ATPF – a dedicated proton therapy facility

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Abstract A proton therapy facility based on a linac injector and a slow-cycling synchrotron is proposed. To obtain good treatments for different cancer types, both the spot scanning method and the double-scattering method are adopted in the facility, whereas the nozzles include both gantry and fixed beam types. The proton accelerator chain includes a synchrotron of 250 MeV in maximum energy, an injector of 7 MeV consisting of an RFQ and a DTL linac, with a repetition rate of 0.5 Hz. The slow extraction using the third-order resonance and together with the RFKO method is considered to be a good method to obtain a stable and more-or-less homogenous beam spill. To benefit the spot scanning method, the extraction energy can be as many as about 200 between 60 MeV and 230 MeV. A new method – the emittance balancing technique of using a solenoid or a quadrupole rotator is proposed to solve the problem of unequal emittance in the two transverse planes with a beam slowly extracted from a synchrotron. The facility has been designed to keep the potential to be upgraded to include the carbon therapy in the future.

Key words hadron therapy, irradiation method, slow extraction, emittance balancing, gantry

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1 Introduction

Nowadays hadron therapy has become a very important method for cancer treatment after many years of clinical studies worldwide. Although the investment in the construction of such a large facility is still very expensive, dedicated hadron therapy facilities hosted by hospitals are rapidly expanding, especially those with proton therapy which requires relatively less investment. China is also on the verge of boosting proton therapy to benefit technical advances and welfare improvement. Based on the expertise accumulated in designing and operating different large-scale accelerators, a team at the Institute of High Energy Physics, CAS has been studying the irradiation method, accelerators, gantries, and nozzles of the proton therapy [1–3]. As an output of the studies, a design scheme to build a dedicated hospital facility–called Advanced Proton Therapy Facility (APTF)–is presented here. This facility can be eventually extended to include the carbon therapy by following the same technical scheme.

2 Design philosophy

The study was focused on what type of beam should be used, what kind of irradiation method should be used and what kind of accelerator scheme should be adopted.

Following the international progress in hadron therapy, we think that both proton and carbon beams are indispensable for the best treatment, but the proton beam should be developed in priority due to its lower investment and the clinically proven treatment effect. Carbon beam or other light ion beams are considered to have better treatment results in highly radio-resistant cancers, but clinical results are still lacking to support the merits of using carbon beam [4]. Therefore, we proposed to build a proton facility first but it will be eventually extendable to include the carbon beam in the future. Apparently, there is another reason for starting with proton whose thera-

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py has a much larger market demand than carbon therapy. It means that in many cases only proton therapy facilities will be built.

The irradiation methods in hadron therapy have also been developing in many facilities. Together with the mature double-scattering method widely used in proton therapy, pencil-beam scanning methods have aroused much attention recently [5, 6]. It is found that the scanning method is very effective in treating tumors that can be immobilized. Even with the double scattering method, the synchronization with respiration becomes more and more practicable. The wobbling method is something between the scattering and scanning method, and is found to be quite efficient in carbon therapy [7]. The irradiation methods in the APTF should be able to reflect all the major progresses.

Among many accelerator schemes applied or proposed for proton therapy such as a linac injector plus a slow-cycling synchrotron [8, 9], a conventional compact cyclotron [10], a superconducting cyclotron [11], a high RF frequency linac with a cyclotron injector [12], a rapid cycling synchrotron with a tandem or linac injector [13] and FFAG series [14, 15], only the first two have long-time medical treatment experience. The accelerator scheme for the APTF should meet the following constraints: technically mature without requiring long time development, relatively lower investment, compatible to all the major irradiation methods as mentioned above, technically applicable to carbon therapy in the future. Another preference condition is that IHEP has already acquired the expertise in designing and building the chosen accelerator type.

We have switched from the original RCMS solution [2] to the present slow cycling synchrotron solution by taking into account the fatal drawbacks of the former: the repetition rate up to 50 Hz is still considered too low for the treatment; it rules out the irradiation methods such as the raster scanning and also the wobbling; it becomes too expensive to build an RCMS for carbon therapy due to the dramatic cost increase in the RF system. The scheme of a linac injector plus a slow-cycling synchrotron is considered to meet all the above constraints, and has been chosen for the APTF. As explained in Section 6, the carbon beam will be provided by an independent accelerator, thus the accelerator design has been optimized only for the proton beam. The main design features of the APTF are shown in Table 1. The general layout of the APTF including future extension is shown in Fig. 1.

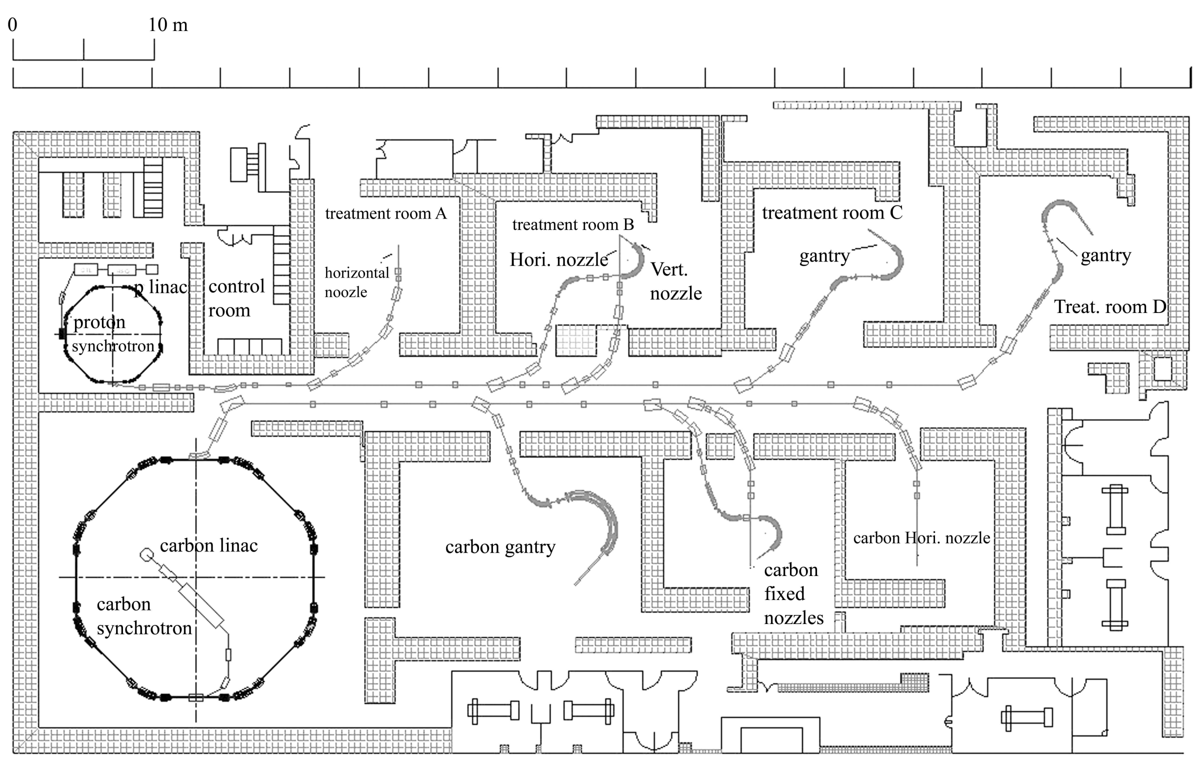

Fig. 1. General layout of the APTF.

Table 1. Main parameters of the APTF.

linac energy/MeV	7
synchrotron energy/MeV	60–250
maximum repetition rate/Hz	0.5
particles per pulse for treatment	1.2×10^{11}
treatment nozzles	2-gantry, 2-horizontal, 1-45°

3 Linac injector

The proton linac injector consists of an ion source of multicusp type, a low-energy beam transport line (LEBT), an RFQ of 2.5 MeV, and a DTL linac of 7 MeV (see Fig. 2). The total length is about 5.5 m. There is a debuncher in the beam transport line from the linac to the synchrotron to reduce the maximum energy spread from a few percent to about ±0.2%. It delivers a proton beam of about 3.6 mA in intensity and 0.15 πmm·mrad (rms) in normalized transverse emittance. The RFQ is designed to have a four-vane structure by following the successful ADS RFQ developed at IHEP [16]. The DTL linac has been designed with high shunt impedance, large transit-time factor and low Kilplatrick surface electrical field [17]. For a DTL linac of such low beam current, it is advantageous to design the drift tube quadrupoles by permanent magnets. The RFQ and the DTL linac have similar RF generators with the frequency of 324 MHz and the powers of 300 kW for RFQ and 400 kW for DTL.

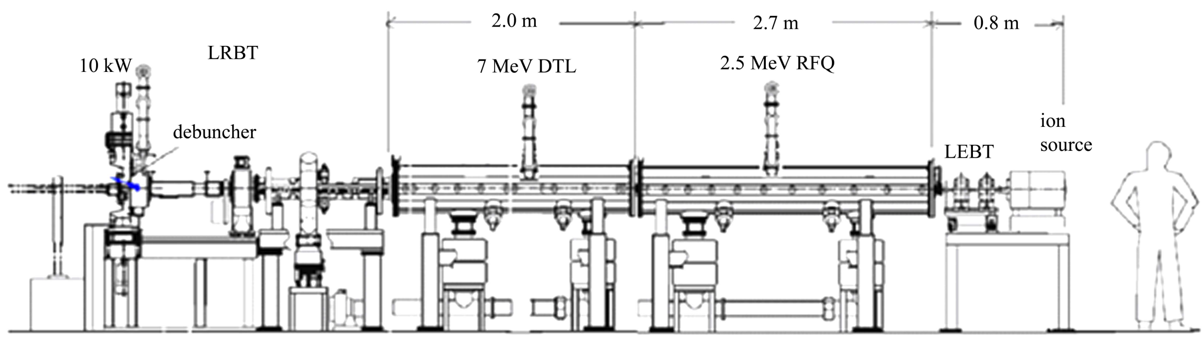

Fig. 2. Schematic of the linac injector.

4 Synchrotron

4.1 Lattice

For such a small ring but with special constraints on the work point, injection and extraction conditions, the lattice design does not have much flexibility. A four-fold FODO configuration has been designed, which has the features of compact structure, small betatron functions in the two transverse planes and four long drift spaces (see Figs. 3, 4). One special merit of the lattice design is that the main dipoles have been designed to have a very weak gradient to help the control on the betatron functions. The long drifts are important for hosting the RF cavity, the injection elements, the extraction elements and the beam diagnostics. The nominal work point is at (1.70, 1.40), and the horizontal tune can be moved close to the resonance $Q_x = 5/3$ just before the extraction. The Hardt condition required for the slow extraction is also met here. The main parameters of the synchrotron are given in Table 2.

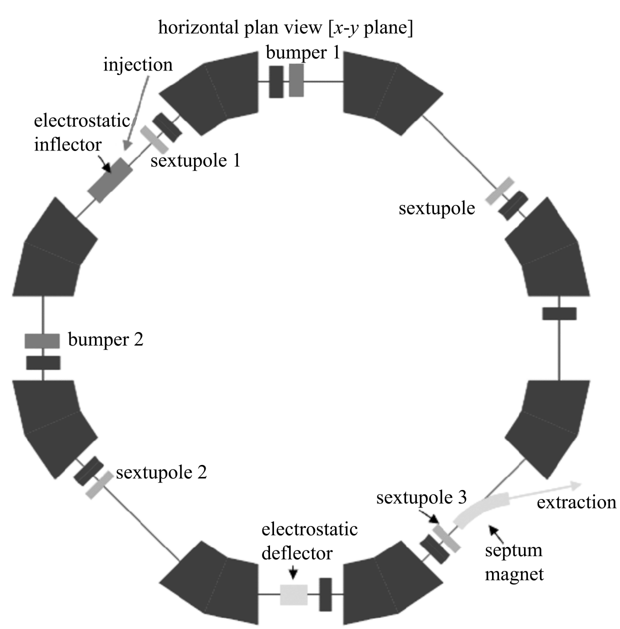

Fig. 3. Layout of the APTF synchrotron.

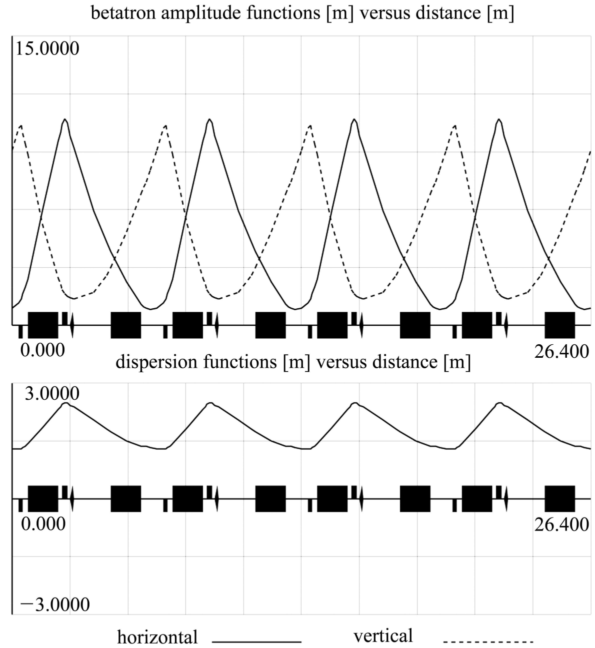

Fig. 4. Lattice functions of the APTF synchrotron.

Table 2. Main parameters of the synchrotron.

circumference/m	26.4
injection energy/MeV	7
extraction energy/MeV	60–250
maximum rigidity/(T·m)	2.432
repetition rate/Hz	0.5
extracted particles per pulse	1.2×10^{11}
physical acceptance/(πmm·mrad)	100/50
injection method	Multi-turn
RF cavity	1
maximum RF voltage/kV	2
RF frequency (h=1, MHz)	1.38–6.97
super periodicity	4
long drifts/m	2.0×4, 1.0×4
focusing structure	FODO
tunes (Q_x/Q_y)	1.70/1.40
maximum β_x/β_y/m	10.076/10.274
maximum dispersion/m	2.52
nature chromaticity ξ_x/ξ_y	$-0.999/-0.077$
transition energy γ_t	1.568

The ring acceptance is defined not only by the beam emittance from the injection energy to the extraction energy but also by the injection and extraction processes, in particular quite a large aperture in the horizontal plane is required at the extraction. This is because a spiral step of 5–10 mm is required to obtain a good extraction efficiency, so that the beam has to execute many turns before reaching the extraction electrostatic deflector to obtain the spiral step as explained in Section 3.4. As a compromise, the ring aperture is defined by the equivalent acceptances of 100 πmm·mrad in the horizontal plane and 50 πmm·mrad in the vertical plane.

4.2 Injection

The beam injection and accumulation are performed by the multi-turn injection method. A pair of bump magnets with a phase advance of π produces a local orbit bump in the horizontal plane that decays during the injection period to fill the phase space. The filling in the vertical phase plane is performed by an injection offset and a special betatron mismatch. An electrostatic inflector of very thin septum is used to minimize the beam loss during the injection. It is important to fill the injected beam into a larger emittance, because the transverse space charge effects are dominant when the beam becomes bunched during the RF capture. The relatively low injection efficiency of 20%–40% is acceptable at such low energy. It is considered that the injection method by stripping H- beam is also feasible. It will produce better beam distribution and less beam loss during the injection with slightly higher cost.

4.3 Acceleration

After the initial RF capture from a coasting beam formed during the injection, the beam will be ramped up to the extraction energy. The acceleration rate is a compromise among different factors. On the one hand, the acceleration time is to be made as short as possible to decrease the waiting-beam time and the treatment time for patients; on the other hand, a slower ramping rate is helpful to reduce the eddy current effect in the magnets and in the vacuum chambers, and to relax the requirement for the RF system. Finally, we have chosen a lower ramping-up rate of 1.64 T/s and a higher ramping-down rate of 3.30 T/s. In order to keep high accuracy of the magnetic field during cycling, the field will be ramped up to the maximum level during each cycle for whatever the extraction energy. The acceleration is carried out by an MA alloy-loaded RF cavity with a maximum voltage of 2 kV. This kind of RF cavity is used widely in medical synchrotrons due to its merit of no need for resonance tuning even with a very large frequency-sweep range. A more traditional ferrite-loaded RF cavity is considered as a backup scheme.

4.4 Extraction

The extraction from the synchrotron should be a slow process according to the treatment requirement. The slow extraction using the third-order resonance is a mature technique, and is also used here. When the beam reaches the extraction energy, the horizontal tune is moved from the nominal 1.70 towards 1.67 that is close to the resonance $Q_x = 5/3$. A pair of sextupoles is excited to shrink the acceptance in the horizontal plane. The particle reaching the acceptance separatrices will go outward following the asymptote with increasing steps, and be extracted by an electrostatic deflector and a septum magnet downstream. The extraction time will vary between hundreds of milliseconds and a few seconds according to the treatment planning. To improve the beam intensity uniformity during the extraction, the RFKO method [18] is also planned, which uses an RF kicker similar to a tune kicker to blow up the horizontal emittance and in the meantime the resonance conditions are then kept unchanged during the spill. This method can also be used to pause and restart the beam extraction process to follow the breathing during the treatment of the cancer tissues moving with the respiration. The extraction design also meets the Hardt condition [19] to reduce the beam loss during the extraction. To benefit the spot scanning method, the extraction energy can be divided into as many as about 200 steps between 60 MeV and 230 MeV.

The ripples of the power supplies of main magnets have a direct influence on the tunes, whereas the change in the horizontal tune affects the extraction process critically as it defines the separatrix of the stable area. Therefore, the power supplies should be designed with the suppression of the ripples to avoid large variation in the extracted beam intensity or a spill. The studies show that the ripple level less than about 2×10^{-6} at 1 kHz band is required.

5 Beam delivery and treatment rooms

5.1 Irradiation methods

According to the clinical experiences, different cancer types require different beam irradiation methods. For example, the pencil beam scanning method is very efficient in treating cancers such as those in the head, neck, spinal chord and lower pelvis where the organs can be immobilized, whereas the double scattering method is more efficient in the breast and abdomen as the respiration will influence the treatment results. Therefore, both methods are planned in the APTF, whereas the beam wobbling method is also very efficient in carbon therapy where we have to minimize the use of the scattering material to avoid the production of reaction fragments.

5.2 Beam delivery lines

The extracted beam will be transported to four treatment rooms with five different treatment nozzles, among them one is equipped with two fixed nozzles using the horizontal and 45° oblique beams, respectively, and two are equipped with rotational gantry nozzles. For the fixed nozzles, both double scattering and spot scanning methods are planned. But the two gantries are designed to equip either a spot scanning nozzle or a double scattering nozzle. For the spot scanning method, the beam stability at the irradiation spot during the treatment and the beam distribution identity when the gantry changed to a different angle are important. Unfortunately, the slowly extracted beam from a synchrotron has a property of very asymmetric emittance in the two transverse planes, with the horizontal emittance much smaller. An emittance balancing technique [20] has been proposed to solve the problem, which uses either a solenoid or a rotator. A rotator is a group of quadrupoles mechanically rotational with the phase advances of 2π and π in the two transverse phase planes. The solenoid or rotator under special matching conditions can produce an identical emittance averaged from the previous two in the two transverse planes. A solenoid is placed just before the gantry using the scanning spot nozzle, and the sum of its beam rotation angle and the gantry angle is either $\pi/4$ or $3\pi/4$. In addition, it is optional to place a solenoid consisting of two identical sections in the trunk line, and the beam rotation angle can be $\pi/4$ with the same polarity or zero with the reverse polarity. The emittance balancing in the trunk line can benefit all the fixed nozzles. Another cheaper solution is also under consideration, which uses a thin foil in the trunk line to blow up the horizontal emittance and produce approximately equal emittance in the two transverse phase planes [21] but the performance is worse than the one with the emittance balancing technique [20].

5.3 Gantries and nozzles

We propose to use two different gantries for the double-scattering and spot-scanning methods. The gantry associated with the double-scattering nozzle will be simple in structure but with a large scale, which to some extent is similar to the one designed by IBA [22]. It will leave a free space of at least 3.0 m from the last magnet to the iso-center. The magnets can be relatively lighter due to smaller beam emittance compared with the degraded beam from a cyclotron. For the spot-scanning gantry, we are considering two solutions: one is similar to the PSI-II type with the scanning magnets placed just upstream of the last bending magnet to reduce the transverse dimension of the gantry [23]; the other one is similar to the one designed by BNL [13] which uses very compact but more magnets to benefit the small and identical transverse emittance. For the last one, two or three quadrupoles after the last bending magnet are needed if one wishes to have a round beam spot. As no beam energy is lost in the scatters, the maximum beam energy of scanning gantries can be lower, e.g. around 200 MeV, to reduce the weight of the magnets.

6 Future extension with carbon therapy

The proton therapy facility can be eventually extended to include carbon therapy by adding a new accelerator which accelerates the carbon beam up to 400 MeV/u. The new accelerator shares almost the same design philosophy but with a larger scale due to the higher beam rigidity for the carbon beam. A slow-cycling synchrotron of about 65 m in circumference can be the choice. It is advantageous to have separate proton and carbon accelerator within the same facility. Thus, the two accelerators can be designed with the best optimization so that the total cost does not increase too much compared with the one synchrotron scheme, and the facility can provide simultaneously the proton and carbon beams for the treatment. Certainly, this arrangement becomes very flexible if one considers that many proton therapy facilities will stand alone without carbon beam.

7 Summary

The conceptual design of a dedicated proton therapy facility has been carried out. The accelerator scheme uses a linac injector and a slow cycling synchrotron. The good quality of the extracted beam can be ensured by the third-order resonance together with the RFKO method. Both the double-scattering and the pencil beam scanning methods will be used. Two fixed-beam treatment rooms and two gantry rooms are planned and the further extension of the treatment rooms is also possible. The facility can also eventually be upgraded to include a carbon accelerator and related treatment rooms.

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