Laser and Particle Beams (2014), *32*, 651–655.

doi:10.1017/S0263034614000676

Heavy-ion radiography facility at the Institute of Modern Physics

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(Received 26 August 2014; Accepted 16 September 2014)

Abstract

In order to identify the density and material type, high energy protons, electrons, and heavy ions are used to radiograph dense objects. The particles pass through the object, undergo multiple coulomb scattering, and are focused onto an image plane by a magnetic lens system. A modified beam line at the Institute of Modern Physics of the Chinese Academy of Sciences has been developed for heavy-ion radiography. It can radiograph a static object with a spatial resolution of about 65 μm (1 σ). This paper presents the heavy-ion radiography facility at the Institute of Modern Physics, including the beam optics, the simulation of radiography by Monte Carlo code and the experimental result with 600 MeV/u carbon ions. In addition, dedicated beam lines for proton radiography which are planned are also introduced.

Keywords: Beam optics; Heavy-ion radiography; Magnetic lens system; Material identification; Simulation

1. INTRODUCTION

Proton radiography was started at the Los Alamos National Laboratory (LANL) in 1995 (Gavron *et al*., 1996; Amann *et al*., 1997; Ziock *et al*., 1998). Since then, proton radiography has been an important tool in the weapons program due to its spatial resolution and material identification. Radiographic information is obtained by measuring the intensity of the shadow of an object in a beam of penetrating radiation (Morris *et al*., 2006). Proton radiography has many advantages to X-ray radiography in beam spot size, penetration capability, energy spectrum, multiple angles radiography, multiple times radiography, and sensitivity to the density and atomic number of the measured object. With the urgent need of knowing the material information of an object, many institutes or laboratories develop proton radiography technique in the United States (Schwartz *et al*., 2007; Morris *et al*., 2011), Russia (Golubev *et al*., 2010; Antipov *et al*., 2010), Germany (Tahir *et al*., 2002; Hoffmann *et al*., 2005), and China (Wei *et al*., 2010; Zhao *et al*., 2012). LANL proposed 3 GeV proton radiography which is upgraded from present 800 MeV protons (Garnett *et al*., 2012). In addition, new facilities are being constructed in Germany and China. A 4.5 GeV proton radiography beam line with 5.0×10^{12} particles/pulse will be operated at the Gesellschaft für Schwerionenforschung for FAIR experiments with great discovery potential for plasma physics and high energy density physics research (Merrill *et al*., 2009). The Institute of Modern Physics (IMP) of the Chinese Academy of Sciences (CAS) has also proposed two proton radiography setups, one is for 2.6 GeV in Heavy Ion Research Facility (HIRFL) in Lanzhou-Cooler Storage Ring (CSR) and the other is for 9 GeV in the High Intensity heavy-ion Accelerator Facility (HIAF) (Zhao, 2011).

Heavy-ion radiography is very similar to proton radiography with respect to great penetration capability, clear imaging, and less number of ions for detection. A high energy heavy-ion radiography facility is constructed at the IMP-CAS for diagnosing static targets, which is expected to accumulate experiment data for ions interacting with matter, verify the theory and simulation of heavy-ion radiography, and make foundation for proton radiography. This paper presents the heavy-ion radiography setup at IMP, shows the beam optics of the facility and the simulation of radiography as well as the performance test results. Furthermore, two new dedicated radiography beam lines in plan are also designed here.

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2. HEAVY-ION RADIOGRAPHY SETUP AT IMP

The heavy-ion radiography setup is based on the HIRFL-CSR, which can provide a variety of ion species from carbon ions to uranium ions and the highest energy is 1 GeV/u for carbon ions. Figure 1 shows the overall layout of the HIRFL-CSR and the heavy-ion radiography beam line.

The heavy-ion radiography beam line with a large field-of-view is modified from an old beam line, and the schematic view is shown in Figure 2. The ions from fast extraction of HIRFL-CSR are first focused onto the object plane with suitable beam parameters by three matching magnets. Then the lens system after the object focuses the transmitting ions onto the image plane to provide image and material identification information. The matching lens system provides the required phase space correlation upstream of the object, and an imaging lens system downstream of the object provides the phase space correlation to maximize the image quality and minimize the chromatic aberration in second order.

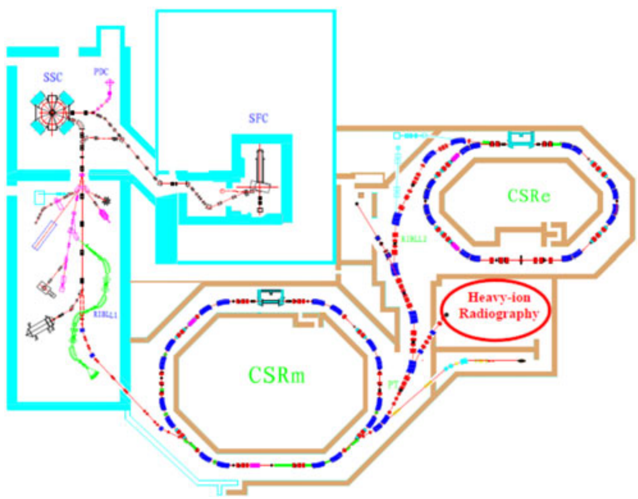

Fig. 1. Overall layout of the HIRFL-CSR and the heavy-ion radiography beam line.

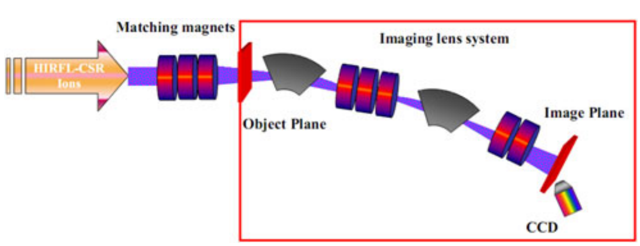

Fig. 2. Schematic view of the heavy-ion radiography beam line at IMP.

The Zumbro magnets are usually used for radiography (Mottershead *et al.*, 1998). They have the useful property of having an "angular focus" at the midpoint, which facilitates to insert a collimator to eliminate the large angle scattered particles to enhance spatial resolution and material identification. But in order to keep the original configuration of the beam line as much as possible, a special radiography beam line is developed at IMP. There is a point-to-point imaging in the first order transfer matrix, so the final position is independent of the initial angle. The second order chromatic correction is achieved by a special position-angle correction at the entrance of the object, that is, $x_0'/x_0 = -T_{116}/T_{126}$ and $y_0'/y_0 = -T_{336}/T_{346}$ (Merrill *et al.*, 2011). x_0 and y_0 are initial half beam spot sizes, x_0' and y_0' are initial half beam angles; T_{116}, T_{126}, T_{336}, and T_{346} are terms of second order transfer matrix in TRANSPORT code. Figure 3 gives the beam optics of the imaging lens system in the first order. Note that, this radiography beam line is not symmetric and doesn't satisfy the Zumbro magnets, but its magnifications are both 1 in the x and y directions.

In order to achieve clear imaging, the positions and angles of heavy ions at the entrance of the object are measured, and a Lutetium oxyorthosilicate crystal scintillator and a charge-coupled device camera are used for image recording online. Mathematical analysis of the image allows separate determination of the atomic number and thickness for object identification (Ryu *et al.*, 2008).

3. SIMULATION AND EXPERIMENTAL RESULTS

The heavy-ion radiography facility at IMP was simulated by Geant4 code with 1 GeV protons. A circular beam spot was first focused onto the object plane by three matching quadrupoles, and then refocused onto the image plane by the imaging lens system. Two detectors were placed at the object plane and the image plane for phase space measurement, respectively. A circular aluminum object (2 cm thickness) with two 10 mm × 3 mm stripes in the center was simulated in the object plane. We use 10^7 particles to simulate here. Figure 4 shows the beam transmission onto the image plane.

A performance test has been carried out to characterize the heavy-ion radiography facility at IMP with 600 MeV/u

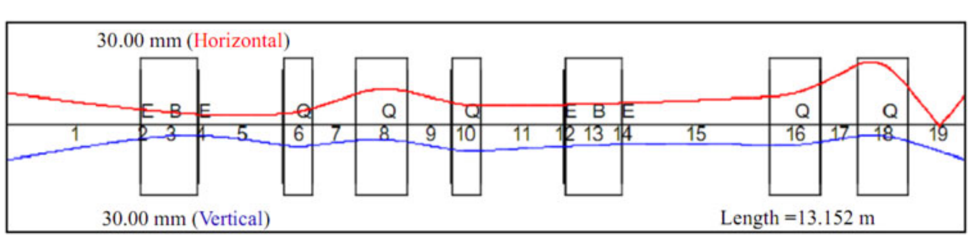

Fig. 3. Beam optics of the imaging lens system for IMP heavy-ion radiography setup.

https://doi.org/10.1017/S0263034614000676 Published online by Cambridge University Press

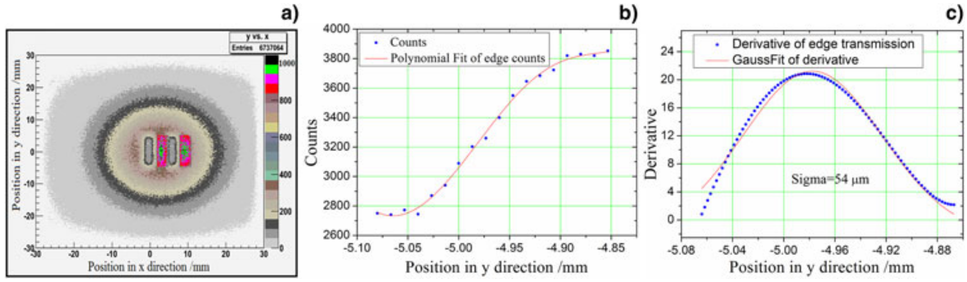

Fig. 4. Beam transmission onto the image plane simulated by Geant4 code; (**a**) Image in x and y directions; (**b**) Transmission in the edge of y direction; (**c**) Gauss fit for derivative of edge transmission.

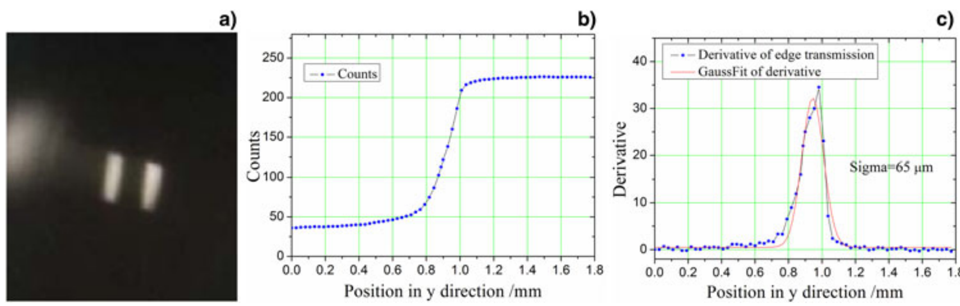

Fig. 5. (**a**) Image for the two stripes in x and y directions; (**b**) Transmission in the edge of y direction; (**c**) Gauss fit for derivative of edge transmission.

carbon ions and 5.0×10^9 particles/pulse. The pulse length of beam for radiography was 300 ns with a cycle of 20 s. The circular moveable aluminum object mentioned above was placed on the object plane. A high sensitive charge-coupled device camera was placed near the image plane to catch the image in real time. Figure 5 shows the image for the two stripes and its vertical edge transmission in the heavy-ion radiography facility at IMP. The spatial resolution is about 65 μm (1 σ) in vertical direction by fitting Gauss curve.

4. PROPOSED DEDICATED PROTON RADIOGRAPHY BEAM LINES

Two new dedicated proton radiography beam lines are proposed at IMP with magnifications of $M = 1$ and $M = 5$, and the imaging lens systems inherits the main features of the Zumbro magnet (Yang *et al.*, 2012). Figure 6 shows the beam optics for the proton radiography with 2.6 GeV at HIRFL-CSR and 9 GeV at HIAF calculated by My-BOC code (Zhang *et al.*, 2010). The limiting spatial resolution is proportional to T_{126} term of transfer matrix, the angular spread and the momentum spread of the beam, and inversely proportional to the magnification. So the limiting spatial resolutions are expected to be 13 μm for 2.6 GeV proton radiography at HIRFL-CSR and 830 nm for 9 GeV proton radiography at HIAF. The corresponding parameters for the proton radiography beam lines are listed in Table 1.

5. CONCLUSION AND OUTLOOK

The carbon ion radiography experiment for static target has been carried out at IMP-CAS, and the spatial resolution is about 65 μm (1 σ), which agrees with the simulation of 1 GeV proton radiography by Geant4 code. Dedicated proton

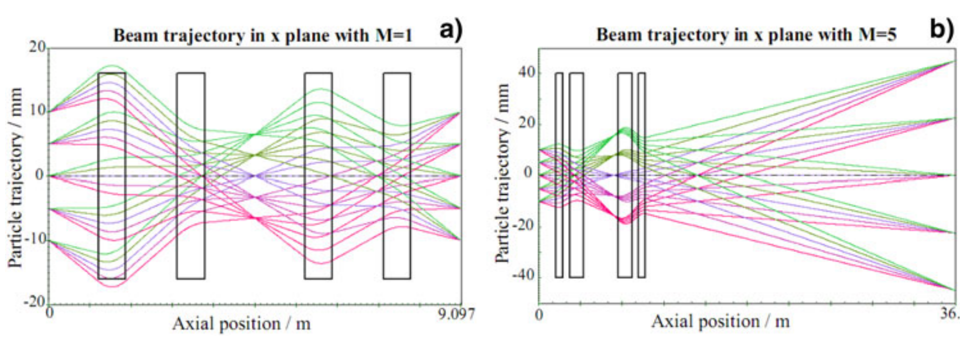

Fig. 6. Beam optics for proton radiography beam lines with the magnification of $M = 1$ (**a**) and $M = 5$ (**b**).

https://doi.org/10.1017/S0263034614000676 Published online by Cambridge University Press

Table 1. *Parameters of dedicated proton radiography beam lines for* M = *1 and* M = *5*

Parameters	Value	Value
Magnification	1	5
Proton energy: GeV	2.6	9
Magnet aperture: mm	100	100
Maximum field gradient: T/m	13.46	17.48
Short quadrupole length: m	0.6	0.6
Long quadrupole length: m	0.6	1.2
L_1 (object to first quad): m	1.105	1.5
L_2 (first to second quad): m	1.138	0.6
L_3 (second to third): m	2.21	3.0
L_4 (last to image): m	1.105	27.0
Total length: m	9.097	36.3
Spatial resolution: µm	13	0.83
Field-of-view: mm	20	20

radiography beam lines with 2.6 GeV at HIRFL-CSR and 9 GeV at HIAF are proposed here, which will enhance the experiment capability in spatial resolution and material identification for thicker object. In addition, sidestep objects will be made radiograph in future. Short-bunch and multi-bunch extraction is improved for HIRFL-CSR at present, and the dynamic experiment can be carried out further.

ACKNOWLEDGEMENTS

This work is supported by the Major State Basic Research Development Program of China (‘973’ Program) No. 2010CB832902 and the National Science Foundation of China under Grant Nos. 11176001 and 10805063. The authors would like to thank the accelerator staffs of IMP and IFP during beam commissioning.

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