A COMPACT PROTON SYNCHROTRON FOR CANCER TREATMENTS

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Abstract

A compact proton synchrotron for cancer treatments is presented. In the present synchrotron, the beam can be accelerated up to 270MeV for the application to proton radiography as well as cancer treatments. In order to shorten the straight section for the extraction deflector such as a septum magnet, the deflections due to the defocusing quadrupole and edge type bending magnets in the synchrotron lattice are utilized effectively. The beam is extracted by the resonant extraction scheme which features that the position and gradient of the extracted beam are constant and the rapid switching is possible. Then, the present synchrotron can be applied to various irradiation schemes such as the double scattering, wobbler and raster scanning methods.

1 INTRODUCTION

A high energy proton beam has been successfully applied to cancer treatments (for example [1]) and patients more than 18000 have been treated worldwide[2]. In cancer therapy, it is expected that varying the energy of the proton beam is necessary when treating a different depth in the tissue because the proton beam shows a sharp Bragg peak. 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 a medical proton synchrotron, the beam energy of 250 MeV is desirable for the treatments of the tumors which depth is 30cm. The medical proton synchrotron should be kept as small as possible in order to be constructed in public hospitals. Futhermore, simple operating scheme is needed for the accelerator and irradiation systems because medical accelerator systems must be used in daily treatments. Considering these conditions, we have presented a synchrotron design of combined function lattice which satisfies the above conditions [3]. Further study is aslo presented in this conference [4].

On the other hand, it has been pointed out that the high energy proton beam can be also applied to radiography as well as cancer treatments [5]. For this application, the beam energy higher than the 250MeV is desirable. Then, we present a compact proton synchrotron of the separated function lattice in which the maximum beam energy reached is 270 MeV and the other above conditions for medical use are kept .

2. SYNCHROTRON

2.1 Machine Parameters and Lattice

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 based on the multi turn injection scheme. The maximum beam energy reached is 270MeV so that the proton radiography may be performed for various cases. The accelerated beam is extracted by the resonanat extraction in which the separatrix of the nonlinear resonance is kept constant and the RF perturbation with a narrow frequency band width is applied to make the beam diffuse to the separatrix [6]. Basically, the procedures of the injection, acceleration and extraction are repeated at 0.5Hz. When the breath synchronized treatment is

Table 1 Machine Parameters

Injection Energy (MeV)	7
Extraction Energy(MeV)	70-270
Superperiodicity	2
Circumference(m)	22.2
Extracted Particle Number (ppp)	$>1.3\text{x}10^{11}$
Tune	
Qx	1.72
Qy	1.74
Bending Magnet	
Deflection Angle(deg)	60
Curvature Radius(m)	1.4
Max. Field Strength iT)	1.8
Twiss Parameters	
βx, max (m)	12
βy, max (m)	11
η max (m)	2.3
Momentum Compaction Factor	
α	0.36
Transition Gamma	
γ tr	1.67
Natural Chromaticity	
ξ x = (ΔQx/Qx) / Δp/p)	-0.24
ξ y = (ΔQy/Qy) / Δp/p)	-1.78

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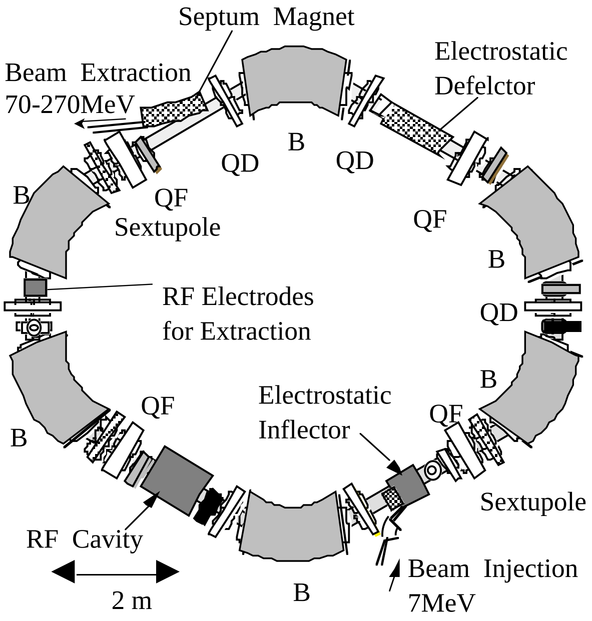

Fig. 1 The Layout of the Synchrotron

necessary, the operation period is changed flexibly and the extraction is switched by the RF perturbation based on the breathing of each patient. Figure 1 shows the lattice of the designed synchrotron. The present synchrotron employs the separated function lattice of two superpriods. Each bending magnet is an edge type and has a curvature radius of 1.4m. The deflection angele is 60 degrees. The maximum magnetic field of 1.8T is needed for the beam energy of 270MeV. The horizontal tune Qx and the vertical tune Qy are 1.72 and 1.74, respectively. There is no structure resonance near this operating point. The horizontal and vertical betatron functions are lower than about 12m and the horizontal dispersion function is sufficently low. The momentum compaction factor is 0.36. Accordingly, the transition gamma is 1.67 and this value is much higher than the maximum gamma of the beam of 1.29.

2.2 Injection

Beam injection into the synchrotron is done during about 10 revolution periods by the multi turn injection scheme. We assume that the dilution factor for the emittance of the injected beam is about 50%. Then, the circulating beam current is about 5 times as large as the injection current from the linac.

2.3 Acceleration

The beam energy is ramped with the current of the bending and quadrupole magnets using the radio frequency (RF) accelerating cavity. The RF acceleration is done using the untuned type cavity which employs Fe-based Nanocrystalline FINEMET cores[7]. Since the untuned RF cavity does not need control of the resonant frequency, the acceleration can be simplified significantly. Generally, the gap voltage of the untuned cavity is relatively low because of its small Q value in comparison with that of the tuned type cavity. Then, the gap voltage of the present RF cavity is increased by matching the impedances of the power source and the untuned cavity due to respective feeding of the RF power to each FINEMET core. The gap voltage for the acceleration can be easily obtained by an RF source with a rather low power.

2.4 Extraction

The beam is extracted by the diffusion resonant extraction scheme in which the separatrix is kept constant and the narrow band RF noise is applied to make the beam diffuse to the separatrix[6]. The frequency of this RF noise ranges from 0.6fr to 0.7fr, 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 nonlinear effect and momentum spread of the beam etc., the beam diffuses due to the RF noise and the particles exceeding the separatrix are extracted. During the extraction, the intensity of the RF noise is slightly increased to obtain the constant spill. The needed maximum voltage of the RF perturbation is lower than 100V for the beam energy of 270MeV. The particles are extracted horizontally through the electrostatic deflector. Figure 2 shows the phase space trajectories at the electrostatic deflector for the particles of different momenta. It is seen that the particles of different momenta are extracted at the same gradients. Furthermore, from the effect of the constant separatrix, the orbit gradients of the extracted particles at the deflector postion are constant without dynamic control of the magnets. As a result, the beam position does not change and the time integrated emittance can be kept very low. These effects have been also studied experimentally in HIMAC[8]. Because of these effects, the present extraction scheme can be applied to various irradiation schemes such as the double scatterer, the wobbler-scatterer, and other scanning methods. Furthermore, the extraction can be switched on and off quickly by the RF perturbation. Then, the breath synchronized operation can be done easily in the present system.

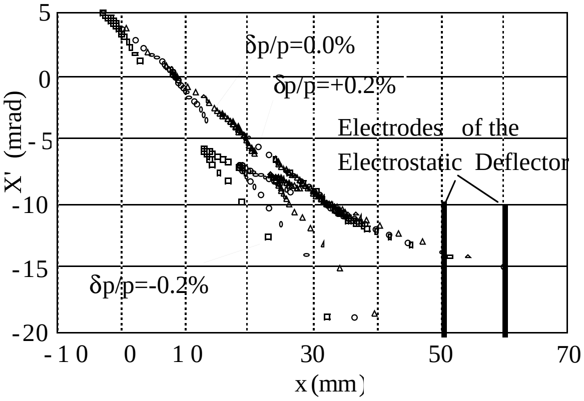

Fig. 2 Phase Space at the Electrostatic Deflector

The particles which exceeds the separatrix are extracted through the electrostatic deflector, the two quadrupole magnets of the defocusing type, the bending magnet in the synchrotorn lattice and the septum magnet. After the deflection by the electrostatic deflector, the extracted particles are further deflected outward by the two quadrupole magnet of defocusing type. Since the present bending magnets is an edge type, the inward deflection by the bending magnet is rather weak. Because of these effects, the separation between the circulating and the extracted particles becomes large at the entrance of the septum magnet. As a result, the septum magnet of the high magnetic field can be applied and its length can be shortened significantly.

2.5 Bending Magnet

The magnetic field of the bending magnets ranges from 0.27T to 1.8T to accelerate the proton beam from 7 to 270 MeV. In order to obatin the good field distribution for the various energy levels, the magnet pole shape has been studied based on the numerical study. Although the saturation effect of the magnet occurs at the high magnetic field, the good distributions of the magnetic field are obatined for various energy levels by shaping adequately the shim of the magnet pole. Figure 3 shows the magnetic field distributions obtained by two dimensional numerical analysis. As shown in the figure, the deviations of the magnetic field from the value at the position of r=1.4m (X=0) are smaller than 0.02% for the energy levels of the injection, acceleration and extraction. Furthermore, the 3D analysis of the magnetic field has been done by using TOSCA to evaluate the nonlinear magnetic field at the circumferential edge region of the magnet. The dynamic aperture has been evaluated based on the above 3D magnetic field analysis and the results show that the sufficient dynamic aperture is kept for all the enegy levels.

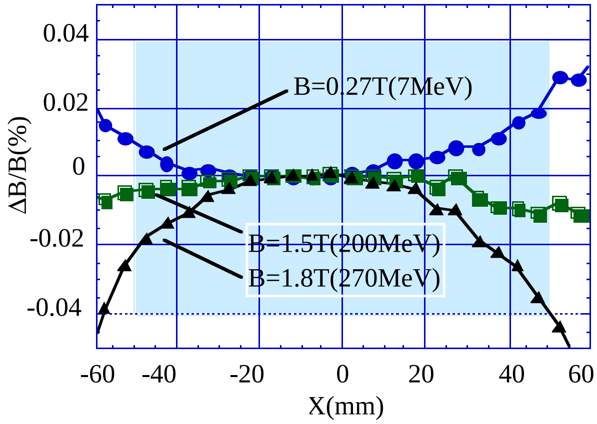

Fig. 3 The Calculated Magnetic Field Distribution of the Bending Magnet

Furthermore, we are investigating the possibility to apply a new type of the bending magnet which has the vacant portions in magnetic poles to control the flow of the magnetic flux in the magnet gap and poles. This new concept has been proposed originally in the project of the development of combined function bending magnets[4] and its effectiveness has been confirmed by the numerical study. This new concept may be useful to enlarge the dynamic range of the magnetic field, that is, the acccleration enegy range for the separated function as well as the combiend function lattices.

3 CONCLUSION

We presented a compact proton synchrotron of 270 MeV for cancer therapy and radiography. In the synchrotron, a separated functionlattice was applied with a slow beam extraction scheme using a transverse radio frequency perturbation of a narrow bandwidth under the contant separatrix. By utilizing the defocusing effects of quadrupole magnets and the bending magnets having an edge effect, the particles are extracted from the rather short straight section.

Since the position and gradient of the extracted beam are constant and the rapid switching on and off for the extraction are possible, the present synchrotron can be applied to various irradiation schemes such as the double scatterer, the wobbller-scatterer and other scanning methods.

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