TABLE-TOP PROTON SYNCHROTRON RING FOR MEDICAL APPLICATIONS

K. Endo, K. Mishima S. Fukumoto and S. Ninomiya, KEK, Tsukuba, Japan
G. Silvestrov, BINP, Novosibirsk, Russia

Abstract

A very small 200 MeV proton synchrotron applying a wide frequency range RF system has been investigated in detail. An adaptable acceleration time is very short due to a heavy heat load to the magnet coil by the large peak current amounting to ~200 kA. An allowable current shape is a half-sine waveform of 5 to 10 msec duration corresponding to 100 to 50 Hz, respectively, and its duty must be very low for easiness of the heat removal. Thus the operation cycle is limited to less than 10 repetitions/sec. To assure the quick excitation of the magnet and to make a magnet compact, a single turn coil is adopted for both bending and focusing magnet. By adopting 2 MeV H^- RFQ linac as an injector, a charge exchange injection method is available for an operation of 10 nA beam current in average. Extraction at 200 MeV is also considered.

1 INTRODUCTION

Since the proton synchrotron has been considered as an effective tool to cure a tumor, a big effort is ever paid to reduce the machine size as small as possible because a hospital environment does not allow a large space for its installation from view points of economy [1-4]. There have been introduced several designs depending on the different ideas. As these designs were based on the proved technology aiming at as early as possible realization, however, the machine size could not be reduced dramatically.

A very small 200 MeV proton synchrotron idea was reported by Averbukh et al [5] by using a strong pulse magnetic field with a fast rise and fall time. It consists of 4 dipoles and 8 quads tightly aligned on the table with a RF cavity in the short straight section. An original design was modified to relax the machine parameters in a conservative way [6]. The present design study extends these predecessors in a sense to be more feasible.

The machine cycle or repetition rate is limited by the cooling requirement of the dipole magnet because of its small available space for the water passage. Hence it is a cycle or a few cycles per sec.

2 DESIGN PARAMETERS

Differences of the machine parameters are tabulated in Table 1 and the present ring layout is shown in Fig.1. Each design has the different dispersion and vertical tune depending on the cell structure. In the present design the defocusing quads are installed between short dipoles which help the precise adjustment of the betatron tunes.

Table 1: Possible machine parameters for a 200 MeV proton synchrotron.

	BINP	Frascati	KEK	unit
Max. energy	200.0	200.0	200.0	MeV
Inj. energy	1.0	12.0	2.0	MeV
Circumference	4.7	6.4	10.5	m
Av. diameter	1.5	2.0	3.3	m
Bending radius	0.43	0.54	0.72	m
Max. dipole field	5.0	4.0	3.0	T
Period	4	4	4	
Tune, ν_x/ν_y	1.4/0.45	1.42/0.54	1.4/0.75	
Max. dispersion	0.4	0.63	1.0	m
Cell structure	FODB	BODO	OFOBDB	
Total weight	~1	~1.5	~2	ton

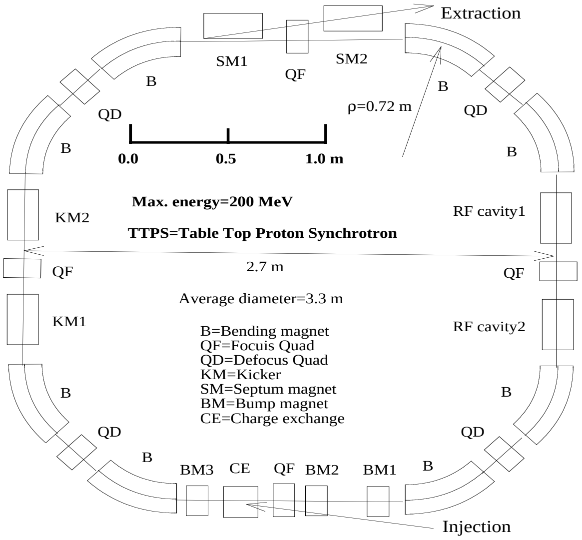

Figure 1: Present ring layout.

3 MAGNET SYSTEM

As the magnet performance will determine the machine reliability, the maximum dipole field is 3.0 T or less to get rather uniform field distribution for the beam aperture. By adopting an edge focus of the dipole for the vertical betatron motion the relatively uniform twiss parameters are expected. Fig.2 shows the beam parameters obtained by a proper combination of the edge angle and the field gradients of the focusing and defocusing quads.

The edge angle is sensitive to both horizontal and vertical tunes, so it should be manufactured accurately within a few tenth degrees as shown in Fig.3 for the cases of ±0.1 deg deviations from a reference 8.9 deg. As an excitation current pulse width is small enough to ensure the lower temperature rise of the coil, an eddy current will cause a field deterioration especially at the dipole ends which will result in the systematic edge angle error. A laminated magnet core must be used to suppress the eddy current effect as low as possible.

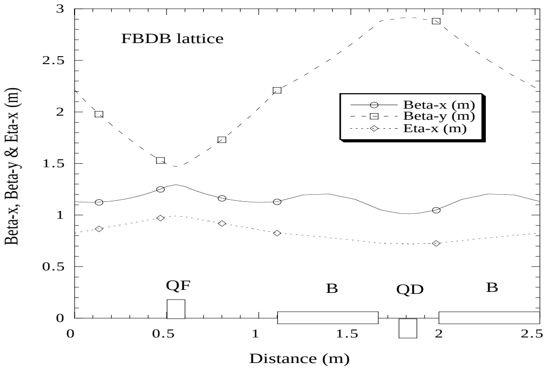

Figure 2: Beam parameters of one period.

Concerning to the high field pulse magnet in addition to the field distortion, however, the mechanical distortion due to the magnetic force is a big problem which also leads to the field deterioration and the mechanical failure in an extreme case.

According to these reasons the machine diameter should be a little bit large to reduce the required field so far as a installation space is allowed at the hospital. Even if the maximum field is 3 T, an average diameter is 3.2 m.

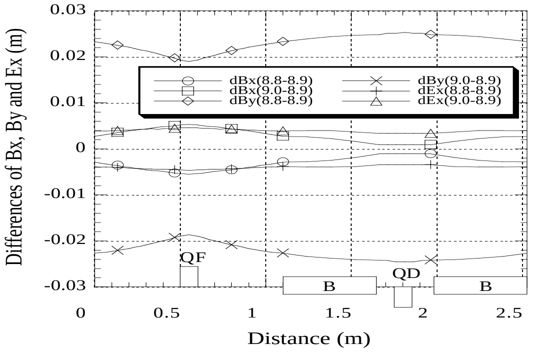

Figure 3: Differences of β_x, β_y and η_x due to ±0.1 deg systematic edge angle error.

As the field gradient of quads must track the dipole field, they are in the same situations but the required field gradient (~10 T/m at max.) is not so large compared to the dipole field.

4 POWER SUPPLY

For a rapid excitation of the dipole a pulse power supply must be used enabling a large peak current as large as 200 kA with a fast rise and decay of the field. This kind of the power supply is realized by a charge-discharge of a condenser bank. As such a discharge current is not controllable, the precise tracking of the quad current must be established by sensing the dipole current or field to give the current reference to the quad power supplies.

5 RF SYSTEM

A small enough cavity is desirable with the view of installing in a short straight section. A wide frequency change of 2.5 ~ 30.8 MHz was tested with a ferrite-loaded quarter-wave coaxial resonator of 250 mm length biased by an external magnetic field [7]. The maximum RF voltage at the accelerating gap was 3.3 kV with a frequency sweep rate of 5600 MHz/sec. As shown in Table 2 the required voltage is not enough with a single short cavity.

Table 2: RF parameters of 200 MeV proton synchrotron assuming ϕ_s=30 deg.

	BINP	Frascati	KEK	unit
Inj. energy	1.0	12.0	2.0	MeV
Freq. range	4.16~36.1	7.4~26.5	1.86~16.2	MHz
Acc. time	2.5	3.5	5.0	msec
Acc. voltage	11.5	12.4	13.0	kV

Even if adopting a core material having a large permeability such as an amorphous Fe-Si-B alloy and a nano-crystalline Fe-Cu-Nb-Si-B alloy (μ_r~10^5 and 10^4, respectively) to obtain a wider frequency range, the frequency is limited to less than 5 MHz because of a large gap capacitance. The breakthrough to the voltage limitation is given by a distribution amplifier scheme for the non-resonant acceleration system in driving several power tubes at the accelerating gap. With this method the frequency range of 0.5 ~ 20 MHz and the gap RF voltage of 20 kV are expected [8].

6 INJECTION

A compact injector is desirable in order to make the whole system as small as possible. So far a van de Graaff generator (1 MeV) or a superconducting cyclotron (12 MeV) for PET (positron emission tomography) is discussed. The RFQ (radiofrequency quadrupole) linac is another candidate which can provide proton or H^- ion with an intensity as high as 60 mA and a normalized emittance of 0.6π mm mrad at energy around 2 MeV. Its length is only 1.6 m for 425 MHz RF frequency. With this intensity only a single turn injection at 1 Hz will give an average available beam current of 10 nA.

If the H^- injection is considered to save the space for injection, the charge exchange method is disadvantageous at low energy because it requires very thin carbon foil to avoid the emittance growth by the multiple scattering of proton. When the low energy H^- ions less than 8 MeV traverse the carbon foil, the yield of proton decreases inversely proportional to the foil thickness less than a few μg/cm^2 and almost complete charge exchange is achieved more than 5 μg/cm^2 [9], but the estimation of the emittance increase of proton is given by $\Delta\varepsilon = 0.5\pi\beta_0 Nnt\sigma_c(\delta y')^2$ where N is the number of the traversals, n the density of the stripper atoms, t the mass thickness of the stripper, σ_c the Coulomb scattering cross-section, $(\delta y')^2$ the mean square scattering angle by a stripper atom and β_0 the machine betatron function at the location of the stripper [10]. The estimated $\sigma_c(\delta y')^2$ for the present N_2 gas is 2.7 x 10^{-28} m^2rad^2/atom which results in $\Delta\varepsilon \approx 0.06\pi N$ mm mrad for 2 MeV at $\beta_0 \approx 1$ m.

The theoretical estimation can be made according to the prediction and experimental curves as in Fig.4 for 2 and 3 MeV H^- beam in N_2 gas [11]. In an estimation of the fraction of total beam it is assumed that the double electron loss cross section by H^- in N_2 is ignored [12]. A gas stripper requires relatively high pressure at a small section (less than 5 cm) in the ring to get a large atom density of 3.3 x 10^{16} atoms/cm^2 equivalent to 0.33 μg/cm^2 if realized in the case of carbon foil. Almost complete charge exchange to proton is accomplished in a few unit thichnesses. Vacuum technique for an ultra-fast gas charge and discharge using a kind of piezo-electric valve system is necessary to maintain the whole ring at high vacuum state.

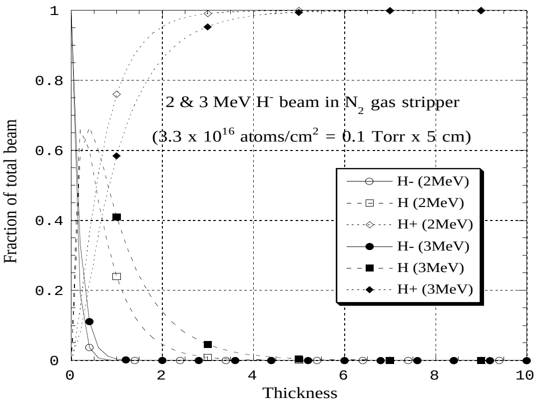

Figure 4: Fraction of the charge state after traversal of 2 MeV H^- beam in N_2 gas stripper. Unit thickness is 0.66 μg/cm^2.

7 EXTRACTION

Shifting a circulating beam to jump into an aperture of a septum magnet by a kicker magnet. As the beam revolution time at 200 MeV is ~60 nsec, the extraction is made during several revolutions successively. A sweep rate of the kicker field is about 3x10^5 T/sec (0.02 T/rev) or more.

Two kicker magnets are placed one period upstream of the septum magnets which extract the beam away from the ring as shown in Fig.5. Extraction should be accomplished in several turns requiring a rapid field rise of kickers. Expected extraction efficiency is also given in Fig. 5.

Compact synchrotron dedicated to special purposes such as radiation therapy, industrial applications and etc. needs the careful R&D research programs to verify its reliability and performance including a very precise timing control for the operation of the machine components to accelerate the beam in a very short time minimizing the beam loss.

Authors are deeply indebted to Professor Y. Hirao who has given an opportunity to investigate the smallest possible accelerator to be useful in practice and to M. Seya of Science Technology Agency who has been advising us to promote new accelerator technologies.

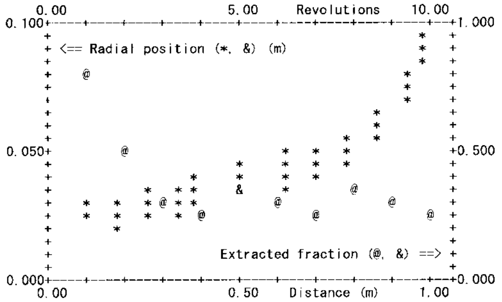

Figure 5: Fast extracted beam trajectory using 2 kicker and 2 septum magnets. Trajectories for particles distributed randomly in the normalized phase space of 3π mm-mrad. Symbols (*, &) is for the trajectories and (@ , &) for the extraction efficiency when particles are extracted over several revolutions.

REFERENCES

[1] K. Endo et al, "Medical Synchrotron for Proton Therapy," Proc. EPAC88, Rome, pp.1459-61.

[2] K. Endo et al, "Size Reduced Design of Medical Proton Synchrotron," Proc. 7th Symp. Acc. Sci. and Tech., Osaka, 1989, pp.364-6.

[3] K. Endo et al, "Smaller Synchrotron Design for Proton Therapy," Proc. EPAC90, Nice, 1990, pp.1784-6.

[4] K. Endo et al, "Study of Gantry Beam Line for the Medical Synchrotron," Proc. 8th Symp. Acc. Sci. and Tech., Saitama, 1991, pp.344-6.

[5] I.I. Averbukh et al, "Project of Small-Dimensional 200 MeV Proton Synchrotron," EPAC88, Rome, 1988, pp.413-6.

[6] L. Picardi et al, "Preliminary Design of a Very Compact Protosynchrotron for Proton Therapy," EPAC94, 1994, pp.2607-9.

[7] I.I. Averbukh, "Accelerator Resonator for an Ion Synchrotron," Nucl. Exp. Tech., 1979, pp.848-9.

[8] S. Ninomiya et al, "Non-Resonant RF Accelerating System," this conference.

[9] I. Yamane, Private communication.

[10] R.K. Cooper and G.P. Lawrence, "Beam Emittance Growth in a Proton Storage Ring Employing Charge Exchange Injection," IEEE Trans., NS-22, 1975, pp.1916-8.

[11] R.C. Webber and C. Hojvat, "Measurement of the Electron Loss Cross Sections for Negative Hydrogen Ions on Carbon at 200 MeV," IEEE trans., NS-26, 1979, pp.4012-4.

[12] H. Tawara and A. Russek, "Charge Changing Processes in Hydrogen Beams," Rev. Mod. Phys., 45(1973)178-229.