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SAPT- A SYNCHROTRON BASED PROTON THERAPY

M. Z. Zhang †, Z. L. Chen, R. Li, M. Gu, L. R. Shen, Z. T. Zhao, Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China
D. M. Li, Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, China
X. B. Wu, Shanghai APACTRON Particle Equipment Co., Ltd., Shanghai, China

Abstract

SAPT is a synchrotron-based proton therapy which built in Shanghai, China. There are 4 treatment rooms and a main ring, a linac injector and the transport lines that between them. The main ring is a 24.6 m long and 8 dipoles synchrotron. The synchrotron employees multi-turn injection and 3rd order extraction. The treatment rooms are ocular beam line, fixed beam line, 180-degree gantry beam line and 360 gantry beam line. Now, the first unit (fixed beam line, 180-degree gantry beam line) has finished the 3rd party testing and clinical trial, will open to patient treatment soon. the accelerator and beam lines will be described in this paper.

INTRODUCTION

As the first proposal by Wilson at 1946 [1], proton deposits most energy at the end of its trace [2], well known as ‘Bragg Peak’. In comparison with photons, the normal tissue that proton passed receive very low dose. The most important thing is proton can stop. And the vital organs are refrained from irradiation, because there is no energy deposited after the ‘Bragg Peak’. These features, proton therapy is known as one of the best ways for cancer treatment. Since the and the first dedicated proton therapy in hospital in 1990s [3], the requirement and application of proton therapy grew rapidly, especially in the 2010s. The number of proton centers in operation increases to 98 and 31 centers under construction at 2022 [4].

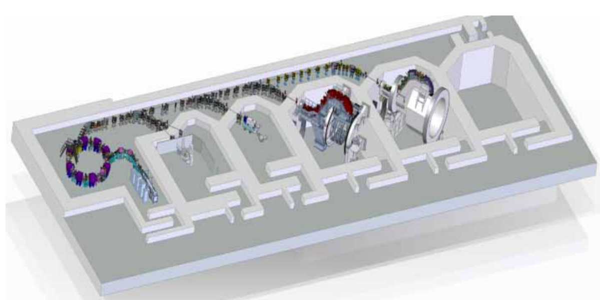

Figure 1: Layout of gantry beam lines.

Shanghai APACTRON proton therapy (SAPT) [5] is a synchrotron-based proton therapy that funded by Shanghai local government and science and technology department of China. There are 4 treatment rooms and 5 beam lines, including an ocular beam line, an experiment beam line, a fixed beam line, a half gantry beam line and a full gantry beam line, as shown in Fig. 1. The installation started at the end of 2016 and the commissioning of the accelerator started at the end of April 2017. The first unit (accelerator, fixed treatment room and half gantry room) has passed the 3rd party testing and clinical trial at 2021 and 2022, and will open to patient soon. The general specifications of this facility are shown in Table 1. The details of accelerator and treatment systems are described in the next sections.

Table 1: General Specifications

Parameters	Value
Energy Range	70~235 MeV
Energy Levels	94
Range in Water:	0~34.0 g/cm^2
Dose rate:	1 Gy/min/Liter
Extraction intensity per spill:	4~8×10^{10}
Accelerator:	FODO, 8 bends
Circumference:	24.6 m
Injection :	Multi turn painting
Extraction:	3rd resonance
Ramping time:	0.7 s
Repetition rate:	0.5~0.1 Hz(variable)
Field size:	30 cm ×40 cm
Beam Delivery Method:	Spot Scanning

ACCELERATOR

The accelerator includes a 7 MeV LINAC, a synchrotron, two different gantries, and transport lines between them. Synchrotron is the main part of the accelerator.

Synchrotron

The synchrotron of SAPT is a FODO-like structure of 4 cells and 2 super periods, totally 24.6 meters long ring. It consists of 8 dipoles and 12 quadrupoles to suppress the beta function to less than 5 meters at the vertical plane in dipole, as shown in Fig. 2. More smaller beta function will make more larger acceptance. The space charge effect [7], which leads to tune shift and limits the maximum beam current, will benefit from the large acceptance. There are 4 long straight section for injection and extraction, RF cavity. 8 short straight sections are used for the beam diagnostic and vacuum elements.

In order to reduce the beam loss at the electronic extraction septum, the Hardt condition that aligns the separatrices of different momentum [8] is satisfied on the lattice. The protons keep below transition energy, and in order to avoid head-tail instability, the chromaticity should be negative. That means the sign of dispersion and its derivative should

† zhangmz@sari.ac.cn

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be different. Two sextupoles are used to correct the chromaticity. The phase advance of these two sextupoles are nearly 2π, thus they affect the resonance driven term very little if the strengths and signs of them are same.

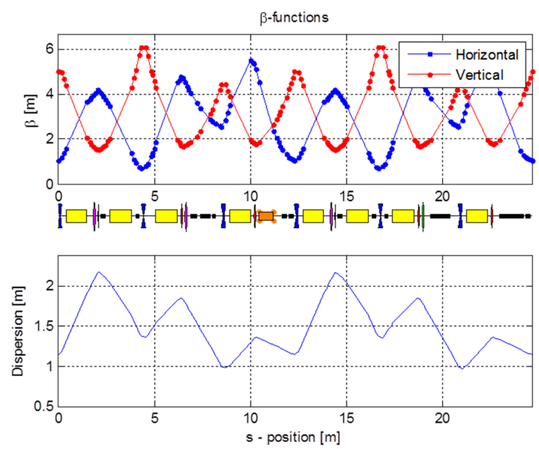

Figure 2: Twiss Function.

Injection

In order to reach the beam intensity requirement, a multi-turn injection scheme is employed for beam accumulation. The injection scheme employed a magnet septum, an electronic septum and two bumps. The beam intensity is limited by space charge effect. The space charge effect can be reduced by enlarge the beam emittance via phase space painting method. Horizontal phase space painting is performed by around 30 turns bump decrease. And the circulating beam current is about 10 times as large as the injection current from the Linac accelerator. Vertical phase space painting is realized by Twiss parameters and orbit mismatch. Figure 3 shows the horizontal phase space painting result.

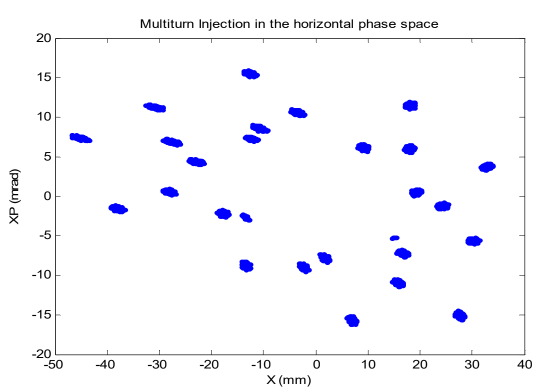

Figure 3: Painted beam in Horizontal phase space.

After injection, the proton beam is captured and accelerated to the required energy. After the eddy current correction by the power supplies [9], the maximum particle number after acceleration is 1.3×10^{11} with second and third harmonic RF voltage.

Extraction

The proton beam is extracted by a 3rd order resonance slow extraction. The horizontal tune should be closed to 2/3. The oscillation of beam is excited by RFKO and the tune is measured by oscilloscope. The current of QF and QD is changed to correct the tune. Two sextupoles are placed on opposite sides of the ring to produce resonance driven term. The strengths of these two sextupoles are opposite, so they will not affect the chromaticity. Figure 4 shows the phase space after sextupoles are turned on. The particles, that enter the unstable region and cross the septum filament, are kicked by the electronic field. Then they pass quadrupoles and dipoles. Finally, they are kicked by magnetic septum and are extracted to the high energy transport line.

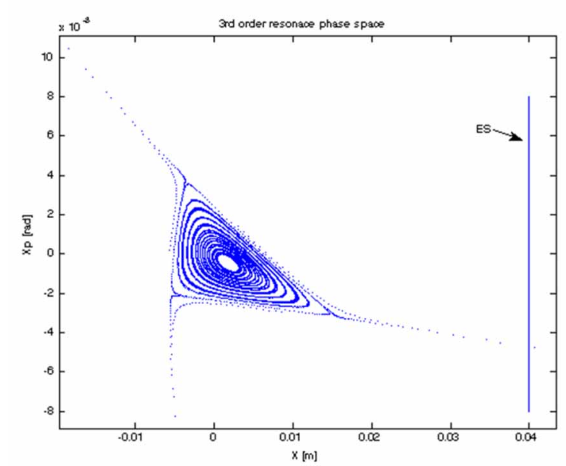

Figure 4: Extraction phase space.

The extraction current, which is decide by the rate of particles enter unstable region, is controlled by the amplitude modulation of RFKO (Radio Frequency Kick Out) system [5, 10, 11]. The extraction beam current is shown in Fig. 5.

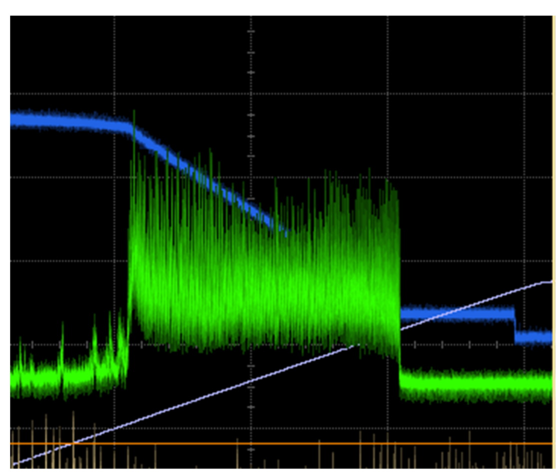

Figure 5: Extraction beam current.

Gantry

Rotating gantry is the most advantage of proton therapy compared to heavy ion therapy. It gives the medical physicist more choice to reduce the dose at normal tissue. Two

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gantries based on round beam method is designed [12]. Figure 6 shows the structure of the half gantry. The magnets of this gantry form a telescope that makes the beam at the exit of this gantry is the same of the one at the entrance. The weight of rotated part is around 100 tons and whole weight is around 170 tons. In order to reduce the size and weight, short SAD and combine function dipoles are used in the full gantry. The measured accuracy at the ISO center is 0.2 mm when the gantry rotated.

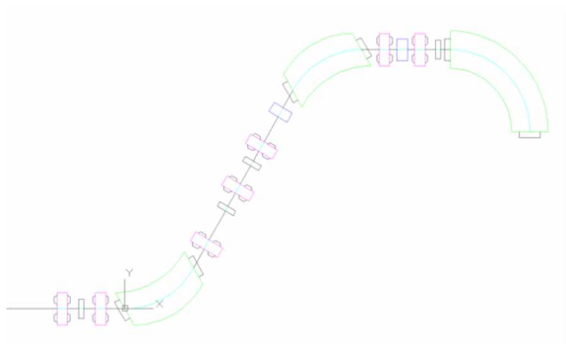

Figure 6: The lattice structure of the full gantry.

TREATMENT SYSTEM

The treatment system includes beam delivery system, positioning system, treatment control system and so on. We positioning the patients or QA equipment to the required place by using a robot couch, laser system and IGRT. The movement and rotation accuracy is 1 mm and 0.2 degree. The treatment control system receives treatment plans and image information from TPS, then send them to IGRT and beam delivery system, respectively. At last, receives and conforms the results after positioning or treatment.

Beam Delivery System

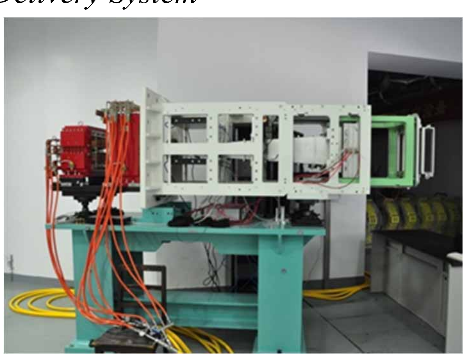

Figure 7: The structure of nozzle.

Pencil beam spot scanning is more and more widely used in the hadron therapies because of the excellent three-dimensional conformability. The beam delivery systems of fixed beam, two gantry beams are all this type. It includes 2 scanning magnets (Horizontal and vertical) in order to swap the beam to the required position. There are also 2 dose monitors and 1 position monitor and their electronics. The former ones are used to double check the passed proton number to control the dose. The later one is used to monitor the beam position They are all iron chambers. Figure 7 shows the structure of these parts, named nozzle. And the control system of the beam delivery system is outside the treatment room.

Beam Performances

The most important beam performances of a therapy facility are always measured in the treatment room. Table 2 shows several parameters of the facility.

Table 2: Beam Performances

Parameters	Value
Dose Linearity	<3%
Dose repeatability	<2%
Dose stability	<2%
Range stability	<0.3mm
Spot Dose accuracy(rms)	<30 counts
Dose rate	8-10 MU/s
Position accuracy	<1mm
Beam Size accuracy	<15%

Figure 8 shows the beam size of every energy, and Fig. 9 shows the beam position at center. All the beam performance passed the 3rd party testing and acceptance of the hospital. And the clinical trials that has finished shows very good curative effect.

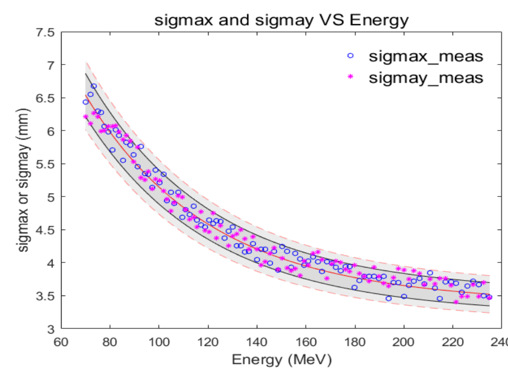

Figure 8: Beam size of every energy.

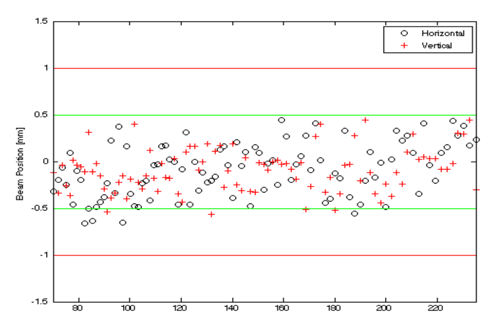

Figure 9: Beam position.

CONCLUSION

A dedicated synchrotron is designed, constructed and commissioned in Shanghai. The lattice, injection, acceleration, extraction, gantry and beam delivery system have been well studied and commissioned. The beam parameters reached the requirements and passed the 3rd party testing and clinical testing. The full gantry room and ocular beam line should take more time for the commissioning.

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