MEDICAL SYNCHROTRON FOR PROTON THERAPY

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A synchrotron is expected as a facility for a proton therapy, because it can provide the beam covering the wide energy range and is considered cost effective compared to other types of the accelerators. The proton beam is extracted from the synchrotron and utilized for the patient treatment through the beam channel. Both slow and fast extracted beams are required to facilitate the therapies with the different approaches. The design studies have been made on various lattices from the view point of the effective beam extraction.

Introduction

The hospital-based proton accelerators have been awaited for a long time duly from the excellent experience obtained in the clinical application of the proton beam from the existing accelerators built for physics researches. The dedicated medical accelerators must be easy and safe in operation, and reliable in treatment. These requirements are not always met in the accelerators available at present.

The former study on the design had been based on an AVF cyclotron from which the continuous proton beam is obtained at enough intensity for the treatment [1]. Average beam current required is 20 nA at most and the maximum beam energy is around 250 MeV for practical purpose [2-4]. Intensity is lower compared to the modern physics application and it is desirable to put emphasis on the design how to realize the economical machine with enough beam stability. Both capabilities of the slow and fast beam extractions considered here limit the selection of the type of the accelerator. The synchrotron has advantages over the cyclotron in many aspects such as in the beam extraction, the energy variability and perhaps the construction cost.

For the design of the synchrotron, the beam aperture in the magnet should be considered in conjunction with the injection energy, the space charge limit and the repetition rate to achieve the required average beam current. Here we assume an injector of 5 MeV examining a commercially available Tandem machine with the terminal voltage of 3 MeV. To the contrary, a possibility using a fast cycling synchrotron of several Hz is discussed to save the injector cost [5].

Synchrotron cell structure

It is possible to adopt higher repetition rate by utilizing the LC resonant network for the power supply of the magnets and to make the flattop during the slow extraction bypassing the oscillating current through the SCR or GTO switches [6]. An advantage of this power supply lies in a cost reduction of the ac power supply facility, in particular, the reactive power compensator, because it enables the use of the power storage capacitor. This type of the power supply, however, is expensive and requires much cares compared to the SCR rectifier. Therefore in our case the trapezoidal current wave form is preferable using the well experienced SCR rectifier. Its repetition is limited mostly by the speed of the current control and the maximum ramping rate of 2.6 T/sec seems to be reasonable. When the slow extracted beam is required, the repetition is 0.5 Hz including flattop of 0.5 sec or so. And when the fast extracted beam is necessary, the repetition rate is increased close to 1 Hz. The selection of either of both modes can be easily made under the computerized control system.

Tracing back from the effective beam of 2-6 nA into the tumor, the beam delivery efficiency of 20-30 % in the double scattering method requires an average current of 10-20 nA in the synchrotron assuming 100 % extraction efficiency [2]. If the raster scanning method improves the beam delivery efficiency, the circulating beam intensity will be reduced. The multi-turn injection into the horizontal phase space will be inevitable to achieve an average beam intensity required. An average intensity of 10 nA will be realized with the effective 10 turn injection allowing the tune shift of 0.15 due to the space charge forces at 0.5 Hz repetition rates. For the fast extraction it will be twice of this value.

Since the medical synchrotron is located at the hospital, it should be compact enough to be installed in a restricted space. Design studies are made on several cell structures considered attractive judging from some points mentioned above. Some of them are listed in Table 1. In the table "No" means that the extraction is very difficult or its efficiency is low.

The cell of BDBO is the design of FNAL under contract to the Loma Linda University Medical Center and uses the edge focus of the bending magnets whose angle should be strict because it only determines the betatron tunes [7]. In the DOFB cell with the long straight sections of 3 m, however, the horizontal and vertical tunes are corrected and varied with the focusing and defocusing quads and the random variation of the edge angle of the bending magnets is allowable within a few degrees. It greatly eases the fabrication of the bending magnet making both ends parallel with the established technique. The effects of the systematic and random variations of edge angle are shown in Fig. 1. As the compensatory range of the vertical tune is less than +2 degrees with the defocusing quad, the systematic variation of the edge angle must be less than +2 degrees. The random edge variation due to the fabrication error is acceptable up to ± 3 degrees.

If the long straight section near the focusing quad is made as long as 3 m or more in the FOBDO'B cell with 6 superperiods, it enables to extract the slow beam from a single straight section. For the case of the combined function FDO structure with 6 superperiods, the separate excitation of the focusing and defocusing magnets or the additional extraction quads and longer straight sections are necessary to get the slow extracted beam. In either case larger circumference is desired for the slow extraction.

Table 1 Several cell structures for the medical synchrotron

Cell	BDBO	FOBDO'B	FDO	DOFB
Focusing	edge	quad	combined	quad+edge
Superperiod	4	4 or 6	6 or 8	6
Av. radius (m)	3.0	4.0 or 5.2	4.4 or 5.0	5.6
Bend. radius (m)	1.6	1.6	2.675	1.55
Tune (H/V)	0.6/1.3	1.75/1.25 or 1.75/1.75	1.75/1.75 or 2.25/2.25	1.80/1.85 1.80/1.85
Tr. gamma	0.583	1.448 or 1.572	1.434 or 1.928	1.561
Edge angle of B. Mag. (deg)	18.8	15	0	30
Slow extr.	Yes	No	No	Yes
Fast extr.	No	Yes	Yes	Yes

B = bending magnet, F = focusing quad, D = defocusing quad
O,O' = long straight section

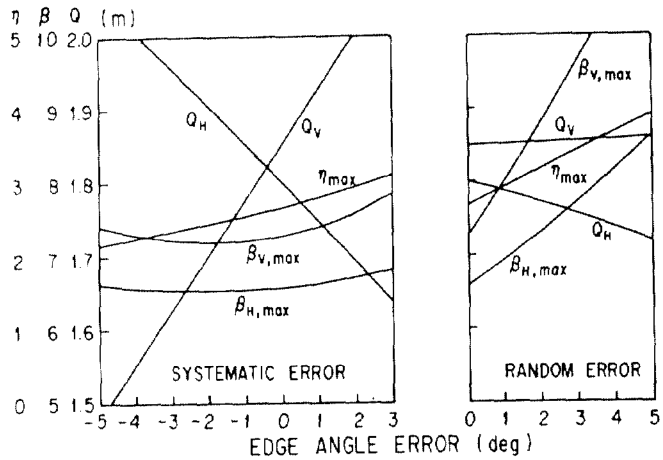

Fig. 1 Effects of systematic and random variations of the edge angle of the bending magnet.

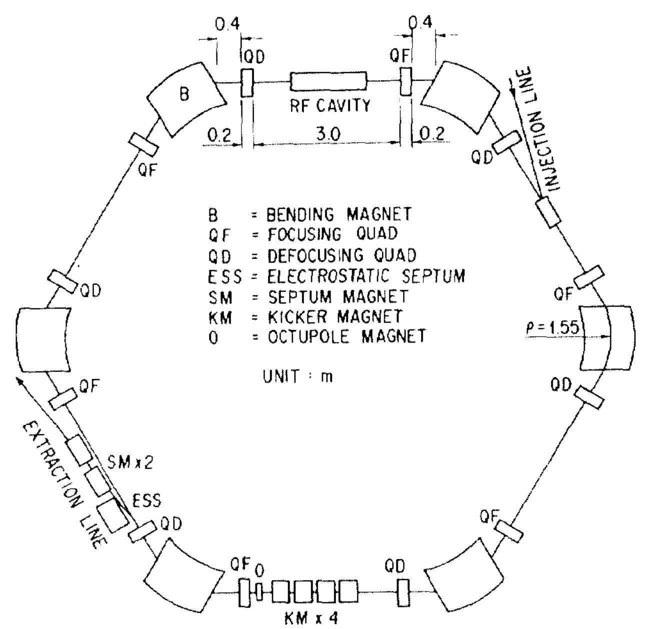

Fig. 2 Proposed DOFB cell structure.

The kicker magnet is used for the fast beam extraction. It requires somewhat large circumference for beam to travel long before the field of the kicker magnet settles. Since the settling time is about 70 nsec in the fastest case, the circumference should be longer than 25 m for the 230 MeV beam. In addition, the space is required to install several sets of kicker magnets.

The proposed DOFB cell structure is shown in Fig. 2 and its parameters are given in Table 2. The lattice is suitable for both slow and fast beam extractions which are treated in details in the next section.

Table 2 Lattice parameters of DOFB cell

Max. energy	230	MeV
Inj. energy	5	MeV
Superperiod	6	
Av. Beam intensity		
0.5 Hz repetition	10	nA
1 Hz repetition	20	nA
Av. radius	5.6	m
Bending radius	1.55	m
RF frequency	0.88 - 5.11	MHz
Betatron tunes		
horizontal	1.80	
vertical	1.85	
Transition gamma	1.561	
β (x) (max/min)	6.439/1.836	m
β (y) (max/min)	6.956/1.685	m
η (x) (max/min)	2.577/1.536	m
Beam aperture (H x V)	170 x 65	mm
Bending magnet	6	units
length	1.62	m
injection field	0.209	T
maximum field	1.5	T
Quadrupole magnet	12	units
length	0.2	m
Max. gradient	6.0	T/m

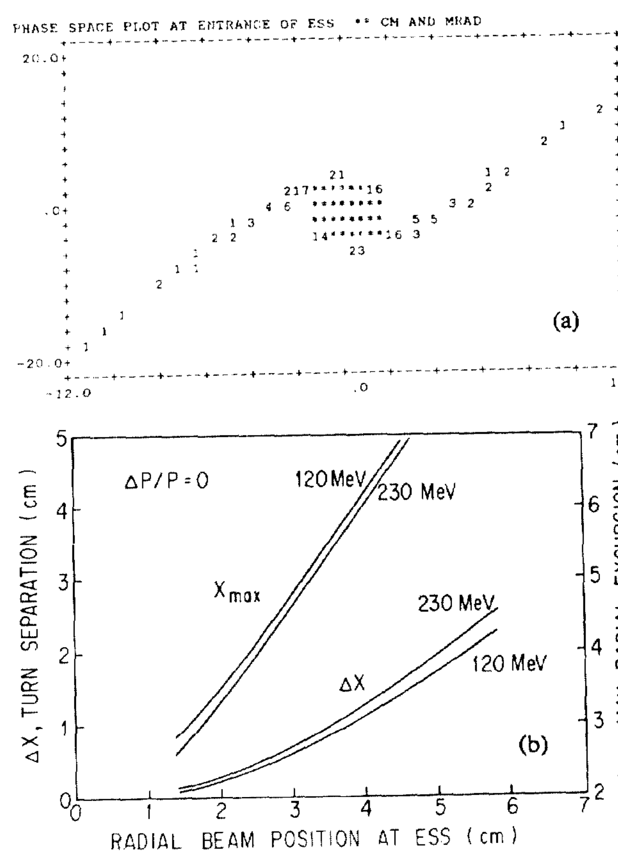

Fig. 3 Behaviour of beam on the separatrices. (a) Separatrices of the half integral resonance, (b) Turn separation and the maximum radial excursion during two revolutions of the beam which starts at ESS with the radial position shown on the horizontal axis.

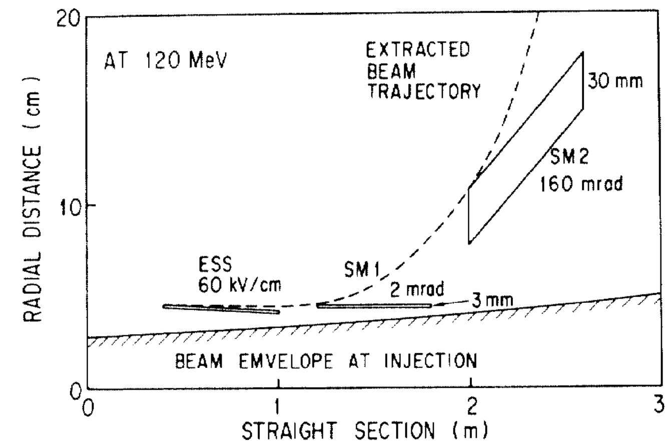

Fig. 4 Beam course for both slow and fast extraction.

Extraction properties

The beam energy range required for the treatment is 120 - 230 MeV and the continuous variation is not always necessary but the discrete beam energy in a few steps is required. To supply the beam to the treatment side in a short time, data to operate the synchrotron should be prepared beforehand as a form of database and transmitted on-line to the respective devices when they are required. The operation of this kind is essential, since the beam energy, the extraction mode - slow or fast extraction, and the beam course are changed frequently in a day and the precise beam delivery is hoped. Both the slow and fast beams are extracted through the same extraction channel for an efficient utilization of the installation space. The reproducibility of the stable beam state is important in the design of the synchrotron so that an exchange between both extraction modes is done efficiently.

The third integral or half integral resonance is considered for the slow extraction. But in most cases shown in Table 1 the third integral resonance extraction is difficult, because the beam on the separatrices hits the chamber wall before reaching an extraction septum.

The beam extracted horizontally through an electrostatic septum and two septum magnets. Separatrices of the half integral resonance extraction is given in the Fig. 3(a) and the turn separation after every two revolutions is in Fig. 3(b) for the case of $dp/p = 0$. Nonlinear perturbation is given by an octupole magnet and every lattice quad is adjusted to lead to the resonance. The momentum dispersion function is not large in the DOFB cell, about 2 m, the shift of the beam trajectory in the phase space has no bad effect on the slow extraction. Amplitude of the local bump orbits, which are necessary for both injection and extraction, is almost flat at the straight section of this cell with the appropriate distribution of the bump magnets. It gives the great benefit on the beam handling. Beam extraction course in both slow and fast modes is shown in Fig. 4 for the beam at an inside edge of each septum. The typical parameters are attached to the figure.

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