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Irradiation methods and nozzle design for the advanced proton therapy facility

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Abstract A conception design of the Advanced Proton Therapy Facility (APTF) has been carried out. The system intentionally employs a slow-cycling synchrotron with a maximum energy of 250 MeV, two rotating gantries and two fixed beam nozzles for the treatment. In this paper, we try to compare the strength and weaknesses between the two treatment methods: the beam spreading and the pencil beam scanning. The application of the pencil beam scanning method and the double-scattering method together with the related nozzle design at APTF is also given. The simulation results of employing the double-scattering method have been given during the preliminary design.

Key words hadron therapy, irradiation method, nozzle, pencil scanning, spreading system, gantry

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1 Introduction

High-energy hadron therapy has been found to be an effective tool for cancer treatment, especially suited for deep-seated tumors, because the dose distribution beyond the Bragg peak is nearly one-third of the peak and after the dose is deposited, it essentially becomes zero [1–6]. This is probably the most important advantage of proton therapy over traditional X-ray radiotherapy, which should be exploited for the irradiation of tumor surrounding the sensitive structures. Protons (and heavier ions) in general bring a significant reduction (a factor of 2 to 5) in the integral dose deposited outside the target volume, thus improving the effect of irradiation localization control [7]. Nowadays, more than twenty-nine facilities around the world are conducting proton and heavy ion therapy. The Institute of High Energy Physics, Chinese Academy Science has also designed a proton therapy facility – APTF (Advanced Proton Therapy Facility) [8], dedicated to boosting the application of proton therapy in China.

Through many years of practice, the irradiation techniques have been divided broadly into two categories: passive spreading and active scanning [9, 10]. Passive spreading technique means to spread out the beam size to cover the field cross section and to extent in depth of the planning target volume (PTV), which was considered as a relatively simple method to achieve an adequate conformation of the dose to the PTV. This technique is well suited to large tumors and to the ones that are movable with respiration. The active scanning technique is using deflecting magnets to scan the pencil beam over the PTV with sub-millimeter accuracy, which can give a better conformal treatment but is considered technically more complicated [11, 12].

The APTF is supposed to be the first home-made proton therapy facility in China. Mature technologies successfully used world wide will be adopted in its design and construction. The irradiation technique of the nozzle and its design for the APTF will be done step by step, employing the double-scattering technique as a first step and then developing the pencil beam scanning technique later. Furthermore, in order to employ the advantage of multiple-field irradiation, the design and the construction of rotational gantries are the keys in the project.

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2 Comparison among beam irradiation methods

Actually the most used technique is the passive spreading method, which specially uses designed single or double scatterers. The beam from the accelerator will be spread out by multiple Coulomb scattering in the scatterers to cover the cross-section of a whole tumor or a large part of it with a good uniformity. With this technique, it includes beam spreading devices, range modulation devices and field-shaping devices. The simplest way to apply the technique makes use of a single scattering foil or plate to shape a two-dimensional Gaussian-like distribution. For example, a beam with a radius of within 2 cm prepared in this way can be used in treating melanoma or other small size tumors. However, the single scatterer method cannot satisfy the requirement of the beam uniformity in large tumor treatments. To solve the problem, HCL and LBL have developed the double-scattering irradiation method.

The double-scattering beam delivery system uses two scatterers of different materials, and the scatterer thicknesses can be changed in steps to achieve a good uniformity within a tumor depth as large as 20 cm. This method was adopted at Loma Linda University Hospital California (LLUHC). However, with this method, when the beam is scattered, the energy loss in the scatterers is also significant, thus higher beam energy is required to achieve the designed stopping range. Furthermore, when the distance between the scatterer and the isocenter becomes shorter, thicker scatterers have to be used to produce a sufficient uniform irradiation field, thus the energy loss also increases. This becomes an important issue in a gantry where the nozzle length is the key point for the gantry size and weight.

The beam wobbling technique has been developed by using two orthogonal electric magnets to replace the first scatterer while a thin scatterer is kept to produce a uniform dose distribution at the isocenter. In this way, it can minimize the material used in the beam path, thus the energy loss in the scatterers becomes significantly smaller. This method is particularly interesting in carbon therapy, where the fragmentation effect of carbon ions in the scatterers is not good for the construction of a uniform dose volume. Furthermore, the two scanning magnets can be installed before the last dipole of a gantry to save space. Though the method is very efficient, it requires precise magnetic and gating controls, synchronous with dose monitoring and is sensitive to a patient's organ motion. This method was firstly employed by the Heavy Ion Medical Accelerator in Chiba (HIMAC). There are several ways to implement the beam wobbling method such as spiral wobbling, zigzag wobbling, regulated zigzag wobbling, and single wobbling [13].

With the irradiation method using a scanning pencil beam, there is no need to put any scatterer in the beam path. It's the simplest optical system but requires a beam with a good uniformity and a very good stability in the beam intensity. Some elaborated systems such as the feedback system of the deposit dose to the beam handling and safety system have to be developed. The most important issue is that the organ movement by respiration will induce the non-uniformity of the irradiation. Therefore, untill now the spot scanning method is still used for only treating immobilized tumors such as those in head and neck [14]. However, scanning modes such as the repainting technique and the intensity modulated scanning are under investigation. The approach to use a pencil beam scanning system as the basic equipment could be possible in the near future. Both PSI and GSI have contributed to the development of the pencil beam scanning method [15–18].

3 Nozzle design

3.1 Spreading system nozzle design

The APTF accelerator system consists of a linac injector and a slow-cycling synchrotron. The whole facility is designed to equip both beam spreading nozzles and pencil beam scanning nozzles. For the first fixed-beam nozzle, we propose an approach of beam spreading method by combining the double scattering and the wobbling in the same nozzle. The dual-ring scatterer consists of an inner disk with a material of large atomic number and an outer ring with a material of low atomic number. The two scanning magnets located between the first and the second scatterers. The layout of the beam spreading nozzle (BSN) is presented in Fig. 1.

As shown in Fig. 1, the BSN will consist of different devices to provide the required functions for the treatment: the double dual-rings can be used to spread the beam and two scanning magnets combined with a dual-ring provide the spiral beam wobbling. The beam should be monitored through the dose monitors and position monitors. The range shifter regulates the stopping range and the Bragg-peak widening adjusted by the ridge filter. The most

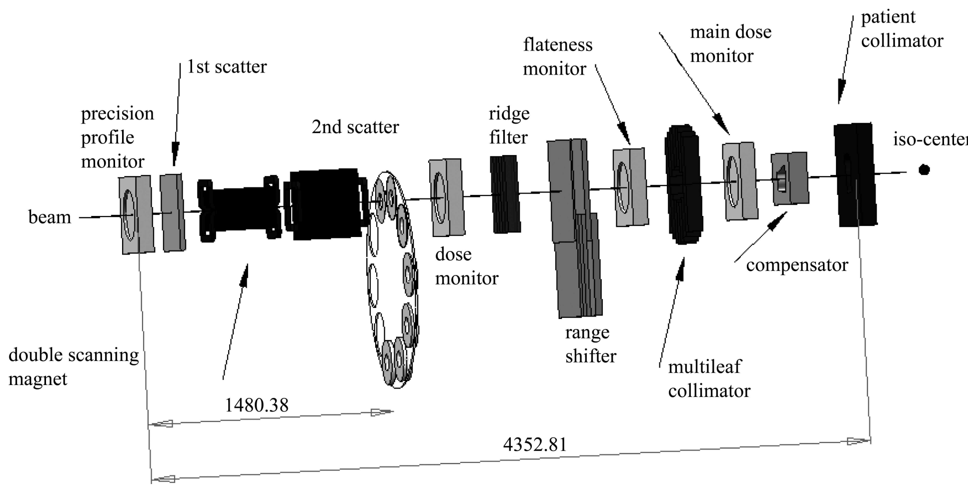

Fig. 1. Scheme of the beam spreading nozzle for the APTF.

important thing is that the patient-position must be aligned during the irradiation. All the elements in the structure are removable from the beam path, which enables an easy switch from the double-scattering mode to the wobbling mode and facilitate the equipment maintenance. Since the uniformity of the irradiation field is sensitive to the deviation of the beam position on the second scatterer, there are at least four monitors to measure the beam position, the profile and the dose. A multi-leaf collimator and a bolus are used for the field-shaping. A patient collimator before the iso-center serves to reduce unwanted proton exposure to the patient. The BSN is designed to measure about 4 m along the beam direction.

We have based the GEANT4 to simulate the double-scattering effect with the given BSN configuration, and obtained an irradiation field of 20 cm in diameter with a uniformity of $\pm 2.5\%$. The main parameters for simulations are listed in Table 1 and the scatterer parameters refer to the results in Ref. [5]. Some particle trajectories are shown in Fig. 2, where 50 particles with energies of 150 MeV and 250 MeV, are used.

Table 1. Double dual-ring mold simulation parameters.

energy	70–250 MeV
beam size	an ellipse of half axis (3 mm, 7 mm)
first scatterer	2 mm Pb+4.6 mm Al, D=35.7 mm
second scatterer	inner part: 3 mm Pb, R=17.85 mm
	outer part: 8.2 mm Al, R=53.55 mm
irradiation uniformity and field	$\pm$2.5%, D=20 cm
beam emittance	5 πmm·mrad
initial beam distribution	Gaussian ellipse in both transverse phase planes

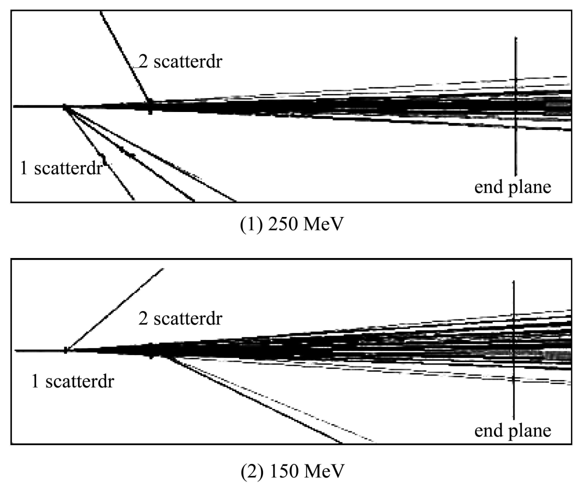

Fig. 2. Trajectories of 50 particles with the two scatterers at 150 MeV and 250 MeV.

As shown in Fig. 2, with the increase in beam energy and the given scatterer thicknesses, the beam spreading becomes weaker. There is also a typical energy distribution after the beam passes through the scatterers, where the particles are grouped into two parts due to the crossing of different materials in the second scatterer. Fig. 3 shows the simulation results about the energy distribution with a total of 1000 particles at these two energies. The results show that the energy loss difference in different materials is even more obvious at lower beam energy. However, this difference is smaller than the energy spread produced by the ridge filter, thus they all contribute to the construction of the spread-out Bragg peak (SOBP).

According to the simulation results, the length of the double dual-ring mold is only around 3 m. If the two wobbling scanning magnets of 25 cm in length each and a gap of 20 cm are added to the nozzle,

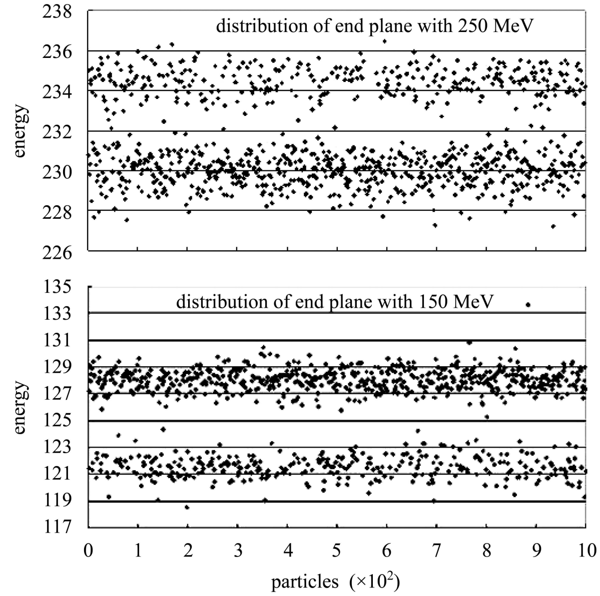

Fig. 3. Distribution at the end plane with 150 MeV and 250 MeV.

about 1 m additional space is needed. Moreover, the X-ray devices providing imaging on the isocenter should be considered to correct the positioning of the patient. The design goal for the BSN is to realize the irradiation in a tumor volume of 20 cm in diameter and 35 cm in depth (water equivalent length) with a uniformity of within ±3.5% by using the double scattering method, and in a tumor volume of 22 cm in diameter and 35 cm in depth with a uniformity of ±3% by using the wobbling method.

3.2 Pencil beam nozzle design

The pencil beam nozzle (PBN) is intended to paint the PTV as the desired treatment planning dose distribution by moving the scanning magnets. There are no other devices between the magnets and the patient except beam monitors (see Fig. 4). The accelerator has to provide long duration and smooth intensity variation beam spills to facilitate the on-line dose detection and patient respiration control.

A PBN usually can work in three different patterns: (1) raster scanning pattern. (2) intensity modulated raster scanning pattern. (3) spot scanning pattern. The basic parameters of the PBN designed for APTF are shown in Table 2. Actually, the pencil beam scanning is considered an advanced technique that is still under development both in laboratories and hospitals. The newest report is that the M.D. Anderson Hospital treated the first patient with proton pencil beam scanning in May 2008 [19].

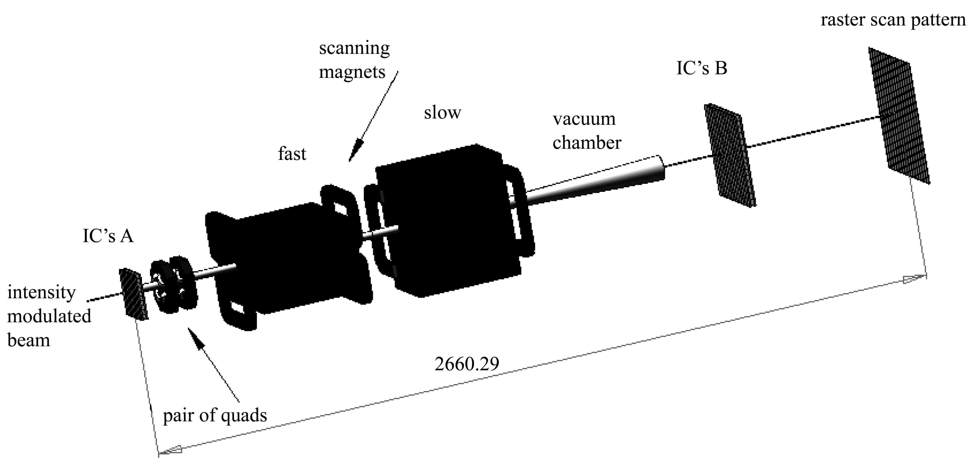

Fig. 4. Scheme of the pencil beam nozzle for APTF.

Table 2. Basic parameters of the PBN for APTF.

irradiation depth (Max.)	⩾30 cm (water equivalent length)
irradiation depth (Min.)	1 cm under skin
lateral penumbra	under skin 10 cm depth about 80% – 20%
distal dose fall-off	about 1.1% of the proton range
dose accuracy (under skin 10 cm depth,	⩽±3%
from 1 cm×1 cm×1 cm to 10 cm×10 cm×10 cm range)	
standard irradiation field	20 cm×20 cm
Min. irradiation field (not including eye treatment)	1 cm×1 cm
extended irradiation field	40 cm×80 cm

4 Related systems with nozzles

A nozzle is the end equipment of a beam transport line. The gantry is a special rotatable transport line to deliver the beam from any direction to the isocenter to conform the PTV. Mounting a nozzle on the gantry can provide more degrees of freedom. However, one of the major problems for a proton gantry is the large installation space. The gantry size becomes even huger when it is designed to have a long nozzle for obtaining a large uniform irradiation field. The alternative way to solve this problem is to consider the gantry and nozzle as an entity especially in the pencil beam scanning. For example, the two scanning magnets can be installed before the last dipole in the gantry. As a result, the transverse dimension can be reduced, but the cost has to be paid by extending the length of the gantry. More information on the gantry design for APTF can be found in Ref. [20].

Besides the hardware related to nozzles, the software also plays an important role in proton therapy, such as the treatment planning system (TPS), the image guided radiation therapy (IGRT), the respiration gate system (RGS), the beam monitoring system (BMS), and the dose safety control (DSC). The images from TPS are imported to the on-line IGRT and the patient alignment (within ± 0.5 mm). The dose deposit measurement should ensure that the applied dose is consistent with the dose planned in TPS. APTF will provide RGS either in a spreading nozzle or in a scanning nozzle to reduce the outer dose of PTV caused by respiration movement. The basic function of BMS is to monitor the dose position and dosage. If accidentally a beam spill has an extremely large instantaneous intensity ($> 10^{12}$ protons/cm^2/s), DSC can dictate the accelerator to stop delivering beam. The online intensity monitoring is also very important to avoid "hot" and "cold" spots in pencil beam scanning.

5 Conclusion

The physical design of APTF nozzles has been discussed above. The principle of the nozzle design is to be reliable, accurate, and easy to realize. As the first beam spreading nozzle to be applied, it will be a combination of the double-scattering using two dual-ring scatterers and the spiral pattern wobbling. Simulations with double dual-ring scatterers resulted in a confirmation of the design concept. The APTF accelerator is able to deliver a good quality beam for the pencil beam scanning method.

The nozzle is a very important and complicated system in proton therapy, and it communicates with different systems including both hardware and software systems. Special attention has been paid to designing a nozzle and a gantry as a whole.

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