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A Compact Proton Synchrotron Based on a Low Emittance Beam Extraction Scheme Using Transverse RF Noise

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Abstract

A compact proton synchrotron for cancer therapy is presented. In the synchrotron, a new operating scheme for resonant beam extraction is applied with a combined function lattice in order to realize small emittance of the extracted beam with simple control for the accelerator system. In the extraction, the amplitude of the betatron oscillations of the particles inside the separatrix is increased by a tranverse RF noise with a narrow bandwidth. During the extraction, the separatrix is kept constant, that is, the magnet currents related to the resonance are kept constant. The emittance of the extracted beam can be kept lower than about 0.1πmm · mrad without dynamic control of the closed orbit.

I. INTRODUCTION

A high energy proton beam is considered to have good potential for cancer therapy because of the sharpness of the Bragg peak in body tissue and the beam ejected from an accelerator has been applied to actual cancer treatments[1][2]. In cancer therapy, varying beam energy should be necessary when treating a different depth in the tissue. Then, a synchrotron seems to have an advantage as an accelerator for cancer therapy because it can accelerate charged particle beams to various energies.

In order to irradiate the tissue precisely, the position change during extraction, that is, the time integrated emittance of the beam extracted from the synchrotron should be as low as possible. This purpose can be realized through a new, simpler operation scheme for slow beam extraction[3][4][5].

On the other hand, control should be simple for not only extraction but also acceleration because the medical accelerator system must be used in daily treatments. The combined function lattice has an advantage of simple operation for the acceleration with the expense of flexibility for selecting operating points compared with the separated function lattice[2][6]. However, in order to obtain a low emittance beam for the treatments by a conventional extraction scheme, it is expected that complex control for the extraction cannot be avoided.

Then, we propose a new synchrotron design for proton therapy with the combined function lattice in which the low emittance extraction scheme using transverse perturbation is employed. By combining this extraction scheme and the combined function lattice, a better beam for medical applications can be obtained by simpler operation of the accelerator system.

II. SYNCHROTRON DESIGN

A. Lattice and Machine Parameters

Machine parameters of the designed synchrotron are listed in Table1. The proton beam is injected from a linac to the synchrotron at the energy of 10 MeV and accelerated to the desired energy, which ranges from 70 to 250MeV. After acceleration, the beam is extracted slowly. The lattice of the designed synchrotron is shown in Fig. 1. There are four superperiods. As shown in the figure, the synchrotron consists

Table 1 Machine parameters

Circumference(m)	27
Injection Energy (MeV)	10
Max. Extraction Energy(MeV)	250
Tune	
Qx	1.75
Qy	0.85
Bending Magnet	
Deflection Angle(deg)	45
Curvature Radius(m)	1.62
Max. Field Strength(T)	1.50
BD K($1/m^2$)	0.2537
n	0.6658
BF K($1/m^2$)	-0.1108
n	-0.2908
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	
$\xi x = (\Delta Qx/Qx)/(\Delta p/p)$	-0.24
$\xi y = (\Delta Qy/Qy)/(\Delta p/p)$	-0.26

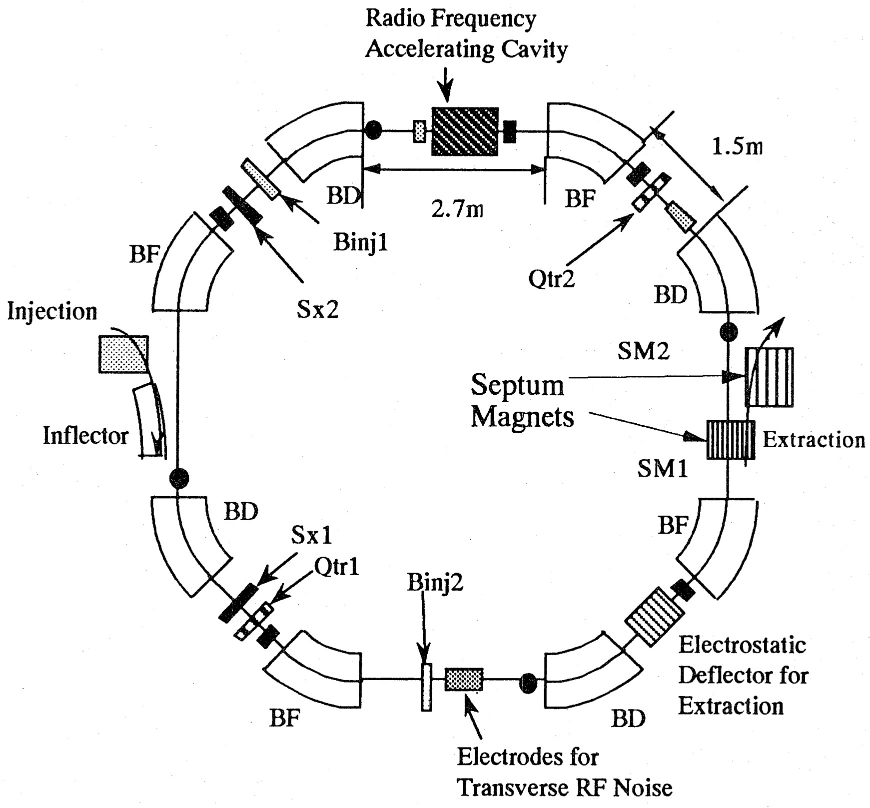

Fig.1 Configuration and lattice of the synchrotron

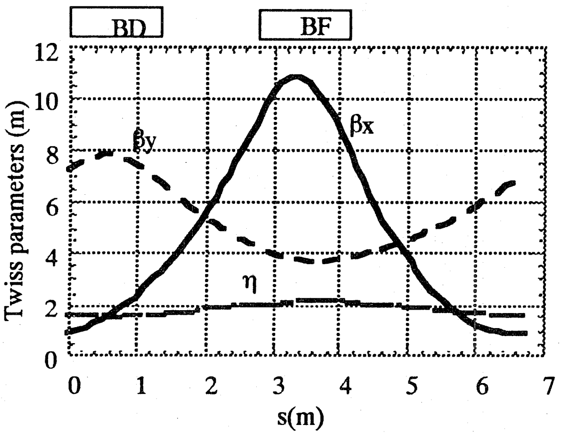

Fig.2 Twiss parameters along one super period

of two kinds of combined function bending magnets, BF and BD, n-indices of which were determined so as to satisfy the following tune values. The deflection angle of each bending magnet is 45 degrees. The maximum magnetic field of the bending magnets is 1.5 T, which results in the curvature radius of 1.62m. The horizontal tune Qx of 1.75 and the vertical tune Qy of 0.85 were chosen so as to avoid structure resonance for the betatron oscillations. The horizontal and vertical betatron functions and the horizontal dispersion function are shown in Fig. 2, as βx, βy and η , respectively. All of these values are kept rather small. As a result of small value of the dispersion function, small natural chromaticities are obtained.

B. Injection

Beam injection into the synchrotron is done during about 20 revolution periods by a multi-turn injection scheme using the two injection bump magnets, B_{inj1} an B_{inj2}. The emittance of the circulating beam is approximately 20 times as large as that of the injected beam. Assuming that the dilution factor of the phase space density in the horizontal phase space is about 50%, the circulating beam current is about 10 times as large as the injection current from the linac.

C. Acceleration

The beam energy is ramped synchronously with the fields of the bending magnets connected in series, using radio frequency accelerating cavity. Radio frequency acceleration is done using the ferrite loaded untuned cavity, the design of which is described in another paper in these proceedings[7].

D. Extraction

The low emittance extraction scheme is applied to the slow beam extraction after the acceleration. The slow extraction is performed based on the third order resonance of the betatron oscillations. The separatrix for the third order resonance is generated by using two sextupole magnets S_{x1} and S_{x2} and decreasing the horizontal betatron tune to 1.67 using the trim quadrupole magnets Q_{tr1} and Q_{tr2}. This generation of the sextupole and quadrupole magnets are performed before starting the extraction, as shown schematically in Fig. 3. The field strengths of all of the

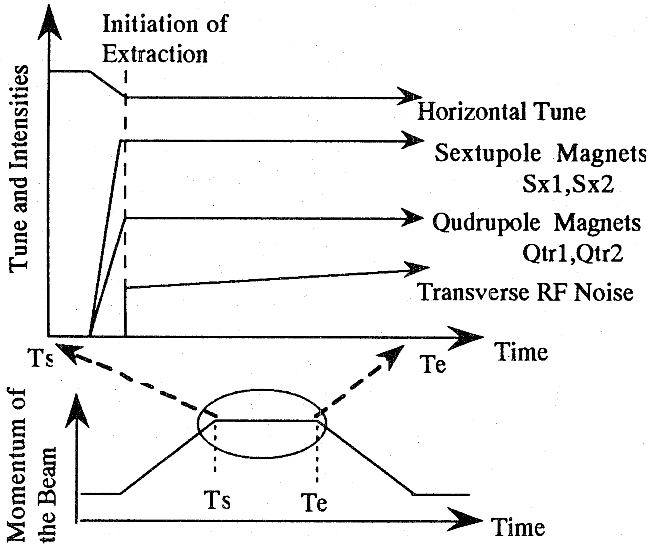

Fig.3 Schematic timing chart

magnets are kept constant during the extraction. Then, the operating point and sextupole strngths are kept constant, i.e.,the separatrix is kept constant. The third order resonancce is reached due to the increased amplitude of the betatron oscillations, which is realized by applying transverse radio frequency (RF) noise with a narrow bandwidth to the beam from the parallel plate electrodes. The frequency of this RF noise ranges from 0.665fr to 0.675fr, where fr is a revolution frequency of the around the synchrotron. Since this frequency range covers the width of the tune of the beam due to the momentum spread, the applied RF noise with narrow bandwidth effectively increases the betatron amplitudes of both the on-momentum and off momentum particles. The intensity of the applied transverse RF noise is slightly increased to obtain a constant spill. The phase space plots of a particle at the deflector position are shown in Fig. 4. It is found that the turn separation at the deflector elctrode is about 8mm. By the effect of the constant separatrix, the change of the orbit gradient of the extracted particles at the deflector position can be kept smaller than 50μrad[3]. Accordingly, the time integrated emittance of the extracted particles can be kept lower than about 0.1πmm · mrad without dynamic control of the magnets. Furthermore, an intermittent extraction can be prevented even under the condition that the magnet current includes a low frequency ripple because random motions of the particles by the applied RF noise mask the effect of the separatrix change due to the ripple in the magnet current[4].

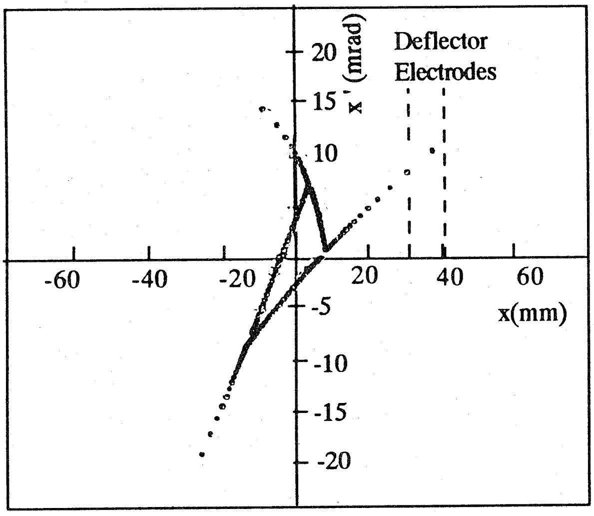

Fig. 4 Phase space plots of an extracted particle at the deflector

III. CONCLUSION

We presented a compact proton synchrotron for cancer therapy. In the synchrotron, an operating scheme for slow beam extraction using a transverse RF noise of narrow bandwidth was applied with a combined function lattice in order to realize small emittance of the extracted beam with simple control for the accelerator system. In the extraction, the amplitude of the betatron oscillations of the particles is increased by the above transverse noise while keeping the separatrix constant. The emittance of the extracted beam can be kept lower than about 0.1πmm · mrad without dynamic control of the closed orbit.

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