ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPM034

BEAM DELIVERY SYSTEM FOR BNCT AT TOKYO INSTITUTE OF TECHNOLOGY

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Abstract

Boron Neutron Capture Therapy (BNCT) is useful for cancer therapy. Accelerator-driven BNCT has been desired to be set up in various locations. To generate safe and efficient neutron beams, proton beams are accelerated up to 2.5 MeV and irradiate a lithium target. We are designing a compact BNCT system using a radio frequency quadrupole linear accelerator (RFQ), which deliver such protons to a lithium target. A high-energy beam transport line from the RFQ to the lithium target was designed in this study. The beamline consists of quadrupole magnets, a bending magnet. The beam transport simulations showed the sufficient large beam diameters were obtained in both horizontal and vertical planes with no beam losses. A H-type dipole magnet was designed as a bending magnet. The magnetic field calculation and a beam transport simulation were results in a small and simple H-type dipole magnet that was sufficient to deflect a 2.5 MeV proton beam.

INTORODUCTION

Cancer therapies can be divided into surgical therapy, chemotherapy, and radiotherapy. Radiotherapy, in particular, is expected to show great potential due to the low physical burden of treatment. Boron Neutron Capture Therapy (BNCT) involves accumulating a boron drug in the cancer cells and irradiating them with thermal neutrons [1]. The $^{10}B(n, \alpha)^7Li$ reaction produces alpha particles and lithium nuclei. High linear energy transfer of alpha particles and lithium nuclei causes significant damage to cancer cells while minimizing radiation damage to surrounding normal cells, because alpha and lithium particles have a short path length of about 5 μm and 10 μm, respectively, which is about the size of a single cell.

As a neutron source for the BNCT, nuclear reactors were initially used [2]. Due to the limited location of nuclear reactors, the time required for irradiation adjustment, the large cost required to maintain the facilities, and the shutdown of the nuclear reactors, the neutron sources for BNCT are shifting from nuclear reactors to accelerator-driven ones [3-6]. Accelerator-driven BNCT can be installed in a small area, such as hospitals and university laboratories, because the entire device can be compact. In addition, accelerator-driven BNCT requires less capital investment and does not require nuclear materials, making it more socially acceptable.

In order to produce thermal and epithermal neutron beams for BNCT, reactions of $^7Li(p, n)^7Be$ and $^9Be(p, n)^9B$ can be used by the accelerator-driven BNCT. The resonance peak of the cross section of the $^7Li(p, n)^7Be$ at a proton energy of 2.25 MeV continues up to around 2.5 MeV. The cross section of the $^9Be(p, n)^9B$ reaction increases as the energy of the incident proton beam increases. To obtain a sufficient neutron flux for BNCT, a proton energy of about 4 MeV is required, which leads to an accelerator system being large. In addition, due to the high energy proton beam, there is concern about radioactivation peripherals. Therefore, the $^7Li(p, n)^7Be$ reaction with a proton beam of 2.5 MeV is suitable for the realization of a compact BNCT system, and then maximum neutron energy is 0.787 MeV [7]. However in all cases, a neutron moderator is needed, and cooling of the heat generated at the moderator is also needed.

In BNCT, a neutron flux diameter of about 150 mm is required to match a typical irradiated area. To obtain such the neutron flux, a proton beam diameter of 100 mm or more is desirable. From the point of view of preventing radioactivation of a radio frequency quadrupole linear accelerator (RFQ) by neutrons emitted from the lithium target, the beamline should be equipped with a bending magnet. Furthermore, the accelerator system should be compact in order to being installed in a small area. To satisfy these requirements, a dedicated BNCT system utilizing a high duty factor RFQ is proposed. A 4-vane RFQ with three-layer structure was developed by a collaboration of Tokyo Institute of Technology and Time Co. [8] A demonstrator of the RFQ is already in practical use. In this study, a high-energy beam line from the RFQ to the target was designed.

DESIGN OF HIGH ENERGY BEAM TRANSPORT LINE

Description of the High Energy Beam Transport Line

A schematic drawing of the high-energy beam line for the BNCT system is shown in Fig. 1. The beam line consists of the upstream triplet quadrupole magnets, the bending magnet, and the downstream triplet quadrupole magnets. Based on a simple geometric design, a 10-degree deflecting angle is found to be sufficient to prevent the backflow of neutrons into the RFQ. The length of the beam line is about 3.6 m. The total length of the BNCT system will be about 8 m, including the ion source and the RFQ (3 m).

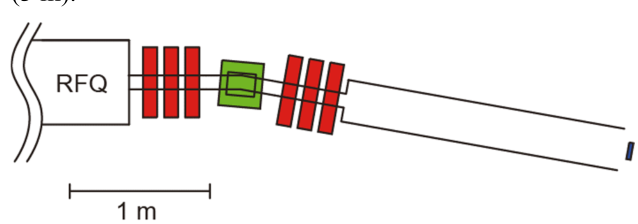

Figure 1: High energy beam line. The red squares represent the quadrupole magnets, the green square represents the 10-degree bending magnet, and the blue square represents the lithium target.

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Beam Transport Simulation

A beam transport simulation of a 2.5 MeV proton beam was performed by using a simulation code WinAGILE [9]. The initial condition of the proton beam is presented in Table 1. These values were calculated on a beam transport simulation in the RFQ.

Table 1: Initial Condition of the Proton Beam

Energy	2.5 MeV
Energy spread	3 %
Normalized RMS emittance	0.29 π mm mrad (hor.) 0.28 π mm mrad (ver.)
Twiss parameter (hor.)	α = 1.46 β = 0.129 mm/mrad
Twiss parameter (ver.)	α = -1.22 β = 0.113 mm/mrad

In this simulation, the focus, defocus, and focus combination in the horizontal plane was set for the upstream triplet quadrupole magnets, while for the downstream triplet quadrupole magnets, the defocus-focus-defocus combination was applied. In order to obtain a large beam diameter at the target position, the length from the downstream triplet quadrupole magnets to the lithium target set as 2.1 m. The normalised quadrupole gradients for the quadrupole magnets were adjusted to obtain a large beam. The simulated beam envelopes and the beam profiles at the target position are shown in Figures 2 and 3, respectively. The RMS beam diameters obtained by using the normalized RMS emittance were about 43 mm and 39 mm for horizontal and vertical planes, respectively. Assuming an overall normalized emittance was five times lager from the normalized RMS emittance, the overall beam diameters were calculated to be 96.0 mm and 87.5 mm for horizontal and vertical planes, respectively. These beam diameters were sufficiently large to obtain the 150-mm diameter of neutron flux, taking account an angular distribution of the neutron from the lithium target [10].

The beam pipe diameter from the RFQ to the downstream triplet quadrupole magnets was set as ϕ 100 mm and was ϕ 400 mm from the downstream triplet quadrupole magnets to the target to accept the large beam diameter at the case of using the five times initial normalised RMS emittance.

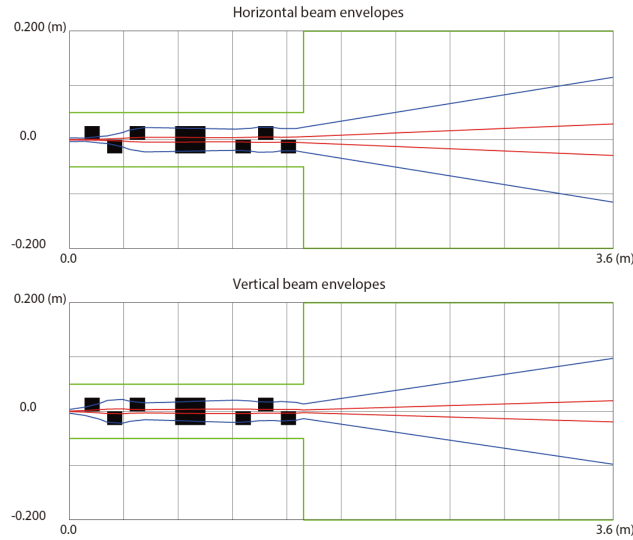

Figure 2: Beam envelopes. The red lines indicate the envelopes using normalized RMS emittance, blue linse using the five times normalized RMS emittance. Green lines are wall of the beam pipe.

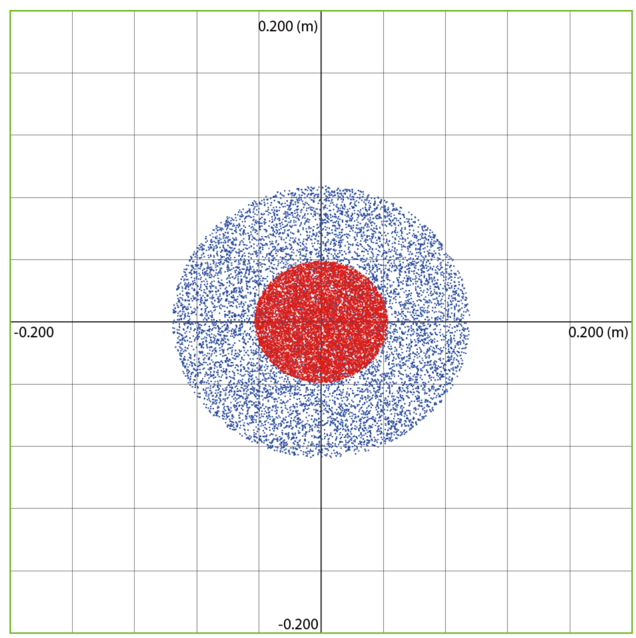

Figure 3: Beam profiles at the target position. The colours are the same as in Fig. 2.

DESIGN OF BENDING MAGNET

As the bending magnet for deflecting 2.5 MeV proton beam, a H-type dipole magnet was designed. The magnetic field calculation and a beam transport simulation were performed by using a simulation code of the CST studio suite [11]. Parameters of the bending magnet are shown in Table 2. A defect angle of 10 degrees was achieved applying 143.8 mT with a central ray radius of 1.59 m. Figs. 4 and 5 show a schematic view of the bending magnet with the beam trajectory, and a calculated magnetic field distribution, respectively. The homogeneity of the magnetic field within a range of ±25 mm was achieved to be 4.2 $\times 10^{-4}$

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adopting the simple-rectangle shape shims. This range was equivalent to the width of the beam assuming the five times normalized RMS emittance. Although a precise design is in progress, this simulation revealed a small and simple H-type dipole magnet is sufficient to deflect 2.5 MeV proton beam.

Table 2: Parameters of the Bending Magnet

Deflecting angle	10 degree
Pole gap	100 mm
Pole length	200 mm
Pole width	160 mm
Entrance angle	5 degree
Exit angle	5 degree
Number of turns	25
Magnetic field	143.8 mT
Radius of central ray	1.59 m

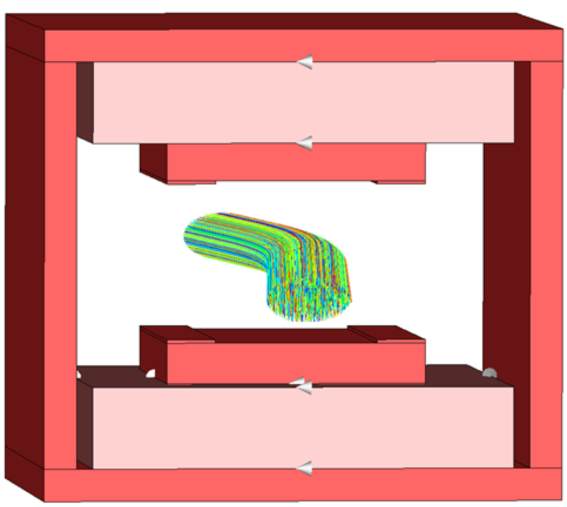

Figure 4: Schematic view of the bending magnet and the beam trajectory.

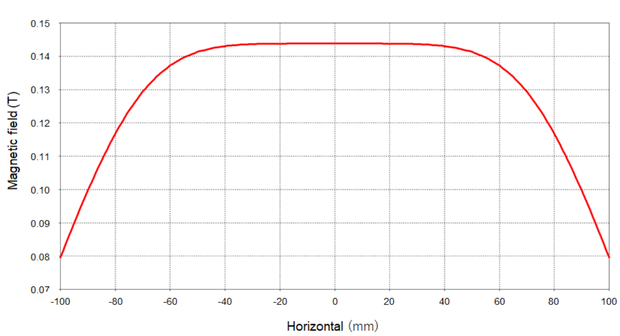

Figure 5: Magnetic field distribution of the bending magnet. A distribution at center of the magnet in the beam direction is shown.

CONCLUSION

The high energy beam transport line for BNCT was designed. The beam line consists of the steerers, the quadrupole magnets and the bending magnet. The 2.5 MeV proton beam transport simulation results showed sufficient large beam diameters were obtained for both horizontal and vertical planes. As the bending magnet, an H-type dipole magnet was also designed, and the beam transport was simulated. Applying 143.8 mT, the 2.5 MeV proton beam was sufficiently deflected about 10 degrees. These simulation results provided prospects for achieving a compact BNCT system.

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