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A 50 MeV PROTON BEAM LINE DESIGN

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Abstract

The cyclotron center at the China Institute of Atomic Energ (CIAE) is now developing a medium-energy proton irradiation device that provides a proton beam with an energy range of 30 MeV to 50 MeV to simulate a space proton radiation environment, which has a significant impact on spacecraft. A beam transport line is designed for irradiation effect study based on this 50 MeV compact cyclotron, which requires continuous adjustment of the beam energy and the beam spot on the target requires high uniformity. The proton beam extracted from the cyclotron is adjusted to the energy required by using the degrader and the energy selected system, then the proton beam will be transported to the target. In order to obtain uniform large-diameter beam spot on the target, a wobbling magnet is installed on the beam line to uniformly sweep the proton beam on the target and finally obtain the proton beam with energy of 10 MeV-50 MeV, current of 10 μA and beam spot of 20 cm*20 cm on the target.

INTRODUCTION

Protons are the main components of the space radiation environment, causing radiation damage to spacecraft materials and devices, as well as induced single-particle effects, which seriously threaten satellite safety, especially the scientific satellite payload is more sensitive to damage caused by space protons. The Research Center of Cyclotron in China Institute of Atomic Energy (CIAE) has designed a medium-energy proton irradiation device, which is mainly composed of a 50 MeV proton cyclotron, a beam transport line and an experimental terminal. The center has already developed several compact cyclotrons and proton beam lines [1-4].

The 50 MeV cyclotron is designed as a compact structure that extracts protons from 30 MeV to 50 MeV, with a lower energy range, a degrader is provided on the beam line to reduce beam energy to 10 MeV. For irradiation effect study in this case, the energy dispersion required is small so the energy selected system is necessary.

A wobbling magnet is installed a few meters in front of the target to provide a magnetic field with periodic rotation changes, which make the beam spot uniformly sweep on the target.

The layout of the beam line and element design is shown in this paper.

LAYOUT OF THE 50 MeV PROTON BEAM TRANSFER SYSTEM

The layout of the 50 MeV irradiation dedicated proton beam transport system is shown in Fig. 1. Since the proton energy extracted by the cyclotron is adjustable in the range of 30 MeV~50 MeV, a combination magnet is placed inside the yoke which will combine proton beams with different energies to one beam line. The diagnostic box is including faraday cup (FC), fluorescent target (SS) and the beam profile monitor (BPM), which are used to measure the beam intensity and the beam profile; D1 is the degrader, which can reduce the beam energy extracted from the cyclotron to a lowest energy 10 MeV by using different thicknesses of graphite; C is a collimator; B1 and B2 are two 45° bending magnets that deflect the proton beam by 90°, and these two bending magnet and the collimators can select proton energy to reduce energy dispersion; Q is a quadrupoles for proton beam focusing; SXY is steering magnet for correcting the particle center; T is the vacuum pump for obtaining the vacuum of the pipe; W is the wobbling magnet that provide a magnetic field with periodic rotation changes. This magnetic field causes the beam on the target to periodically rotate and scan to improve the uniformity and the size of the beam spot on the target [5].

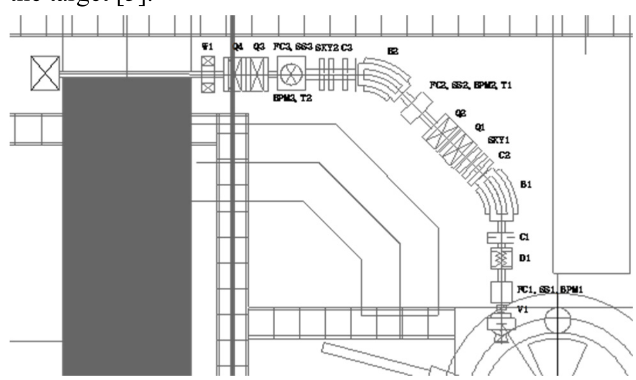

Figure 1: The layout of the 50 MeV beam transfer system.

The total length of the beam line is about 12 m, the inner diameter of the beam pipe is Φ78 mm, and the material is aluminium. The optics and the magnets design will be given in detail.

OPTICS RESULTS

The 50 MeV compact proton cyclotron uses a stripping method to extract the proton beam with the energy range 30 MeV~50 MeV, the maximum beam intensity is 10 μA, and the minimum intensity is 10 nA. The beam with different energy after the stripping foil is transported through the combination magnet into the same beam pipe. The initial input parameters for the optical matching are the σ matrix of the beam on the stripping film provided by the extraction system (calculated by using the COMA program) and the beam transfer matrix of the stripping foil to the exit of the combination magnet (by using GOBLIN and STRAPUBC). The optical matching of the beam line

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is using TRACE 3-D, which uses matrix multiplication to obtain beam characteristics for any section of the beam line [6].

The layout of the beam line, as shown in Fig. 1, has two bending magnets and four quadrupoles to assist with the optics matching.

In the matching, the proton beam of 10 MeV-50 MeV and 10 μA was simulated respectively, and the parameters of each quadrupole were adjusted in the matching to get the size of the beam spot on the target is Φ20 mm.

Figure 2 shows the optics matching results for 30 MeV and 50 MeV. The protons in this energy range can be directly extracted from the cyclotron without the degrader. The matching starts from the exit of the cyclotron. Figure 2 also shows the envelope in both horizontal and vertical directions, the upper one is the optics result of 50 MeV beam and the nether on is 30 MeV. The magnetic field gradient of each quadrupole is shown in Table 1. The beam spot on the target for both 50 MeV and 30 MeV is Φ20 mm.

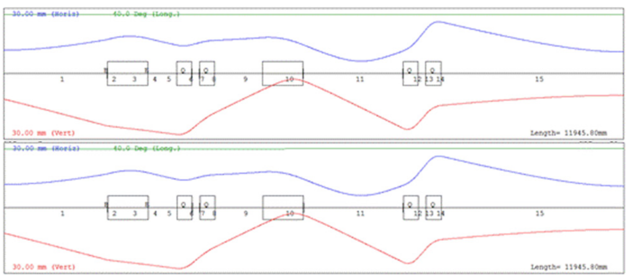

Figure 2: The optics results of 50 MeV (upper) and 30 MeV (lower).

Since the minimum energy extracted from the cyclotron is 30 MeV, the lower energy beam requires by using a degrader, the parameters of the proton beam after the degrader are determined by the collimators. In the matching, after the degrader, the beam parameter is chosen as x=y=8 mm, and x'=y'=3 mrad. The matching is starting at the outlet of the degrader. The optical matching results of the 20 MeV and 10 MeV proton beam are shown in Fig. 3, the upper one is the optics result of 20 MeV beam and the nether on is 10 MeV, the magnetic field gradient of each quadrupole is also shown in Table 1.

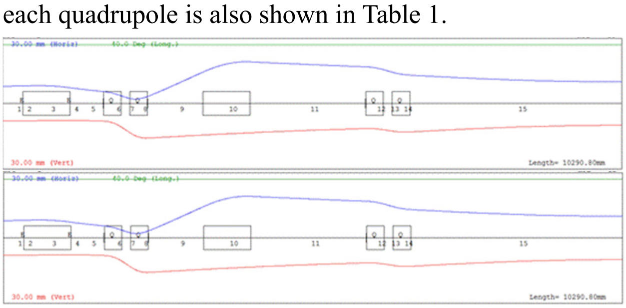

Figure 3: The optics results of 20 MeV (upper) and 10 MeV (lower).

In summary, we can adjust the parameters of each collimators and magnets to obtain the beam energy, beam spot size, envelope size and other parameters that meet the design requirements.

Table 1: Field Gradient of the Quadrupoles for Different Beam Energies

Field / Energy	Q1 T/m	Q2 T/m	Q3 T/m	Q4 T/m
50 MeV	-2.91	1.36	-5.48	5.40
30 MeV	-2.25	1.05	-4.22	4.15
20 MeV	4.18	-2.88	0.91	-1.00
10 MeV	2.95	-2.03	0.64	-0.71

MAGNET DESIGN

Bending Magnet Design

There are two 45° bending magnets on the beam line, which deflects the 10 MeV~50 MeV proton beam to the terminal station and selected the beam energy. The magnetic rigidity of the 50 MeV proton is 1.034 Tm, and the bending radius of the magnet is 1 m, so the maximum magnetic field of the magnet is 1.034 T. The magnet is designed to take a maximum magnetic field of 1.1 T. According to the envelope size of the proton beam in the magnet, the field of the magnet is required to be ±25 mm, and the uniformity of the magnetic field is better than 5×10^{-4}.

The cross section of the magnet is shown in Fig. 4. This figure is a 1/4 model of the magnet cross section. To improve the uniformity of the magnetic field, the padding is added on both sides of the magnetic pole surface. Figure 4 is also shows the distribution of the magnetic field in the magnet. The magnetic field distribution in the magnet is calculated, as shown in Fig. 5. It is calculated that within ±25 mm of the good field, the calculated uniformity of the magnetic field is 1.28×10^{-4}, which satisfies the design requirements.

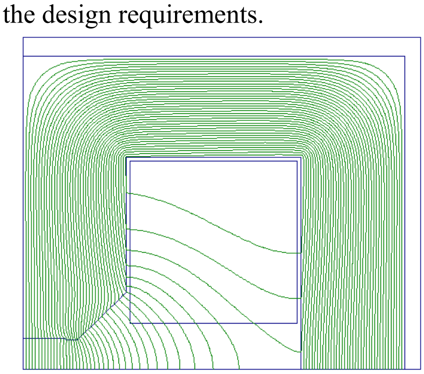

Figure 4: Cross section of the bending magnet.

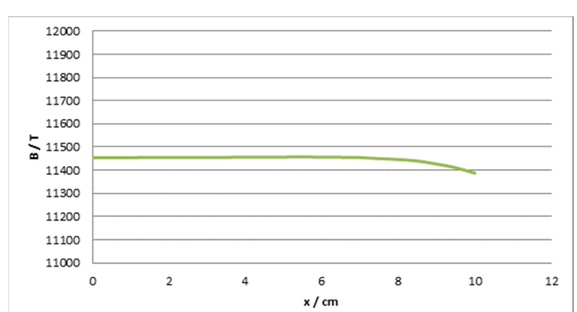

Figure 5: Field distribution along the radial center.

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Quadrupole Design

With the field gradient, the effective length, and the inner bore of the quadrupole, we can determine the pole face width and pole face shape of the magnet and the yoke thickness. Based on these basic parameters, we designed a quadrupole magnet using the two-dimensional computational magnetic field calculation program POISSON.

Based on accurate numerical analysis of magnetic fields and the past experience, here we choose a quadrupole structure with a polygonal tip section as a fold line instead of the theoretical hyperbolic structure. Such a structure has the advantages of simple processing, easy installation and positioning, etc. The difficult is to accurately designing the shape of the magnetic pole through accurate numerical analysis of the magnetic field.

Since the quadrupole magnet is an axisymmetric component, in the design we chose one-eighth model to calculate the field. The specific structure is shown in Fig. 6. The figure also shows the magnetic field of one-eighth of the magnet. distributed.

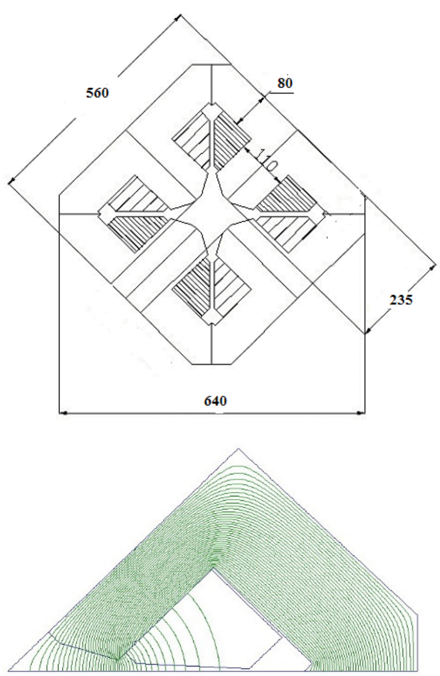

Figure 6: Cross section of the quadrupole.

Wobbling Magnet Design

The wobbling magnet produces a periodic magnetic field perpendicular to the direction of particle motion, which produces a periodically varying force on the particle that causes the particle to scan over the target, as shown in Fig 7.

The voltage applied to the wobbling magnet changes periodically, so that the magnetic field generated by the magnet also changes periodically. The force applied to the particles changes periodically, too. The radius of the particles scanned on the target periodically changes and then get a large uniform beam spot.

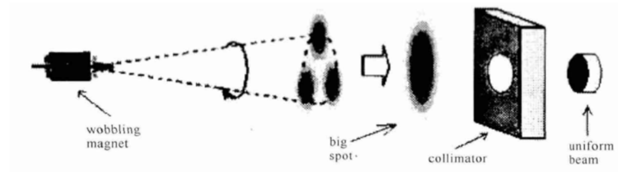

Figure 7: Working principle of the wobbling magnet.

CONCLUSION

Based on the development of a 50 MeV compact cyclotron in the cyclotron center of CIAE, a radiation-specific proton beam line is designed to get the proton beam of 10 MeV-50 MeV, 10 nA-10 μA.

At present, the layout design and optical matching of the beam line have been completed, and various elements such as magnets and diagnostic systems are in the process of mechanical design and processing. It is expected that the installation and beam commission will be completed in 2020.

REFERENCES

[1] T. Zhang *et al.*, "The cyclotron development activities at CIAE", *Nucl. Instr. Methods Phys. Res., Sect. A*, vol. 269, no. 24, pp. 2863-2870, Dec. 2011. doi.org/10.1016/j.nimb.2011.04.047

[2] T. Zhang and J. Yang, "The beam commissioning of BRIF and future cyclotron development at CIAE", *Nucl. Instr. Methods Phys. Res., Sect. B*, vol. 376, pp. 434-439, Jun. 2016. doi.org/10.1016/j.nimb.2016.01.022

[3] S. Wei *et al.*, "Beam line design for a 100 MeV high intensity proton cyclotron at CIAE", *Nucl. Instr. Methods Phys. Res., Sect. B*, vol. 261, no. 1-2, pp. 65-69, Aug. 2007. doi.org/10.1016/j.nimb.2007.04.232

[4] S. Wei *et al.*, "Transfer beamline design after stripping", *Nucl. Instr. Methods Phys. Res., Sect. B*, vol. 266, no. 19-20, pp. 4697-4701, Oct. 2008. doi:10.1016/j.nimb.2008.05.119

[5] Xianlu Jia *et al.*, "Wobbling magnet design on the beam line for a 30 MeV medical cyclotron", High Energy Physics and Nuclear Physics, no. 3, pp. 292-295, 2007.

[6] K. R. Crandall and D. P. Rusthoi, *TRACE 3-D Documentation*, Third Edition, May 1997, Los Alamos National Laboratory.