

PROTON RADIOGRAPHY EXPERIMENT BASED ON A 100 MeV PROTON CYCLOTRON*

J.J. Yang[†], X. Zhen, S.M. Wei, Y.L. Lv, F. Wang, Y.W. Zhang, L.P. Wen, J.Y. Liu, H.R. Cai, T. Ge, S.P. Zhang, L. Cao, T.J. Zhang, Z.G. Li
 China Institute of Atomic Energy, Beijing, 102413, China

Abstract

A proof-of-principle test-stand for proton radiography is under construction at China Institute of Atomic Energy (CIAE). This test-stand will utilize the 100 MeV proton beam provided by the compact cyclotron CYCIAE-100, which has been built in the year of 2014, to radiograph thin static objects. The assembling of the test-stand components is finished by now. We will carry out the first proton radiography experiment in this July and hopefully we can get the first image before the opening of this conference. In this paper, the designing, constructing and commissioning of the proton radiography system will be described.

INTRODUCTION

Proton radiography is a new scatheless diagnostic tool providing a potential development direction for advanced hydrotesting research. In comparison with flash radiography, proton radiography has higher penetrating power, higher detection efficiency, less scattered background, inherent multi-pulse capability, more exact material identification and large standoff distance between test objects and detectors. Proton radiography was firstly used for dynamic experiments on a proton energy 800 MeV linear accelerator facility at the Los Alamos National Laboratory [1]. Proton radiography on static objects with a single pulse and energy to 24 GeV was carried out at the the Brookhaven National Laboratory in the year of 2011 [2]. In 2014, a low energy proton radiography system was developed at Chinese Academy of Engineering Physics, which utilizes a 11 MeV proton beam to radiograph thin static objects [3].

As a driving accelerator for Beijing Radioactive Ion-beam Facility (BRIF), a 100 MeV H- compact cyclotron, normally referred to as CYCIAE-100, was constructed to provide the proton beam of 70-100 MeV with beam current of 200 μ A [4]. The first beam of CYCIAE-100 was extracted on July 4, 2014 [5]. The operation stability have been improved and beam current have been increased gradually. 720 μ A beam was got on the internal target at the beginning of 2016. The effort for mA beam is continuing and 1135 μ A beam was got on the internal target in June of 2016. This cyclotron can provide two proton beams simultaneously for the ion source of the Isotope Separation On-Line system (ISOL) and experimental instrument in the experiment hall, as is shown in Figure 1. In the experiment hall, a switching magnet guides the

beam to different beam lines. It is scheduled to build a low energy proof-of-principle test-stand for proton radiography based on the down-left beam line.

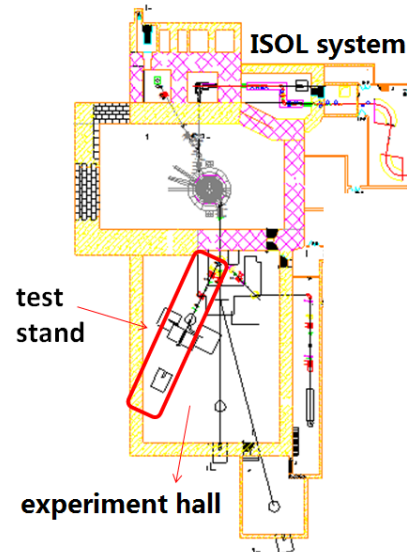


Figure 1: Layout of the BRIF facility.

BEAM LINE DESIGN

Proton radiography requires a particular magnetic lens system to provide a point-to-point imaging from the object to the image. Zumbro, Mottershead and Morris suggested a type of lens, normally referred to as Zumbro lens, whose first-order transfer matrix is the $-I$ matrix, which means the matrix element $R_{12} = R_{34} = 0$ [6]. The Zumbro lens has a Fourier plane at the mid-plane of the lens, where the position of a particle is determined by its initial angle only and is independent of its initial position (angle sorting), as is shown in Figure 2. The particles of large MCS angle in a matched beam can be removed through a transverse collimator at the Fourier plane. To form a Fourier plane, the incident particle's transverse displacement ω and angle deviation along beam direction ω' must be strongly correlated and comply with the following formula:

$$\omega \equiv \omega' / \omega'' = T_{116} / T_{126} \quad (1)$$

where T_{116} and T_{126} represents the second order chromatic aberrations of the Zumbro lens in TRANSPORT notation [7]. This means the matched beam emittance should equal zero, as is shown in Figure 3 (left).

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[†] yangjianjun2000@tsinghua.org.cn

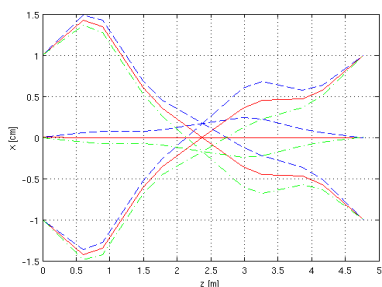


Figure 2: the point-to-point imaging in Zumbro lens. The Fourier plane is formed in the mid-plane of the lens.

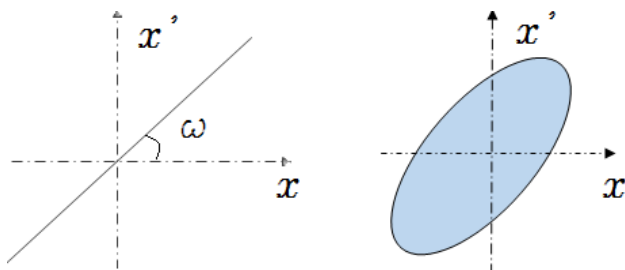


Figure 3: schematic of the ideal (left) and practical beam distribution from cyclotron (right).

But in reality, the transverse emittance of the beam from the the 100MeV cyclotron is typically nonzero, as is shown in Figure 3 (right). Therefore, it is necessary to reformulate the beam shape. In the design, the 100 MeV proton beam passes through a pinhole collimator of a inner diameter of 2 mm. The preserved central particles of the beam passes through a thin aluminium diffuser to expend the angular divergence and then passes through a sets of quadrupoles to reach the required correlation between particles' transverse displacement and angle deviation, as is expressed in formula (1).

Then the matched beam penetrates the thin object and the transmitted protons pass through the Zumbro magnetic lens system to form a point-to-point focusing from object to image. A radio-chromic film is positioned on the image plane. The optical density distribution of the film varies linearly with absorbed doses of the particles. The particles with large multiple Coulomb scattering angle can be removed through transverse collimation at the Fourier plane, where the proton is sorted by its angular divergence.

The design philosophy of the test-stand is fully using the existing devices and equipments and minimize the additional required ones. There are seven spare quadrupoles on site. So four sets of them are used in the imaging lens section and three sets of them are used in matching lens section. In addition, since the pinhole collimator will be heavily radio-activated during beam operation, this equipment must be positioned in the blockhouse and be shielded.

The beam optics design was done by using TRANSPORT code. As the first step, the imaging lens fitting determines the magnetic field strength of the four imaging quadrupoles and the value of ω , which was taken as the fitting conditions for the matching lens fitting process. The resultant beam envelopes in the beam line in both the horizontal and vertical directions are shown in Figure 4. The length of the imaging lens and matching lens are 4.76 m and 6.28 m, respectively.

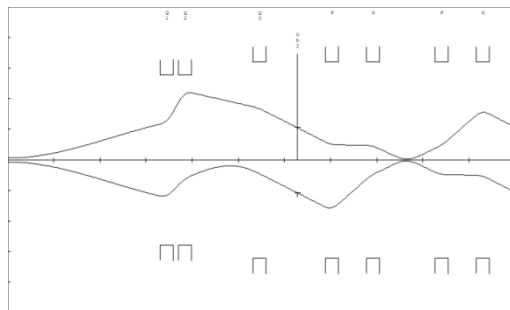


Figure 4: Beam envelopes of the beam line .

MECHINCIAL DESIGN

Based on the physical design, the detailed mechanical design of the beam line elements and the radiation shielding are carried out. Figure 6 shows the mechanical assembling drawing of the beam line. Besides the seven quadrupoles, the beam line also includes a couple of steering magnet, two diagnostic boxes (installing two faraday cups, one double-wire scanner, one quartz plate and two turbo pumps) , one object box, one collimator box, one imaging box and a beam dump in the end.

The pinhole collimator is a critical equipment, because up to 80% of the 100 MeV, 200 μ A beam will be lost on it and the power dissipation is about 16 kW. Therefore the water-cooling needs to be designed very carefully. The designed pinhole collimator consists of a inner cone and a sleeve. The cone surface was designed to increase the effective beam-heating area. A 3D FEM model was built to carry out thermal analysis. The steady temperature distribution is shown in Figure 5. The result shows the maximal temperature is 534 K under the condition of the water flow rate of 2 m/s, which is lower than melting point of copper material.

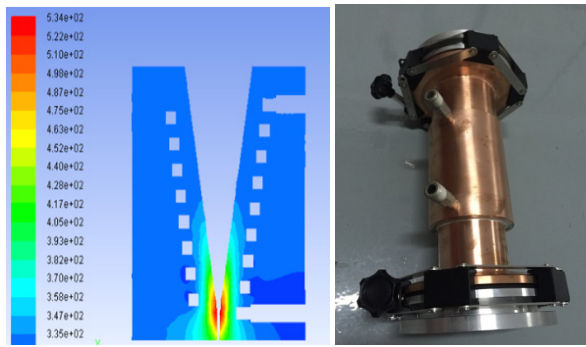


Figure 5: Steady temperature distribution in the pinhole collimator(left) and its photo of this device (right).

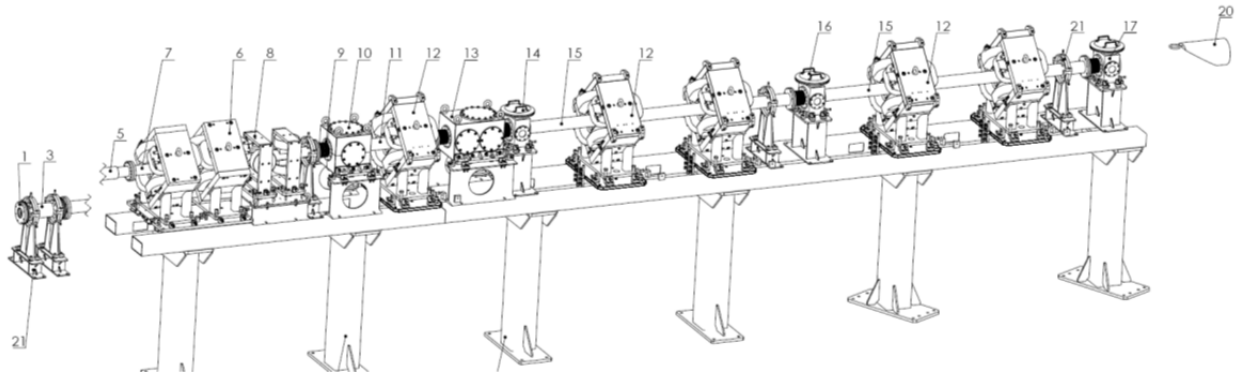


Figure 6: The mechanical assembling drawing of the test-stand.

TEST-STAND CONSTRUCTION

Manufacturing of all the test-stand components was finished and installed on site by June of 2016, as is shown in Figure 7.



Figure 7: Photo of the assembled proton radiography test-stand.

The alignment accuracy of beam line element is better than 0.1 mm. Two Faraday cups are installed to monitor to measure the beam current, one two-wire scanner is installed to measure the beam profile. Two movable fluorescence targets are installed to monitor the beam position at low beam current. In order to maintain good vacuum conditions, two turbo pumps together with vacuumeters are installed on the bottom side of the diagnostic boxes. The vacuum leak test shows no evident vacuum leakage exists on the beam line and the vacuum pressure can reach 1.0E-6 mbar within 30 minutes. In order to reduce the radiation level of the beam line, the pinhole collimator and the diffuser are positioned in the shielding blockhouse. A

beam dump is positioned at the end of the beam line to collect the proton beam. The EPICS-based remote control system is already installed in the control room. The design detail of the control system is described in the reference [8]. Fig.8 show several manufactured objects of different the pattern thickness and material for proton radiography test.



Figure 8: The manufactured objects of different.

CONCLUSION AND OUTLOOK

The test-stand is now ready for beam commissioning. The proton radiography experiment is scheduled in next month. In the first step, the pinhole collimator will be replaced by a straight beam pipe and beam test will be carried out to make sure that the beam passes through the centre of pinhole collimator and quadrupoles. Once the operation parameters of the beam line elements is finalized, the pinhole collimator will be installed to its position to carry out proton radiography experiment.

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