_0 + T_{126}\times x_0', T_{336}y_0 + T_{346}y_0')\Delta \\
&= (R_{11}\times x_0, R_{33}y_0) + (T_{116}\times x_0 + T_{126}\times x_0', T_{336}y_0 + T_{346}y_0')\Delta,
\end{aligned}
$$

where T_{116} and T_{126} are the second order transfer matrix elements of magnetic imaging lens. The last term including Δ can be eliminated if the initial transverse distribution of protons has the correlation $x_0'=w_x\ {}_{x0}$ and $y_0'=w_y\ y_0$, where coefficients $w_x=-T_{116}/T_{126}$ and $w_y=-T_{336}/T_{346}$ are called chromatic matching coefficients. Therefore, to reduce the chromatic aberration, there should be a matching section between proton source and magnetic imaging lens to modulate the incident protons to fulfill this correlation.

After penetrating test object, the chromatically matched probing proton exits with an extra scattering angle φ, so its transverse angle is $x_0'=w_x\ x_0+\varphi_x$ and its final position at imaging plane is x_f $=-R_{11}\times{}_0+T_{126}\ \varphi_x\Delta$. Therefore, the position error in the x-direction of an off-energy proton is $T_{126}\ \varphi_x\Delta$, where T_{126} is called the chromatic aberration coefficient of the imaging lens. Analogously, the position error in the y-direction is $T_{346}\ \varphi_y\Delta$.

Moreover, there is a plane in the imaging lens called x-Fourier plane, the transfer matrix M from object plane to which fulfills the correlations $M_{11}+w_xM_{12}=0$. The transverse position of chromatically matched proton arriving x-Fourier plane is

$x_{\mathrm{Fourier}}=M_{11}\times x_0+M_{12}(w_xx_0+\varphi_x)=M_{12}\varphi_x$,

which only depends on φ_x, thus protons are sorted by their initial derivative scattering angles at x-Fourier plane (see Fig. 2). Similarly, there is also a y-Fourier plane, where protons are sorted by φ_y. Hence the deviation scattering angles of passing through protons can be confined by setting collimators at x- and y-Fourier planes.

3. Low-energy pRad using identity imaging lens

The 11 MeV low-energy pRad beamline using identity imaging lens was built at CAEP in 2013. The layout of the beamline is shown in Fig. 3. The proton beam extracted from a proton cyclotron [15] passes through a ⌀1 mm pinhole and a 20 μm thick Al foil diffuser first. The well-proportioned central part of the beam is picked up and diffused to illuminate a ⌀30 mm area at the end of the matching section and the two quadrupoles of matching section chromatically match the diffused beam before it probes test object [12]. After penetrating test object at the object plane of identity imaging lens, exiting protons are focused onto LSO (Lu_2SiO_5) scintillator and transformed into optical signals recorded by CCD camera.

The identity imaging lens consists of four magnetic quadrupoles of equal strengths and alternative polarities (see Fig. 4) [4].

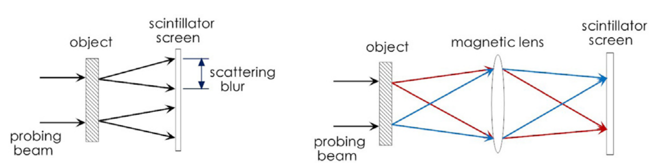

Fig. 1. pRad with (right) and without (left) magnetic imaging lens.

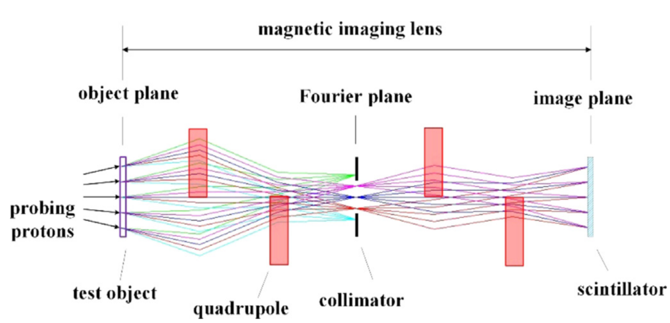

Fig. 2. Schematic of proton trajectories through magnetic imaging lens.

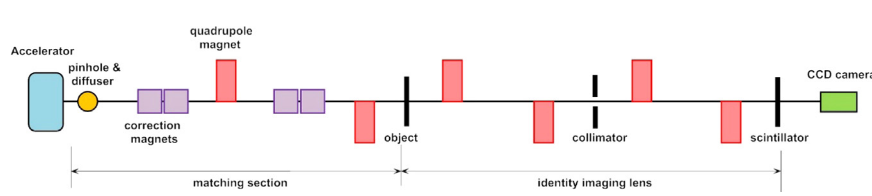

Fig. 3. Layout of pRad beamline at CAEP.