Smaller Synchrotron Design for Proton Therapy

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An effort to make a proton synchrotron smaller has been done for years intending to be equipped with at the university hospital and/or at the city hospital for cancer therapy facilities. A modification to the original 230 MeV proton synchrotron design has been tried. Since the quality of the extracted beam for the clinical treatment should be asked at the design stage, more attention has been paid to the studies on the feasibility of the slow beam extraction.

Introduction

The size of the proton synchrotron shall be made as small as possible to reduce the cost including both the machine construction and the civil engineering, as long as the quality of the beam delivered to the treatment room is not deteriorated. Easy operation shall be also taken into account considering the situation that the machine operators are not always necessary to be experienced well in the accelerator technology and physics. Fundamental parameters of the dedicated cancer therapy proton accelerator are the maximum beam energy and the beam intensity. The former is determined from the range in the tissue and the latter from the treatment time which is bearable to the patient. The extracted beam intensity is 6 ~12 x 10^{10} pps either at 230, 180 or 120 MeV which is determined from the experiences on the patient treatments at PARMS using the beam from the booster of KEK-PS during past several years. Although a synchrotron can provides the beam of arbitrary energy, we choose the discrete three energy levels to tune in the shortest time using the preset machine parameters which will be stored in the control computer. If the energy less than these values is required, the energy degrader is used.

An injection energy of the synchrotron is determined mainly from the beam tune shift at injection. The higher the injection energy, the more the allowable intensity. The minimum injection energy will be 5 MeV. An injection scheme depends on the type of injector and the available maximum current. A candidate of the injector is Tandem or RFQ-DTL combination. For either of these injectors the multi-turn injection scheme will be adopted.

The present proton synchrotron design for PARMS is rather conservative and is based on the strong focusing lattice with 6 DOFB cells (PARMS#1) [1,2]. Another approach has been tried to reduce the average machine diameter - that is, allowing the minimum installation requirement for rf cavity, injection device and extraction device for slow extraction, several lattice designs with three periods had been studied, but larger edge angle was required for the bending magnet and large variation of the dispersion function was observed when the horizontal tune was shifted toward the third or half integral resonance for slow extraction[3]. Larger excursion of the orbit for the off-momentum proton will result in the bad extraction efficiency. In the course of this study it is seemed that the extension to four cell structure with tunable horizontal and vertical focusing quads (OFOBDB cell) is promising.

Lattice structure for medical synchrotron

The average diameter of the proposed design is 11.2 m which is about twice as large as that of LLUMC (Loma Linda University, Medical Center) [4]. This design has 3 m long straight sections. The drift length had been determined from the edge focusing effect of the bending magnet which will be made by simply stacking a steel lamination upon another along an arc. This method of magnet fabrication has an advantage over a sector magnet in the manufacturing cost. Instead the vertical focusing becomes rather strong and the drift length shall be determined so that both horizontal and vertical tunes are appropriate.

A remarkable point of the small synchrotron is that the transition energy appears in the neighborhood of the beam energy at flattop when the horizontal tune is more than 1.0. If the transition energy is hoped higher enough than the flattop energy, the horizontal tune should be large enough. On the contrary, if the transition energy is hoped less than the injection energy, the horizontal tune should be less than 1.0 - what is called weak focusing in the horizontal plane. PARMS#1 has aimed to expel the transition far above the maximum beam energy chosing the horizontal tune at near 1.8. If the synchrotron is made smaller than this, the transition shall be avoided to expel it lower than the injection energy by making use of the edge focusing of the bending magnet.

To allow the easy modification of the operating point in tune diagram, both horizontal and vertical focusing quads are also used in a smaller synchrotron in addition to the edge effect. From the studies of beam behavior in several small synchrotron[3], the lattice structure with 4

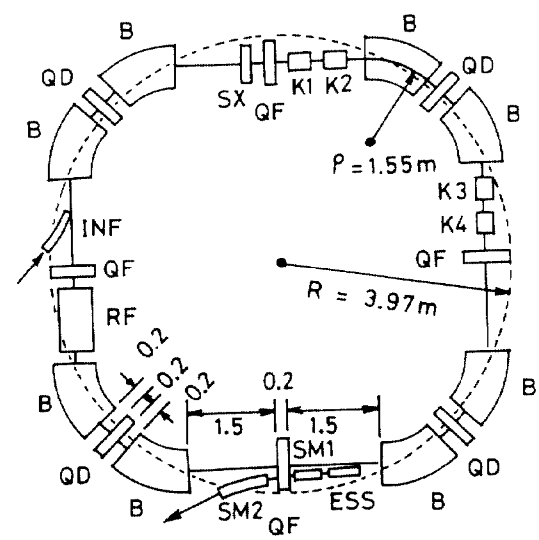

Fig.1 Design of the proton therapy synchrotron with the fourfold symmetry, PARMS#2.

fold symmetry (PARMS#2) has relatively a good property as regards the slow extraction. A unit cell is composed of OFOBDB and whole ring is shown in Fig.1. Lattice parameters along the orbit shown on the horizontal axis is given in Fig.2. This structure is unintentionally similar to that of LLUMC except for the horizontal focusing quad which is used to adjust the horizontal tune. It is placed at the center of the straight section. The minimum length of the straight section is determined from the arrangements of the devices other than the main dipoles and quads. Most of the vertical focusing is given by the edge focusing of the dipole. So the relation between an edge angle and the tunes is shown in Fig.3. From the variation of the horizontal tune the possible choice of the edge angle is around 19 degrees. It can be said that the slow extraction shall be done at the third integral resonance to avoid the larger dispersion (η in Fig.3).

Chosing the edge angle as 19 degrees, the horizontal tune variation is given in Fig.4 as a function of the strength of the focusing quad. As seen from the figure the horizontal tune can be adjusted leaving the vertical tune almost unchanged. It is convenient when the slow extraction is done using horizontal plane.

Comparison of small synchrotron designs

As the main emphasis of the synchrotron design is placed on the tunability, an additional space is required for the focusing quad. Thus, the average machine radius becomes larger than that of LLUMC. Comparisons between three designs are made in Table 1.

Table 1 Comparisons of the medical proton synchrotron designs

	PARMS#1	PARMS#2	LLUMC
Beam energy (MeV)	230	230	250
Repetition (sec)	2	2	2
Av.beam current (nA)	10	10	10
Unit cell	DOFB	OFOBDB	BDBO
Superperiod	6	4	4
Focusing	edge+quad	edge+quad	edge
Edge angle (deg)	30	19	19.8
Av. ring rad. (m)	5.6	4.0	3.2
Bending rad. (m)	1.55	1.55	1.6
Hor./ver. tune	1.8/1.85	0.75/1.7	0.6/1.3
Transition gamma	1.56	0.7	0.6
Max.dispersion (m)	2	7	9
Aperture H x V (mm)	170x65	202x60	100x50
Injection	multi-turn	multi-turn	single-turn
Inj.energy (MeV)	5.0	5.0	2.0
Slow extraction	1/2	1/3	1/2

New design PARMS#2 is intermediate between two designs, PARMS#1 and LLUMC. If the focusing quad is omitted from PARMS#2, it becomes same as LLUMC. Using the focusing quad, an accuracy of the edge angle is less stringent and it affords the easy machine tuning. To attain the design intensity the effective multi-turn number is 10, so it will be enough about 20 turns for injection which corresponds to an injection time of about 20 μsec.

Lattice dependence of slow extraction properties

Modifications of PARMS#2 are OFOB with 3 superperiods and OFOB with 4 superperiods. Their average ring radii are 3.1 m and 3.6 m respectively. The slow extraction properties are compared in Fig.5 for 3 cases, including the case of PARMS#2. In smaller synchrotrons other than PARMS#1 the extraction is made at the 2/3 resonance, because the dispersion function becomes large

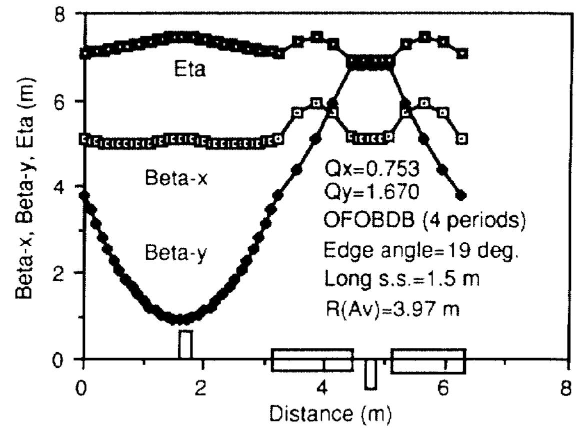

Fig.2 Lattice parameters of PARMS#2 along the orbit of a unit cell. The cell structure is given on the horizontal axis.

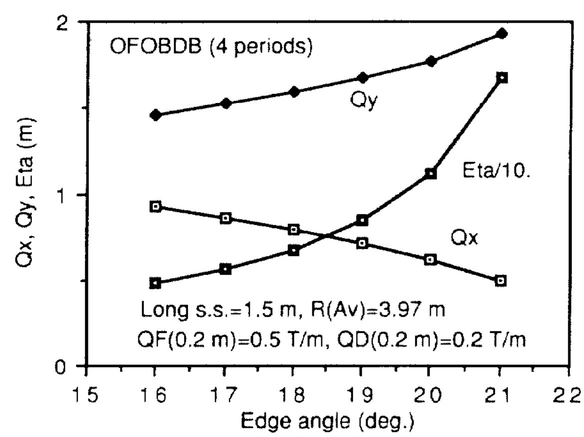

Fig.3 Dependence of tunes and dispersion on the edge angle of the dipole magnet.

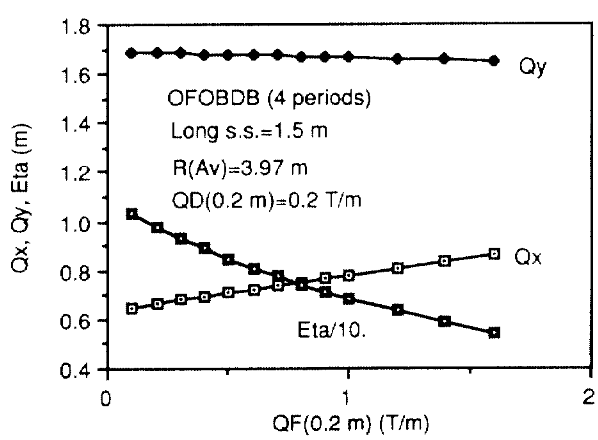

Fig.4 Horizontal tune and dispersion variation due to the strength of the focusing quad, assuming the edge angle of 19 degrees.

for 1/2 resonance. The smaller the ring, the larger the orbit excursion somewhere in the ring before the extraction begins for the electrostatic septum waiting at the same radial position. Xmax means the magnitude of the maximum beam excursion as a function of the radial position of the septum. If Xmax is larger than the useful aperture, the beam is lost hitting the vacuum chamber before reaching the extraction septum.

In the lattice structure with more than 4 superperiods, it is possible to install the fast extraction system but it is required to extract both fast and slow beams through the same extraction channel to save the space. Fig.6 shows the both extraction trajectories at 230 MeV. Kickers for the fast extraction are distributed as shown in Fig.1. Traversals of protons in a quarter of the phase space at 120 MeV are given in Fig.7 which shows the peripheral particles to enter the electrostatic septum. The assumed momentum spread is ±0.1%. Particles enclosed are guided into the extraction channel.

References

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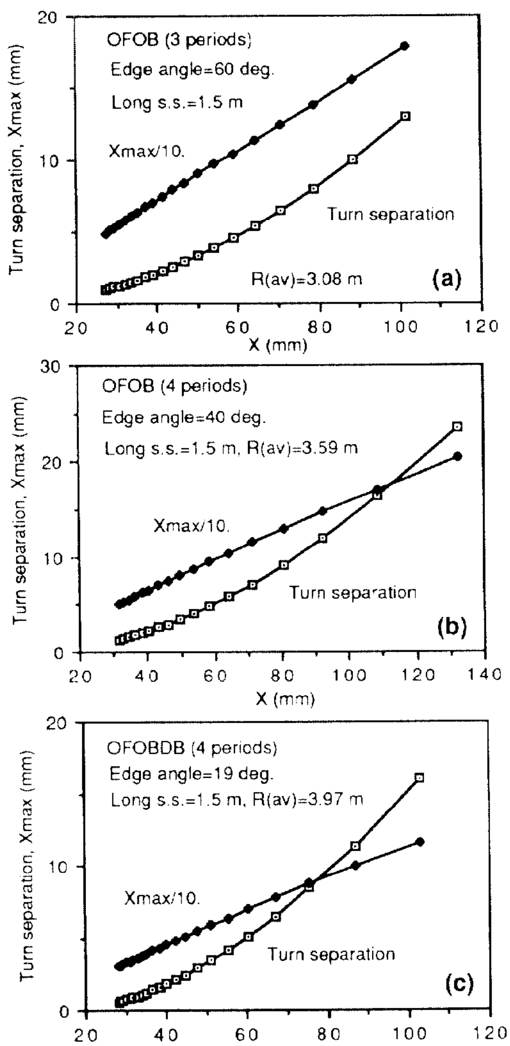

Fig.5 Beam properties of the slow extractions from different lattices - (a) OFOB with 3 superperiods (av. radius; 3.1 m), (b) OFOB with 4 superperiods (av. radius; 3.6 m) and (c) PARMS#2 av. radius; 4.0 m).

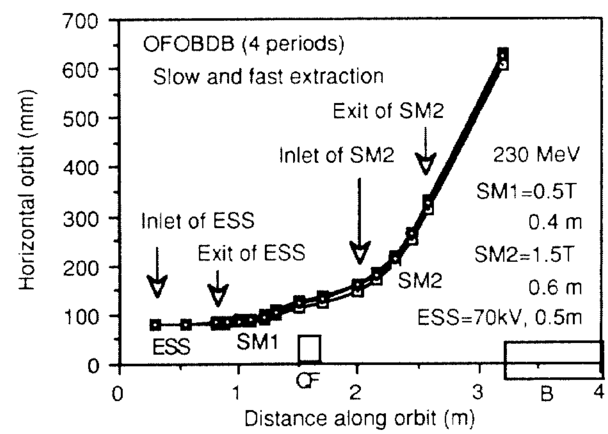

Fig.6 Beam trajectories through the same extraction channel for both the fast and slow extraction at 230 MeV.

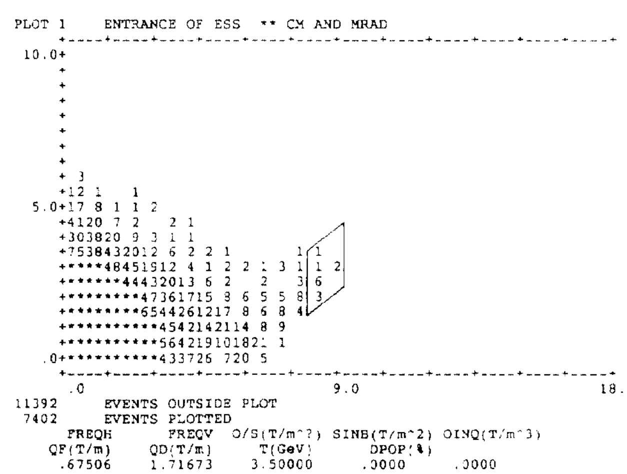

Fig.7 Numbers of traversals by 100 protons in a quarter of the phase space at 120 MeV, assuming the momentum spread of ±0.1%. Particles enclosed will be extracted. Revolutions traced are upto 200 and '**' means more than 100 traversals.