# HEAVY IONS RADIOGRAPHY FACILITY AT IMP*

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*Abstract*

In order to identify the density and material type, high energy protons, electron, and heavy ions are used to radiograph dense objects. The transmitted particles through the object undergo the multiple coulomb scattering, and focus on an image plane by a magnetic lens system. A transformed beam line in the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences (CAS) has been developed for heavy ions radiography. It can radiograph a static object and the spatial resolution is about 65μm (sigma). This paper presents the heavy ions radiography facility at IMP, including the beam optics, the simulation of radiography by Monte Carlo code and the experiment result with 600MeV/u carbon ions. In addition, the dedicated beam lines for proton radiography in plan are also introduced.

## INTRODUCTION

The proton radiography was started from Manhattan Project in the Los Alamos in 1995 [1-3]. Since then, proton radiography has been an important tool in weapons program for its effect on spatial resolution and material identification of radiographic image. Radiography information is obtained by measuring the intensity of the shadow of an object in a beam of penetrating radiation [4]. And proton radiography has many advantages to X-ray radiography in beam spot size, penetration capability, energy spectrum, multiple angles radiography, multiple times radiography, and much sensitive to the density and atomic number of measured object. With the urgent need of knowing the material information of one object, many institutes or laboratories develop proton radiography technique in the USA [5, 6], Russia [7, 8] and China [9, 10]. Los Alamos National Laboratory (LANL) proposed 3GeV proton radiography which was upgraded from present 800 MeV protons [11]. In addition, new facilities are being constructed in Germany and China. A 4.5 GeV proton radiography beam line with $5.0\times10^{12}$ particles/pulse will be operated at Gesellschaft für Schwerionenforschung (GSI) for FAIR experiments with great discovery potential at plasma physics and high energy density physics research [12]. The Institute of Modern Physics of Chinese Academy of Sciences (IMP, CAS) has also proposed two proton radiography setups, one is for 2.6 GeV in Heavy Ion Research Facility in Lanzhou-Cooler Storage Ring (HIRFL-CSR) and the other is for 9GeV in the High Intensity heavy-ion Accelerator Facility (HIAF).

Heavy ions radiography is very similar to proton radiography for its great penetration capability, clear imaging, and less number of ions for detection and so on. A high energy heavy-ion radiography facility is constructed in the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences (CAS) for diagnosing static target, which is expected to accumulate experiment data for ions interacting with matter, verify the theory and simulation of heavy ions radiography, and make foundation for proton radiography. This paper presents the heavy ions 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.

## HEAVY IONS RADIOGRAPHY SETUP AT IMP

The heavy ions radiography setup is based on the Heavy Ion Research Facility in Lanzhou – Cooler Storage Ring (HIRFL-CSR), which can provide a variety of ion species from carbon ions to uranium ions and the highest energy is 1GeV/u for carbon ions.

The heavy ions radiography beam line with a large field-of-view is transformed from an old beam line, and the schematic view is shown in Figure 1. The ions from fast extraction of HIRFL-CSR are first focused on the object plane with suitable beam parameters by three matching magnets. Then the lens system after the object focuses the transmitted ions on 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.

The –I lens is the best choice for radiography. The –I lens has a useful property of having an "angular focus" at its midpoint, which facilitates to insert a collimator to eliminate the large angle particles to aid dimension and material identification [13]. But in order to keep the original configuration of the beam line to the maximum, an especial radiography beam line is developed at IMP.

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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 $y_0'/y_0 = -T_{336}/T_{346}$ ($x_0$, $y_0$ are initial half beam spot sizes, $x_0'$, $y_0'$ are initial half beam angles; $T_{116}$, $T_{126}$, $T_{336}$ and $T_{346}$ are terms of second order transfer matrix in TRANSPORT code) [14]. Figure 2 gives the beam optics of the imaging lens system in the first order. Note that, this radiography beam line is not symmetry and doesn't satisfy the Zumbro magnets, but its magnifications are both 1 in x and y directions.

In order to achieve clear imaging, the positions and angles of particles at the entrance of object are measured, and a scintillating fiber optic array and a CCD camera are used for image recording online. Mathematical analysis of the image allows separate determination of the atomic number and thickness for object identification [15].

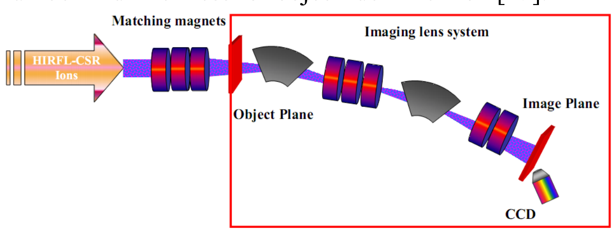


Figure 1: Schematic view of the heavy ions radiography beam line at IMP.

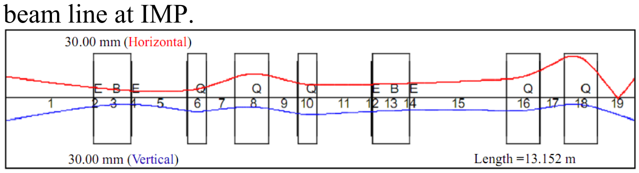


Figure 2: Beam optics of the imaging lens system for IMP heavy ions radiography setup.

## SIMULATION AND EXPERIMENT RESULTS

The heavy ions radiography facility at IMP was simulated by Geant4 code with 1GeV protons. A circular beam spot was first focused on the object plane by three matching quadrupoles, and then refocused on 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 (2cm thickness) with two 10mm×3mm stripes in the center was simulated in the object plane. $10^7$ particles are chosen to track through the whole beam line. Figure 3 shows the beam transmission on the image plane.

A performance test has been carried out to characterize the heavy ions radiography facility at IMP. 600MeV/u carbon ions with $5.0\times10^9$ particles/pulse were used for commissioning. The pulse length of beam for radiography was 300ns with a cycle of 20s. The circular moveable aluminum object mentioned above was placed on the object plane. A high sensitive CCD camera was placed near the image plane to catch the image in real time. Figure 4 shows the image for the two stripes and its vertical edge transmission in the heavy ions radiography facility at IMP. The spatial resolution is about 65 μm (sigma) in vertical direction by fitting Gauss curve.

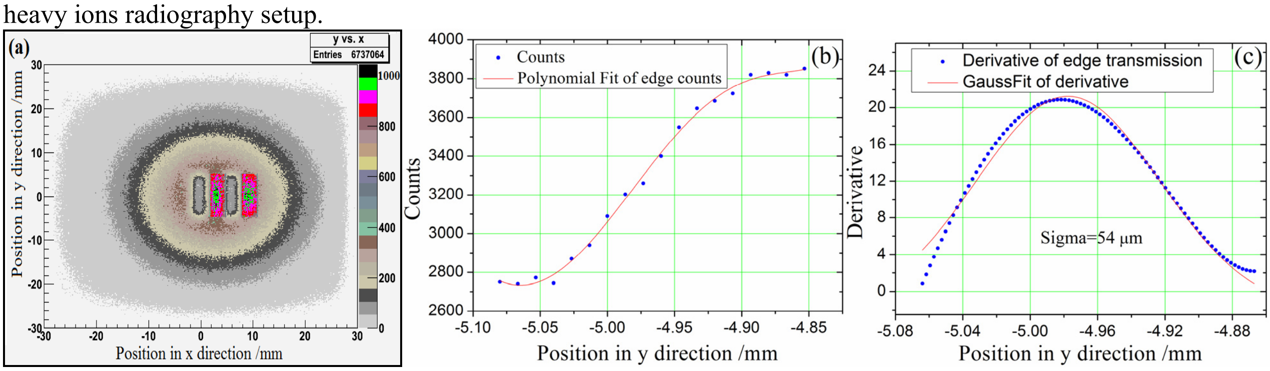


Figure 3: Beam transmission on the image plane simulation by Geant4 code; (a) Image in x and y directions; (b) Transmission in the edge of y direction; (c) Gauss fit for derivative of edge transmission.

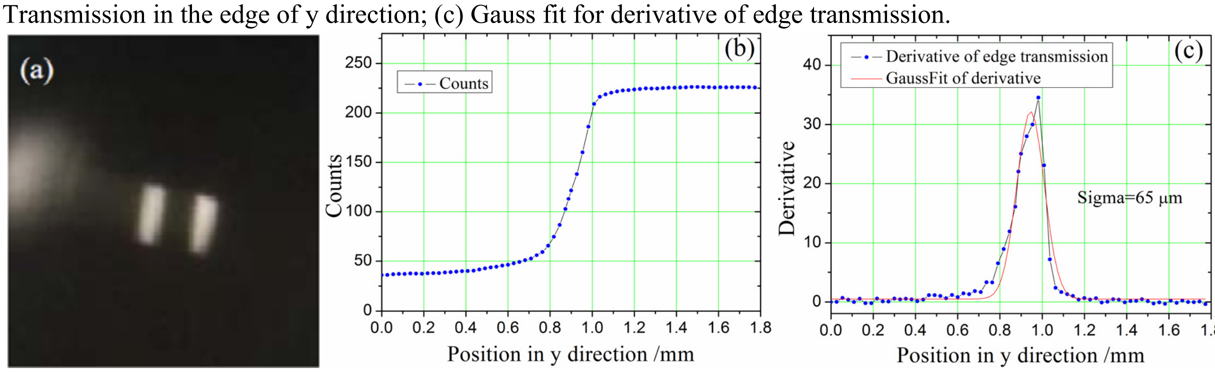


Figure 4: (a) Image for the two stripes in x and y directions; (b) Transmission in the edge of y direction; (c) Gauss fit for derivative of edge transmission.

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## PROPOSED DEDICATED PROTON RADIOGRAPHY BEAM LINES

Two new dedicated proton radiography beam lines are proposed at IMP with the magnification of 1 and 5, and the imaging lens systems inherit the main features of Zumbro magnet [16]. Figure 5 shows the beam optics for the proton radiography with 2.6GeV in HIRFL-CSR and 9GeV in HIAF by code My-BOC [17]. 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 13μm for 2.6GeV proton radiography in HIRFL-CSR with the angular spread of 2mrad and the energy spread of 0.05%, and 830nm for 9GeV proton radiography in HIAF with the angular spread of 1mrad and the energy spread of 0.005%. The corresponding parameters for the proton radiography beam lines are listed in Table 1.

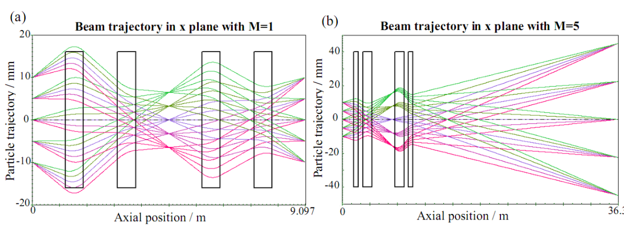


Figure 5: Beam optics for proton radiography beam lines with the magnification of 1 (a) and 5 (b).

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 |

## CONCLUSION AND OUTLOOK

The carbon ion radiography experiment for static target has been carried out at IMP, CAS, and the spatial resolution is about 65μm (sigma), which agrees with the simulation of 1GeV proton radiography by Geant4 code. Dedicated proton radiography beam lines with 2.6GeV in HIRFL-CSR and 9GeV in 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.

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