Bull. Inst. Chem. Res., Kyoto Univ., Vol. 73, No. 1, 1995

A Compact Proton Synchrotron with a Combined Function Lattice Dedicated for Medical Use

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Received January 23, 1995

A proton synchrotron for cancer therapy is presented. The combined function lattice is employed to reduce the size of the synchrotron and make the control to be simple. The present synchrotron employs an RF acceleration cavity of the untuned type, in which higher RF voltage is applied to the acceleration gap with a rather low input power by feeding the RF power to each ferrite respectively. In the beam extraction, the transverse perturbation of the radio frequency is applied to make the beam diffuse and reach the separatrix of the nonlinear resonance. This scheme realizes a simple and low emittance beam extraction with a high duty factor. Furthermore, a new irradiation scheme for treatment is presented in which the proton beam is defocused in the deflecting plane of the bending magnets of the treatment gantry and scanned normal to the deflecting plane. Since the scatterers are not employed, loss of the beam can be significantly reduced.

KEY WORDS : Cancer Therapy/ Synchrotron/ Combined Function/ RF Cavity/ Slow Beam Extraction/ Gantry

1. INTRODUCTION

A high energy proton beam has been successfully applied to cancer treatments[1,2] and sixteen proton therapy centers are presently being operated world wide[3]. In cancer therapy, variable energy of the proton beam is necessary when treating different depths in the tissue. Then, a synchrotron seems to have an advantage as an accelerator for the cancer therapy because it can accelerate charged particle beams to various energies.

Simple operating schemes are needed for the medical proton synchrotron because it must be used in daily treatments. Considering this condition, a new synchrotron for proton therapy is designed with the combined function lattice, a new type of the untuned RF (Radio Frequency) cavity[4] and a simple resonant extraction scheme[5-7]. The combined function lattice has an advantage of simple operation for the beam acceleration, although this is gained at the expense of flexibility in selecting operating points in the separated function lattice. Although the untuned RF cavity has a feature that it does not need control of the resonant frequency, the gap voltage is generally rather low. Then, the present design employs a new scheme of the power feeding to the RF cavity[4] developed for the increase of the gap voltage with a rather low input power. In the extraction, a transverse perturbation of radio frequency is applied to make the beam diffuse in

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the transverse direction and reach the separatrix of the resonance of the betatron oscillations. Hereafter, we call this scheme the diffusion-resonant extraction. This diffusion-resonant extraction has a feature that the currents of the magnets in the synchrotron and the intensity of the electrostatic deflector can be kept constant.

Finally, we present a new irradiation scheme in which the beam is defocused, with flattening of the distribution in the deflecting plane, and swept across this plane. Since this scheme does not employ scatterers, loss of the beam can be significantly reduced.

2. SYNCHROTRON SYSTEM DESIGN

2.1 *Lattice and machine parameters*

The main machine parameters of the designed synchrotron are listed in Table 1. In the present synchrotron, a proton beam of 7 MeV is injected from a linac to the synchrotron. The unnormalized emittance of the injected beam is assumed to be 10 πmm·mrad (90%) in horizontal and vertical planes. The maximum beam energy reached is 230 MeV. After the acceleration,

Table 1. Machine parameters.

Circumference (m)	22.9
Injection Energy (MeV)	7
Max. Extraction Energy (MeV)	230
Super Period	4
Tune	
ν_x	1.75
ν_y	0.85
Bending Magnet	
Deflection Angle (deg)	45
Curvature Radius (m)	1.62
Max. Field Strength (T)	1.44
BD K (l/m^2)	0.344
n	0.904
BF K (l/m^2)	−0.228
n	−0.559
Twiss Parameters	
β_x, max (m)	10.8
β_y, max (m)	7.8
η, max (m)	2.2
Momentum Compaction Factor	
α	0.417
Transition Gamma	
γ_{tr}	1.55
Natural Chromaticity	
$\xi_x=(\Delta\nu_x/\nu_x)/(\Delta p/p)$	−0.24
$\xi_y=(\Delta\nu_y/\nu_y)/(\Delta p/p)$	−0.26

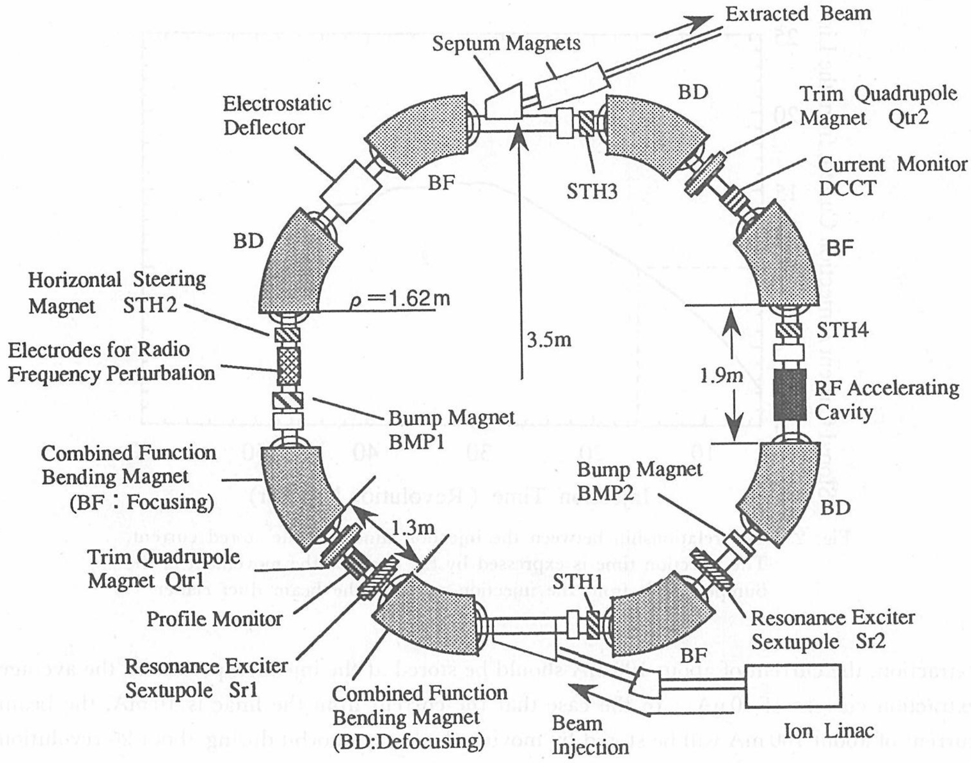

Fig. 1. Configuration of the proton synchrotron.

the beam is extracted by the diffusion-resonant extraction. The average extraction current of 10 nA is targeted. These procedures are repeated at 0.5 Hz.

Fig. 1 shows the lattice of the designed synchrotron. The synchrotron magnet system consists of two kinds of bending magnets with combined function, BF and BD. The deflection angle of each bending magnet is 45 degrees. The maximum magnetic field of the bending magnets is 1.44 T, which results in the curvature radius of 1.62 m. These magnets are excited in series. n-indices of the magnets BF and BD are determined so as to satisfy the horizontal tune $\nu_x=1.75$ and the vertical tune $\nu_y=0.85$. These tune values are chosen so as to avoid structure resonance for the betatron oscillations. If needed, fine control of the betatron tune can be done using the trim quadrupole magnets Qtr1 and Qtr2.

2.2 *Injection*

The beam is injected into the synchrotron by a multi-turn injection scheme using the two injection bump magnets, BMP1 and BMP2. The amount of the stored current mainly depends on the time for moving the bumped orbit from the injection point to the center of the beam duct. The stored current by this multi-turn injection scheme was analyzed by the computer simulation based on the assumption that the beam has no momentum spread. The effects of the momentum spread are left for future investigations. Fig. 2 shows that the relationship between the stored current and the time for moving the bumped orbit from the injection point to the beam duct center. When assuming that about 60% of the beam is lost during the acceleration and

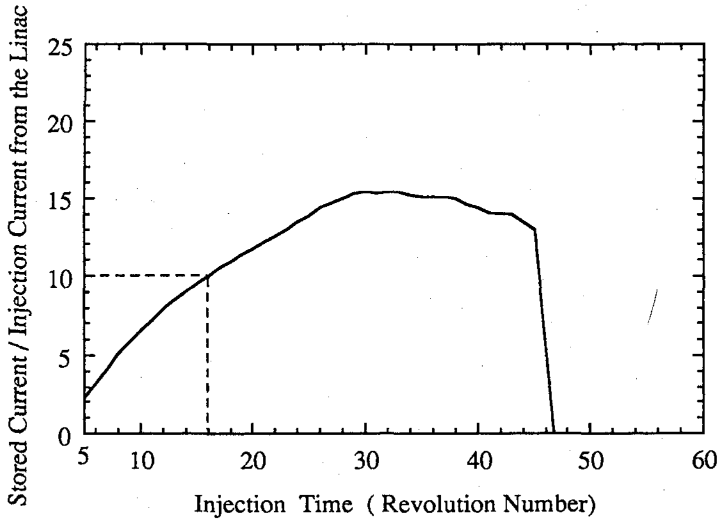

Fig. 2. The relationship between the injection time and the stored current. The injection time is expressed by the time for the movement of the bumped orbit from the injection point to the beam duct center.

extraction, the current of about 100 mA should be stored at the injection period for the average extraction current of 10 nA. In the case that the current from the linac is 10 mA, the beam current of about 100 mA will be stored by moving the bumped orbit during about 20 revolution periods.

2.3 *Acceleration*

The current of the bending magnets is ramped to keep the beam orbit unchanged as the beam energy increases. The revolution frequency of the beam also goes up as the velocity of the beam increases. The beam is accelerated by the radio frequency (RF) accelerating cavity, whose frequency should be proportional to the revolution frequency. The RF cavity employs Ni-Zn ferrite cores and is untuned. Since the untuned RF cavity does not need any control of the resonant frequency, the control system can be significantly simplified. However, the gap voltage of the untuned cavity is relatively low, because of the small Q value and the impedance mismatch between the RF power source and the RF cavity. In the present cavity, the impedance mismatching is improved by feeding the RF power to each ferrite core separately, and then the higher gap voltage is achieved at the same input power. It is expected that the gap voltage of about 500 V required for the acceleration is easily obtained at rather low power level. The design of the untuned cavity is discussed in another paper[4] in this bulletin.

2.4 *Extraction*

One of the features of the present synchrotron is that a low emittance beam can be extracted slowly by a very simple operating scheme, that is, the diffusion-resonant extraction scheme. The diffusion-resonant extraction is schematically shown in Fig. 3. A schematic time chart of the extraction is shown in Fig. 4. The separatrix for the resonance is generated after Ts, that is, the end of the acceleration, by using the two sextupole magnets Srl and Sr2, and decreasing the horizontal betatron tune to 1.67. The separatrix is kept constant, as shown in Fig. 3, by the

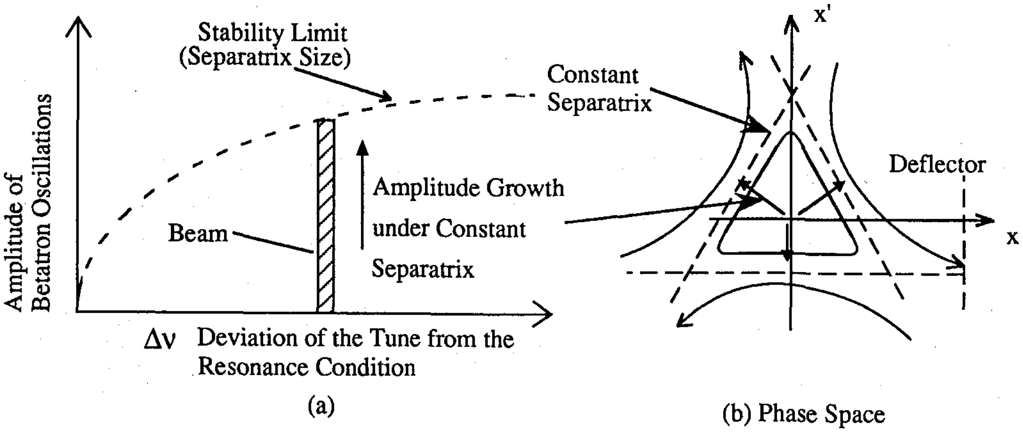

Fig. 3. The scheme of the diffusion-resonant extraction.

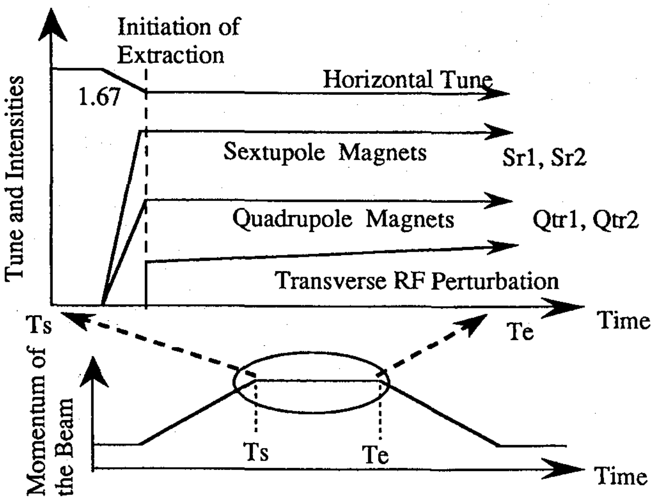

Fig. 4. Schematic time chart of the extraction.

operation that field strengths of all of the magnets are kept constant after the initiation of the extraction shown in Fig. 4. On the other hand, the transverse radio frequency perturbation with a frequency width is applied to the beam to make it diffuse and reach the separatrix of the resonance. The frequency of this perturbation ranges from 0.66 fr to 0.68 fr, where fr is the revolution frequency of the beam around the synchrotron. Since this frequency range covers the width of the frequencies of the betatron oscillations, which occurs due to the momentum spread of the beam etc., the beam diffuses and the particles reaching the separatrix are extracted. During the extraction, the intensity of the radio frequency perturbation is slightly increased to obtain the constant spill. The needed maximum voltage of the radio frequency perturbation is about 50 V for the beam energy of 230 MeV.

The particles are extracted horizontally through the electrostatic deflector and the septum magnet. From the effect of the constant separatrix, the orbit gradients of the extracted particles are almost constant without dynamic control of the magnets[5-7]. Because of this effect, time integrated emittance can be kept low. This effect has been confirmed experimentally in TARN

II[7] and HIMAC[8].

Furthermore, the intermittent structure of the extracted current can be improved significantly even under the condition that the magnet current includes a low frequency ripple[8,9]. The number of the extracted particles per unit time is expressed as NV where N (l/mm) is the number of particles on the separatrix in the phase space and V (mm/s) the speed of the particles reaching over the separatrix. Since N is large and V is small in the conventional extraction, the value of V is significantly modulated by the ripple of the magnet current. This results in the intermittent extraction. In the diffusion-resonant extraction, since the value of N is small, a large V is needed for obtaining the same flux as that by the conventional scheme. As a result, the modulation of V due to the current ripple of the magnets is much smaller than that in the conventional extraction. Then, the time structure of the extracted beam intensity can be improved significantly.

2.5 *Irradiation*

The extracted particles are transported to the treatment room. The present system employs a new scheme for expanding the irradiation field in the treatment room as follows. (i) The beam is defocused in the deflecting plane of the treatment gantry by quadrupole magnets. (ii) The beam distribution in the deflecting plane is flattened by a nonlinear magnet such as an octupole or a duodecapole magnet. (iii) The beam is swept by the dipole magnet across the deflecting plane.

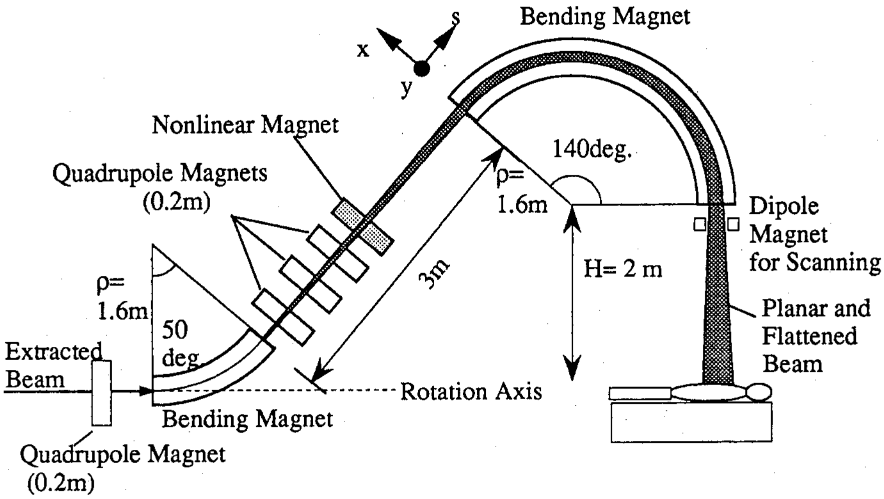

Fig. 5. The gantry for treatments using a new irradiation scheme.

Fig. 5 shows an example of the gantry to which the present scheme is applied. The rotation radius of the gantry on the design orbit is about 3.5 m. This value is smaller by about 1 m than the rotation radius of the gantry using scatterers.

The beam distributions in the deflection plane just before the patient are shown in Fig. 6 for the cases using only octupole magnetic field and both octupole and duodecapole magnetic fields, respectively. The phase space plots of the beam at the position just after the nonlinear magnet are shown in Figs. 7(a), (b). As shown in Fig. 7(a), the change of the orbit gradient by the

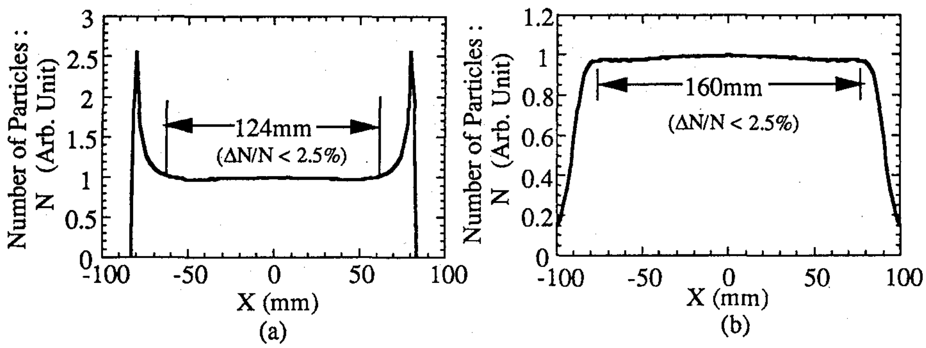

Fig. 6. Beam distribution in the deflecting plane at the position just before the patient. (a) With beam flattening by octupole magnetic field, (b) With beam flattening by octupole and duodecapole magnetic fields.

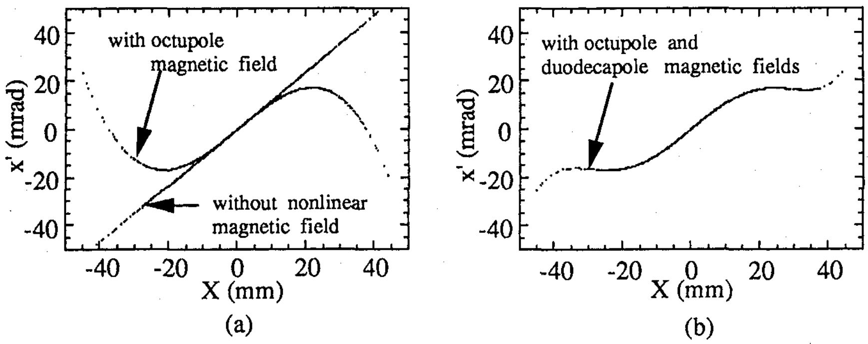

Fig. 7. Phase spaces at the position just after the nonlinear magnet. (a) With beam flattening by octupole magnetic field and without flattening, (b) With beam flattening by octupole and duodecapole magnetic fields.

octupole magneic field results in the twist in the phase space. This effect generates the localized increase at the edge in the beam distribution in Fig. 6(a). The changes of the orbit gradients due to the octupole and duodecapole magnetic fields are proportional to x^3 and x^5, respectively, where x is the displacement from the magnet center. Then, by combining the octupole and duodecapole magnetic fields, the polarities of which are inverse in the deflecting plane, the twist in the phase space can be prevented, as shown in Fig. 7(b). As a result, the flattened width of the beam increases as shown in Fig. 6.

Since a square irradiation field is obtained by the present irradiation scheme, the beam is collimated before the irradiation. It is expected that the beam loss due to the collimator is lower than about 15%. When using the scatterers for the beam shaping, about 60% of the beam is lost by the scatterers. Accordingly, in the present scheme, the beam loss can be reduced significantly in comparison with the scheme using scatterers.

3. CONCLUSION

We presented a compact proton synchrotron system for cancer therapy. In the synchrotron, a combined function lattice was applied with a new type of the untuned RF cavity and a slow beam extraction scheme using a transverse radio frequency perturbation of a narrow bandwidth. Control for acceleration and extraction is very simple, and a low emittance beam can be extracted. The time structure of the extracted current is improved even under the condition that the magnets have current ripples of low frequency.

We also presented a new irradiation scheme which employs defocusing a beam in the deflecting plane in the gantry and sweeping it across the plane. The distribution of the beam is flattened in the deflecting plane by the nonlinear magnetic field. Then, the beam loss, occurring in the case using scatterers, can be reduced significantly.

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