The Lattice design of a proposed Beijing Therapy Proton synchrotron

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1 INTRODUCTION

Beijing Therapy Proton Synchrotron (BTPS) will be a dedicated machine for medical purpose. The injector is an RFQ linear accelerator which energy is 6 MeV, the extracted energy is from 70 MeV to 200 MeV. The injection with single turn is chosen and the fast extraction is adopted, the slow extraction will be considered in the next step. The extracted beam current is 5 nA, the repetition rate is 2 Hz and the extracted particle number is 3×10^{10} protons per second. Two long straight sections are used to install injection and extraction elements. This paper gives a lattice design of the synchrotron and discusses some of its advantages.

2 LATTICE OF THE SYNCHROTRON

The machine consists of two super-periods. There are three bending magnets, five quadrupoles and two sextupoles in each super-period. One long straight section is used in each period in order to install the cheaper elements for injection and extraction (Fig. 1).

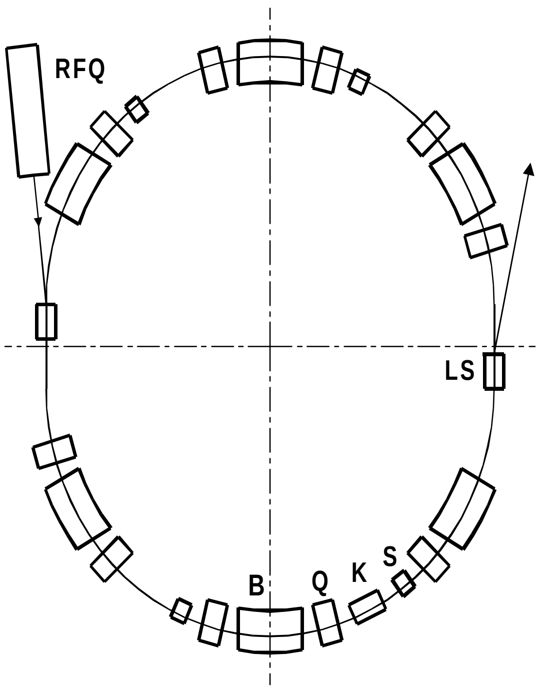


Figure 1. The layout of the BTPS

From the viewpoint of the budget, considering the space charge limits and the aperture size, one skew quadrupole is used to adjust the coupling of the emittance to keep the horizontal and vertical emittance same when the beam is extracted but the emittances in horizontal and vertical plane are different during the beam injection. To take the advantage of the edge focusing, several quadrupoles are missed and the long straight section can be more longer. The longer straight sections are used for injection and extraction so that the strength of the elements can be reduced lot. Only one kicker is used in the machine for both injection and extraction.

The parameters of the machine are listed in table 1.

Table 1 Parameters of the machine

Injection energy	6.0	MeV
Extraction energy	70 ~ 200	MeV
Circumference	34.4	m
Space charge limit of injection	5×10^{10}	Proton/per pulse
Injection time	1.081	μs
Extraction time @ 70 MeV	0.3132	μs
@ 200 MeV	0.2025	μs
Repetition rate	2	Hz
Accelerating time	0.25	s
Extracted particle number	1×10^{10}	ppp
Extracted current	5.0	nA
Lattice structure	DOFB	
Long straight section	3.7	m
Q_x / Q_y	1.76/1.72	
Maximum β-function β_x / β_y	7.8/7.9	m
Emittance @ 6 MeV	28.9	mm·mrad
@ 70 MeV	10.8	mm·mrad
@ 200 MeV	6.2	mm·mrad
Vaccum chamber size (H×V)	75×50	mm·mm
Radio frequency	0.7504 ~ 4.9345	MHz
Maximum voltage of RF	800	Volt
Energy spread @6 MeV	3.2×10^{-3}	
@70 MeV	7.9×10^{-4}	
@200 MeV	3.0×10^{-4}	

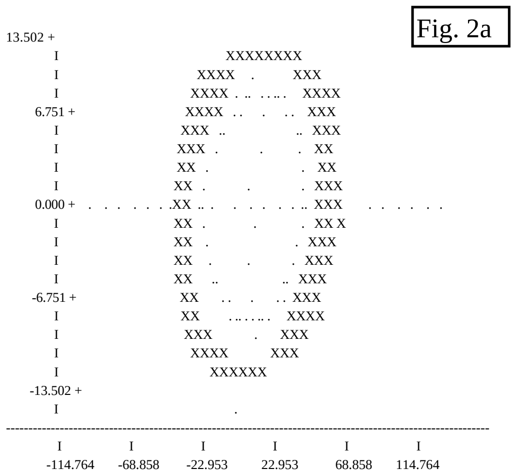
3 APERTURE

According to the medical requirements, the extraction beam current is 5 nA which corresponds the particle number is 3×10^{10} protons per second. The single turn injection scheme is chosen in the design, the beam injection time is 1.081μs. The fast extraction is used in the first step of the design with the beam extraction time is from 0.2042 μs to 0.3323 μs which corresponds the extraction energy from 70 MeV to 200 MeV. The accelerating time is 0.25 s and the restoring time of the magnetic field is 0.25 s. We assume that each effeciency of injection, capture, acceleration, extraction and the beam transfer (before injection and after extraction respectively) is 80 %, then the total effeciency is about 26 %.

After the beam accelerating from 6 MeV to 70 MeV, the factor of the emittance adiabatic condence is $\beta\gamma$ (6 MeV) / $\beta\gamma$ (70 MeV) = 0.2878. Assuming the emittance is increased 2 times naturely due to some of other reasons, the real emittance condence is about 60 %. According to the medical treatment purpose, the extracted beam from the synchrotron may be bent in horizontal and vertical plane. We use one skew quadrupole in the design to adjust the horizontal and vertical plane during the acceleration of the beam so that the magnet vertical aperture can be fully filled by the beam in the whole acceleration progress and the beam transverse shape can be controlled as a circular while the beam is extracted. In order to keep the vertical beam size unchanged and the horizontal beam size condenced gradually in the whole acclerating process, the coupling of the emittance ε_h / ε_v from the linac should be larger than 1.

4 CHROMATICITY CORRECTION

The natural chromaticities of the synchrotron are ξx /ξy = -0.2854/-2.8205. In order to eliminate the head-tail instability of the lowest mode and reduce the frequency spread which caused by energy spread, four sextupoles in two families are used to correct the chromaticity larger than zero. After tracking study by the computer code, the chromaticity correction makes the dynamics aperture larger than the physics aperture. The tracking results in the phase space are shown in Fig. 2.



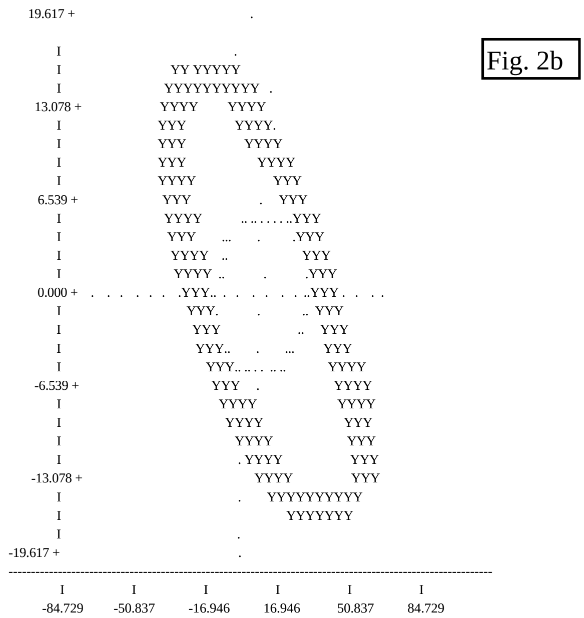


Fig. 2 Tracking results of the synchrotron

5 INJECTION AND EXTRACTION

The lattice pattern is of great advantage to beam injection and extraction. On the first stage, we only consider the fast extraction. The layout of the injection system laid on the longest straight section consists of only two components: a septum magnet and a kicker magnet. Because of the straight section is long enough so that the beam from the injector can be entered directly into the septum magnet with a small angle leading to needlessness of a deflector. Injection takes place in the horizontal plane. The effective length of one turn septum magnet is 30 cm. The Lamination core is curved for increasing the effective aperture. The septum thickness is 3 mm, and the maximum field is nearly 1 kG excited by a pulse current. The peak exciting current is about 2 kA supplied by a half sine wave power supply . The bottom length of the half sine wave is 0.5 ms. Pulsing magnet eliminates the need of water cooling. In order to reduce the cost, it is suggested to use one kicker system for both injection and extraction. This suggestion is based on the following considerations:

First, the kicker strengths required by beam injection and fast extraction are close to one another (0.14 kG-m and 0.16 kG-m) in spite of beam energies for both are quite different. Second, according to our experiences, the very short fall time (~50 ns) of the pulse field needed by injection can be realized by using clipper switch. Third, the pulse resonant power supply used for charging the PFN will make easy to change the kicker strength for both usage. The kicker consists of a C-core ferrite transmission-line type magnet of cellular construction excited by a double-cable pulse forming network via main switch and clipper switch (the later is only for injection). The magnetic field of the kicker is about 270 Gauss excited by a pulse current of ~1 kA. The maximum charging voltage is about 50 kV. So the thyratron CX1168 will be suitable. The sketch of this kicker system is shown in Fig. 3.

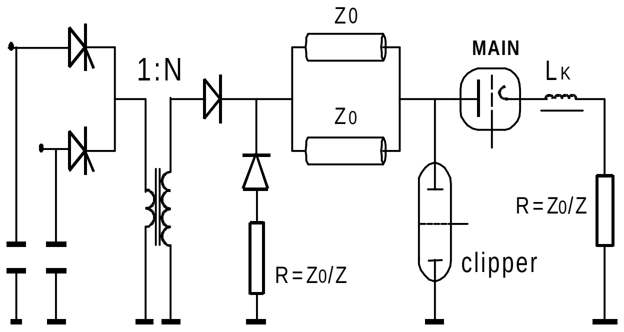


Fig. 3 Sketch of the kicker system

The proton beam is extracted vertically by a Lambertson magnet located on the downstream straight section. The phase advance between the kicker and Lambertson magnet is 85 degree. Two bumpers move the close orbit somewhat towords the extraction septum and then the fast kicker kicks the beams into the otherside of the septum. Finally, the beam is bent down 13.5 degree by the Lambertson magnet, and if not bent back to the horizontal plane, continues straight down to a beam dump embedded in the floor. That is to say, a downsream magnet must be energied to take beam to the treatment rooms. The effective length of the Lambertson magne is 100 cm. The maximum field is about 5 kG excited by a DC current of 400 A and the septum thickness is 3 mm. A second vertical dipole similar to the Lambertson magnet but without the septum is used to deflect the beam back to the horizontal plane for transferring down the beam line. The synchrotron comes naturally with another longest straight section that can be used for slow extraction of the beam and we are reserving it in our design for possible future use.

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