COMPACT PROTON SYNCHROTRON

K. Endo, Z. Fang and S. Ninomiya
High Energy Accelerator Research Organization (KEK)
1-1 Oho, Tsukuba-shi, Ibaraki-ken 305-0801, Japan

G.I. Silvestrov
Budker Institute of Nuclear Physics (BINP)
RU-630090 Novosibirsk, Russia

Abstract   A present-day synchrotron dedicated to the medicine has become small in its size and is being installed at the several hospitals for the purpose of the radiation cancer therapy. However, it accompanies the big investment in manufacturing the accelerator in addition to the big space required to its installation. These are the limiting factors in introducing the advanced radiation treatment system utilizing the accelerator technologies. An idea to make the synchrotron compact has a promise to equip it with a reasonable investment but it needs the careful R&D programs.

1 INTRODUCTION

The proton synchrotron of 250 MeV installed at the university hospitals and the self-governmental hospitals has now a circumference of as small as 20 m. It depends on the well understood technologies which have been optimized so as to attain the beam intensity required by the cancer therapy. The synchrotron circumference is mainly determined by the field strength of the dipole magnet which guides the beam on the circular orbit. If the field much higher than 2 T, to say, 3 T or higher, can be used, the circumference becomes smaller depending on the field strength. The synchrotron having the circumference of about 10 m or less is termed here as the compact synchrotron [1, 2]. As the most prevailing proton energy for the radiation treatments is less than 200 MeV, it is assumed here as the maximum energy at 3 T. However, the higher beam energy will be obtained by increasing the dipole field.

By choosing the high dipole field the synchrotron becomes so compact that it can be installed in an appropriate experimental room. It means that the compact proton synchrotron can be easily equipped by the reasonable investment at the hospitals and even at the laboratories where the accelerator of this class is needed.

The main issues of the compact synchrotron to be solved are treated here with some numerical results.

2 MAIN FEATURES OF COMPACT SYNCHROTRON RING

2.1 Magnet system

If the synchrotron size becomes small, the allowable spaces for the components such as magnets and the radiofrequency (RF) accelerating cavities are inevitably limited. Magnets should have a good field properties during acceleration from injection to the maximum field in a small beam aperture. The available space of the conductor is also limited and the heavy heat load due to an ohmic loss by a large current through the conductor limits the acceleration and deceleration times.

As the magnet saturates heavily at the high excitation level, the maximum current of the dipole is as large as 200 kA for a single turn coil. Supplying this current in a short time imposes the restriction on the power supply, that is, the current should be supplied by the discharge of the stored energy of a capacitor [3]. The main parameters of the magnet system are given in Table 1.

Table 1: Main parameters of the magnet system.

Item	Parameter	Unit
Max. proton energy	200	MeV
Injection energy	2	MeV
Circumference	11.3	m
Max. dipole field	3	T
Bending radius	0.72	m
Number of dipoles	4	
Max. quad gradient	42	T/m
Number of QF quads	8	
Number of QD quads	4	
Unit cell structure	ODOFBF	

The original design of the compact synchrotron is missing the focusing quad (QF) [4]. By adding QF the tunability increases in both horizontal and vertical planes, otherwise the focusing force to the proton beam is given by the dipole which cannot be used as a tuning element because it determines the bending radius of the beam. With QF's at both ends of dipoles the normal beam entry to and exit from the dipole are assured and the betatron function at dipoles remains small. This lattice structure benefits in reducing both the gap height of the dipole and the stored energy of the capacitor of the power supply but sacrifices quads by increasing their field gradient. The focusing and defocusing quads (QD) are connected in series separately and excited with individual power supplies by tracking the dipole field accurately.

The configuration of the compact proton synchrotron is shown in Fig.1. There are 8 long straight sections which are occupied by the RF cavities, injection system, fast extraction system and so on.

The twiss parameters are given in Fig.2 for a unit lattice. Beam optics is chosen so as to minimize the vertical betatron function at the dipole to reduce its gap height.

For low energy injection, the required beam aperture becomes large as shown in Fig.3 for the normalized emittance of 10π mm mrad in both planes.

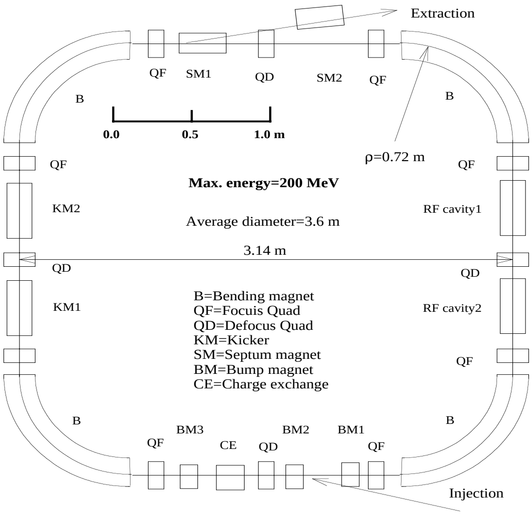

Figure 1: Lattice structure of the compact proton synchrotron.

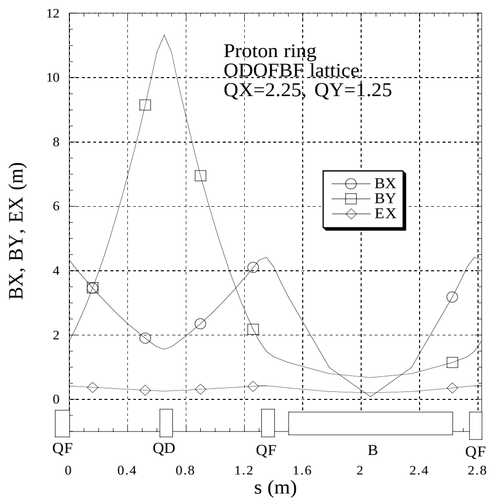

Figure 2: Twiss parameters of a unit lattice of which magnet arrangement is at the bottom of the figure.

2.2 Pulse power supply

Dipoles are connected in series and powered by the discharge of the capacitor bank. To assure the same instantaneous current all the time during acceleration, the multi-mesh circuit shown in Fig.4 is preferable. By putting the earth point at the middle of one of the coils, the phantom null voltage point is generated at the middle of others and the peak terminal voltage of every dipole is about ±40 V as shown in Fig.5. The discharge current is stepped up with the intermediate pulse transformers. All elements consisting the circuit including capacitor, transformers and dipoles are adjusted to form the resonant circuit of which frequency determines the acceleration and deceleration times. Dipoles are excited only by the half sinusoidal current pulse.

After reaching the maximum dipole field the residual energy in the secondary circuit should be restored to increase the repetition rate of the compact synchrotron. By forced switching of the power switch elements from the discharge to the recovery mode, most of the energy initially stored in the capacitor bank can be restored except for the resistive loss.

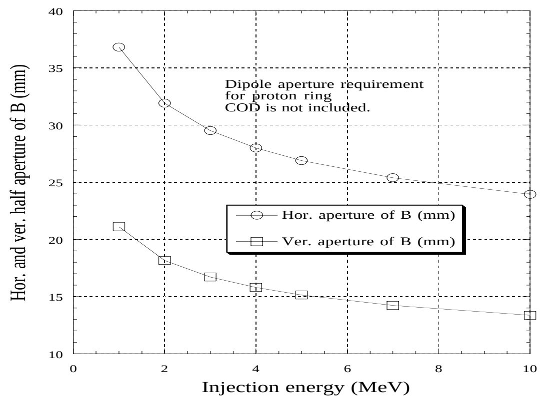

Figure 3: Required half beam aperture at the dipole magnet including no closed orbit distortion.

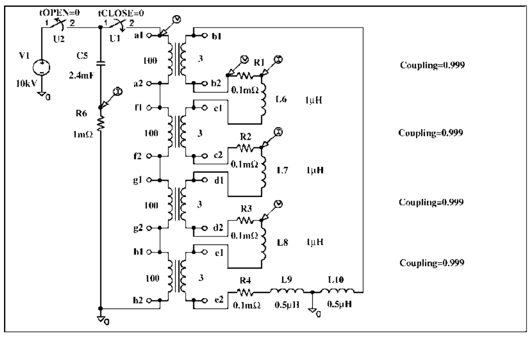

Figure 4: Multi-mesh circuit to assure the same instantaneous current for all dipole magnets. Inductors L6~L10 are dipoles.

2.3 RF system

As for the RF cavity, the space allowed for installation is two straight sections both sides of one of QD's. Two short coaxial a quarter wavelength cavities of 50 cm or less in length are installed in each straight section and will be energized with a common high voltage RF distributed amplifier [5]. Main parameters of the RF system are given in Table 2 and their time variations are shown in Fig.6. The serious problem is the large momentum swing during acceleration due to the synchrotron oscillation. The proton will be injected when the dipole field corresponds to the injection energy of 2 MeV. Injection takes place at instant while the dipole field is ramping according to the sinusoidal current variation by the discharge of the capacitor bank.

The frequency range of 0.5 ~ 20 MHz and the gap voltage of 20 kV are expected by adopting a core material with large permeability such as an amorphous alloy or a nano-crystalline alloy and a distribution amplifier for the non-resonant acceleration cavities.

Table 2: Main parameters of RF system.

Item	Parameter	Unit
Max. RF voltage	20	kV
Harmonic number	1	
Synchrotron oscillation	32.1 - 25.5	kHz
Frequency range	1.7 - 15.0	MHz
Acceleration time	5	msec
Number of cavity	2	

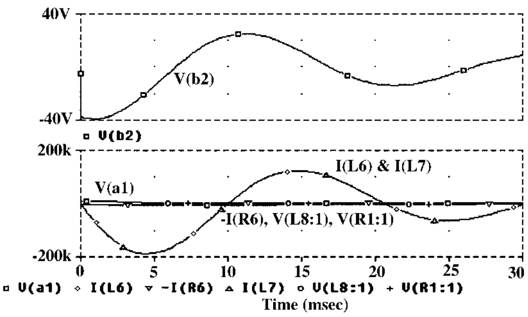

Figure 5: Current and voltage behaviors of the multi-mesh circuit. (a) Terminal voltage of each dipole, and (b) currents and voltages at the probe points in Fig.4.

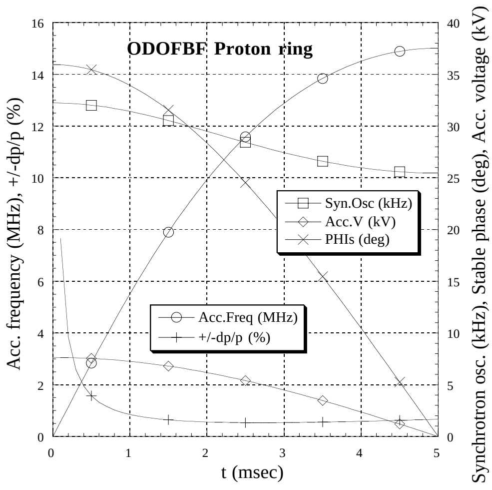

Figure 6: Time variation of the RF parameters.

3 INJECTION SYSTEM

It is desirable to adopt a low energy but powerful injector to make the whole system compact. There are several candidates such as Van de Graaff, cyclotron and linac. Presently the 2 MeV RFQ linac with H^- ion source is considered. Its expected intensity is 60 mA and a normal emittance is 0.6 π mm mrad. With this intensity an estimated average available beam intensity at 1 Hz is about 10 nA by a single turn injection. This intensity is the maximum value when every scheme goes well, however, some relief measure is required so as to increase the repetition rate of the synchrotron operation [3].

The H^- injection at low energy requires the charge exchange method using the gas stripper. At higher injection energy the thin carbon foil can be used as a stripper, but at 2 MeV it must be as thin as 1 $\mu g/cm^2$ which is difficult to attain.

The stripping efficiency of the N_2 gas can be theoretically estimated as in Fig.7 for 2 and 3 MeV H^- beam using the prediction and experimental curves [6]. In an estimation the double electron loss cross section by H^- in the N_2 gas is ignored [7]. The gas stripper requires relatively high pressure at a small section (to say, 5 cm of the vacuum chamber) to get a large atom density 3.3 x 10^{16} atoms/cm^2 (equivalent to 0.33 $\mu g/cm^2$). Almost complete charge exchange to proton is expected in a few unit thickness. The vacuum technique for an ultra-fast gas charge and discharge is essential.

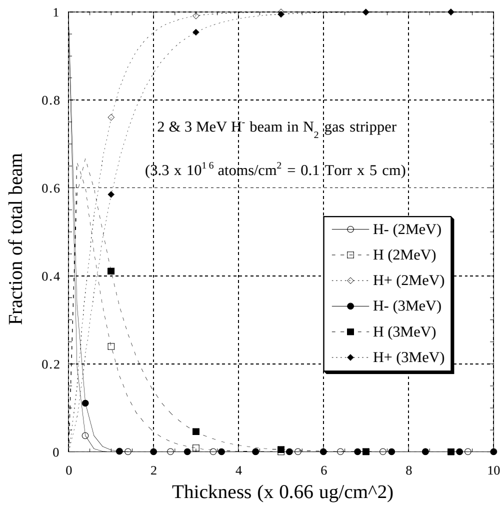

Figure 7: Fraction of the charge state after traversal of 2 and 3 MeV H^- beam in the N_2 gas stripper. A unit thickness is 0.66 $\mu g/cm^2$.

4 FAST BEAM EXTRACTION

At the peak field of the dipole the proton beam is fast extracted. The beam kicked vertically by two 0.4 m kicker magnets is extracted horizontally with two septum magnets. The extraction by the horizontal kick is difficult with the horizontal tune of 2.25. As the revolution period at 200 MeV is 66.6 nsec, to extract in one turn the rise time of the ferrite kicker magnet must be so short that its field must be 0.02 T during the beam interval, to say, in 45 nsec or less. Assuming the gap height of 8 cm and the aperture of 7 cm, the single turn coil kicker magnet has 0.44 μH inductance, 60 μΩ resistance and 63 nsec rise time for the 7 Ω characteristic impedance. If the single turn coil is separated into two circuits, upper and lower legs, as shown in Fig. 8 and they are connected to the separate PFN's (pulse forming networks), the rise time is 32 nsec and the pulse width is 30 nsec using 10 m coaxial cable as PFN. Assuming the lossless distributed constant circuit for the shake of simplicity the single turn extraction will be possible by applying 10 kV to PFN. This scheme needs 4 PFN circuits.

Another method is to drive the kicker magnets with the high voltage dc power supply. During the ramping the protons traverse the kicker field several times before they are extracted or lost. Protons have a different phase shift of the betatron oscillation after each revolution, so the extraction efficiency will decrease compared with that of the single turn extraction. Numerical estimation of the multi-turn extraction efficiency is given in Fig.9.

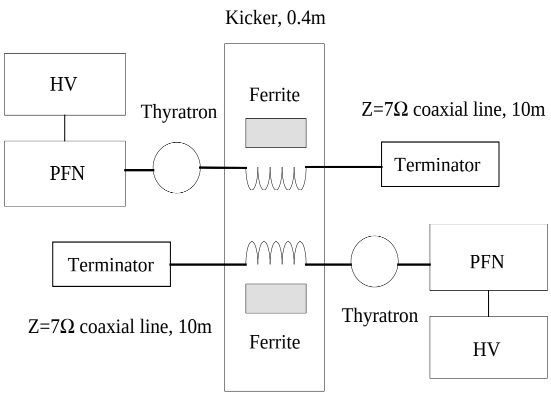

Figure 8: PFN for one kicker magnet for the case of single turn extraction.

Many issues mentioned above must be solved theoretically before manufacturing the hardware systems to realize the reliable compact synchrotron. There are other problems relating to the development of synchrotron components such as the dipole magnet, quadrupole magnet, correction magnets, beam monitors, vacuum chamber and etc. These problems will be treated elsewhere separately.

Authors are grateful to Professor Y. Hirao for the valuable directions in the research of the advanced accelerator technologies.

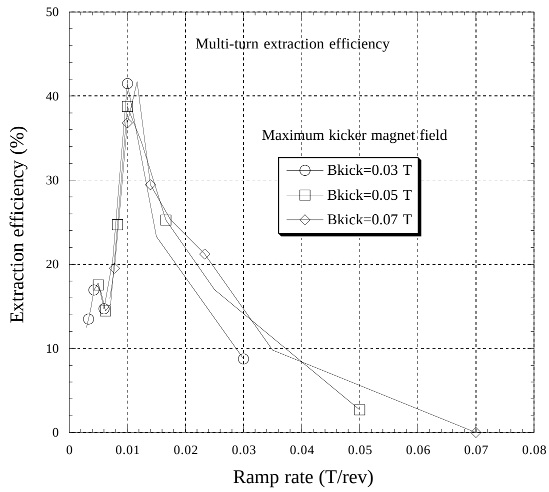

Figure 9: Estimated efficiency of the multi-turn extraction scheme. Optimum ramp rate of the kicker magnet is 0.01 T/rev.

REFERENCES

[1] K. Endo et al, "Table-Top Proton Synchrotron Ring for Medical Applications," EPAC2000, Wien, pp.2515-7.

[2] K. Endo et al ,"Compact Proton and Heavy Ion Synchrotron for Medical Treatment and Bio-Science," to be appeared in the Proc. of 13th Symp. Acc. Sci. and Tech., Osaka, 2001.

[3] K. Endo et al, "Resonant Pulse Power Supply for Compact Proton and/or Heavy Ion Synchrotron," APAC'01, to be published.

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

[5] S. Ninomiya et al, "Non-Resonant RF Accelerating System," EPAC2000, pp.1981-3.

[6] 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.

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