A COMPACT PROTON ACCELERATOR SYSTEM FOR CANCER THERAPY

A.Yamaguchi, K.Nakayama, T.Rizawa, S.Sukenobu, K.Satoh, Y.Morii, Y.Tanabe and Y.Chiba
Toshiba Corporation
2-4, Suehiro-cho, Tsurumi-ku, Yokohama, 230 Japan

Abstract

The basic design of a compact proton accelerator system for cancer therapy is described. The system consists of a 30keV ion source, a 3MeV RFQ linac, and a rapid-cycling 235MeV synchrotron. A strong focusing combined function magnet, which has both focusing and defocusing section in a unit, is adopted instead of a quadrupole magnet. The rf system applies a compact ferrite loaded tuning-free cavity which has no bias windings. The synchrotron is operated at 20Hz repetition with fast beam extraction. It is the same method as the KEK booster synchrotron, which has been using for proton therapy studies by Tsukuba University. In this system, a breath synchronized irradiation method is easily realized and the energy of proton beam can be changed flexibly within few minutes.

1 INTRODUCTION

It is fundamentally required for a medical accelerator to be reliable, safe, stable, easy to operate and compact. Its beam energy must be changed with depth of a tumor. A synchrotron, which is inherently energy variable, is enough to achieve this purpose. It allows a beam delivery system without an energy degrader, therefore unwanted irradiation and beam quality degeneration are avoided.

About a compact synchrotron, because of severe requirement for rf voltage, rapid-cycling operation has, which all. 20Hz operation obtains lower injection energy, which makes the injector more compact. For the reasons, a rapid-cycling synchrotron is less expensive. been believed to be hard to achieve. If the rapid-cycling compact proton synchrotron up to 20Hz repetition is realized, it has many merits.

A rapid-cycling synchrotron with fast extraction is most adequate for changing the beam energy, because only the timing of the extraction system needs to be changed. A rapid-cycling one has fewer elements by using combined function magnets, one-turn injection and fast extraction. The injection and extraction method brings small aperture, which allows compact bending magnets with small running cost. 20Hz repetition obtains lower injection energy, which makes the injector more compact. For the reasons, a rapid-cycling synchrotron is less expensive.

The repetition rate of 20Hz is high enough to carry out breath synchronized irradiation easily by beam switching at its injector section. In addition, efficiency is nearly 100% for the fast extraction. Beam current of the system at an irradiation point is 20nA, which is sufficient for cancer therapy.

One of the pioneer facilities of proton therapy, Proton Medical Research Center, Tsukuba University (PMRC) has been studying with a 20Hz repetition booster synchrotron at KEK[1]. Many results and experience which can be applied to the rapid-cycling synchrotron have been accumulated at PMRC.

In order to realize the rapid-cycling synchrotron, it is necessary to develop a wide-band high-voltage compact rf cavity, a high-field small combined function magnet and a fast-pulsed kicker magnet. After these subjects have been studied, a rapid-cycling proton synchrotron system for hospital use is designed, which is discussed at following sections.

2 INJECTOR

The injector system consists of a 30kV ion source, a 3MeV RFQ linac and a debuncher cavity. The ion source creates proton beam using a duoplasmatron and a single gap extractor with voltage of 30kV. A beam transport line uses an einzel lens to focus the proton beam from the ion source to the RFQ. The RFQ operating at 425MHz accelerates, focusing and bunching the proton beam from the ion source to 3 MeV. To provide the required input beam momentum spread with $\pm 0.3\%$ at the synchrotron injection point, a single gap debuncher cavity with the same frequency as the RFQ is located in the beam transport line. The beam current at the extraction is 15mA and the stability of current is $\pm 0.1\%$. The normalized emittances at extraction are 0.12 and 0.11 πmmmrad for horizontal and vertical direction.

The 20Hz synchrotron obtains fewer protons per an accelerating cyclesothat the effect of space charge is weaker[2]. Therefore the injection energy can be lower and the injector can be shorter. The injector length without the debuncher is 3m, so the injector system can be placed inside the synchrotron.

3 SYNCHROTRON

3.1 Lattice

The synchrotron is a combined function type which has no quadrupole magnets. The lattice functions of the unit cell are shown in Fig. 1. The magnet lattice has an FDFO structure, and 4 superperiods. The n-value of the magnet is determined as ± 10.5, considering small beam size and also the sensitivity of the magnet imperfection to the lattice functions.

The layout is shown in Fig. 2. A kicker magnet for beam injection, a septum magnet for beam extraction and an rf cavity are located at long straight sections and a kicker magnet for beam extraction is at a short straight section.

The parameters of the synchrotron are summarized in Table 1. The horizontal and vertical tunes are 2.2 and 2.3, respectively.

Table: 1 The parameters of the synchrotron

<Lattice>

Circumference	28.2m
Injection energy	3MeV
Extraction energy	70~235MeV
Repetition rate	20Hz
Straight sections	1.8/2.2m
Injection method	one-turn (on-axis)
Extraction method	fast extraction
Tune (• x/• y)	2.2/2.3
Emittance (at extraction)	0.3• mmmrad
Energy spread (at extraction)	< ± 0.1%

<Combined Function Magnet >

Bending angle per unit	45°
Bending radius	1.9m
Magnetic field	0.13~1.2T
N-value	± 10.5

<RF Cavity >

Rf frequency	0.85~6.4MHz
Peak voltage	5.8kV
Rf input power	2.1kW × 4
Cavity length	1.9m

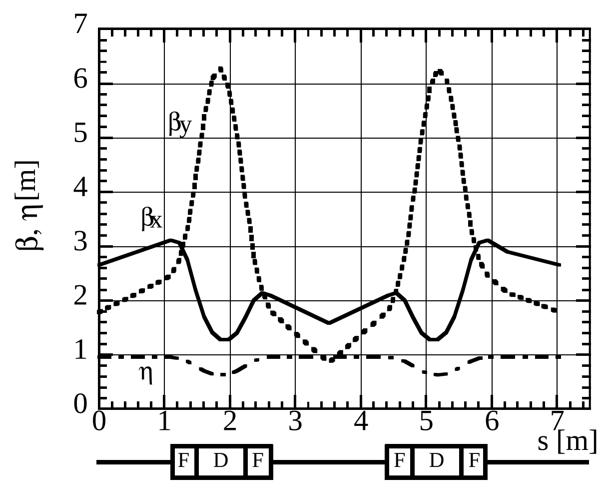

Figure : 1 The lattice function of the unit cell

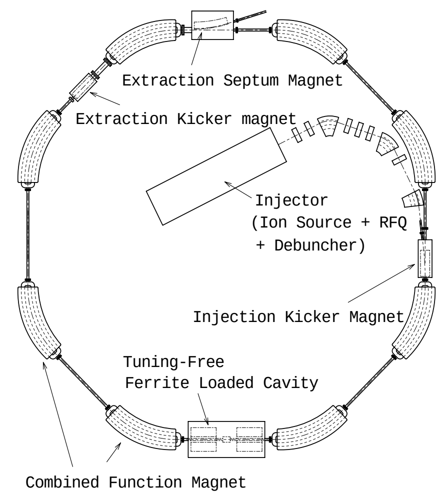

Figure : 2 The layout of the synchrotron

3.2 Bending Magnet

The synchrotron magnet system consists of 8 units of H-type combined function magnets with F-D-F structure. The bending angle of the F section is 11.25° each, and 22.5° for the D section. The n-value of each section is rather large as ± 10.5, in order to make magnets small. A sector type magnet is adopted because of simpler field distribution at the edge region than that of a rectangular type. The bending radius is 1.9 m. The magnetic field at injection and extraction are 0.13 T and 1.2 T respectively. The required good field region is ± 20mm, smaller than one of a conventional synchrotron[3].

The magnet core is made of oriented low-silicon steel of 0.35 mm thickness, which has high permeability athighfield region. The magnet has large n-value as well as soft edge structure relaxing magnetic saturation effect at the edge and the transition between the F and the D section.

Three dimensional analyses with taking account of saturation effect using TOSCA have been performed at both injection and extraction field strength in order to optimize the pole profile, the configuration of the transition and the edge. According to the results of these calculations, saturation doesn't decrease the good field region much in case of the pole width of 150 mm. A prototype magnet has been fabricated for a further experimental study to prove the calculated estimation and the field measurement is in progress now.

Eight magnets connected in series are excited by a single resonant network with a dc bias. The magnet current is 1500A and the voltage is 2.9kV peak.

3.3 RF Cavity

The problem of high voltage (more than 5kV), wideband (frequency ratio up to 1:8) and compact (less than 2m) accelerating structure, which has prohibited a compact synchrotron from rapid-cycling operation, has solved by a new concept of a tuning-free cavity. The method, proposed by Prof. Sato of Osaka University[4], is that a ferrite cavity as an LC parallel circuit, is placed at the center leg of a bridged-T type all-pass network. Its impedance is kept constant as an external resistance R at any frequency, which allows that the circuit is driven by a commercially available amplifier through an impedance transformer.

In the tuning free cavity, a ferrite core is used in the absence of bias field. Therefore it is free from restrictions of bias response and high-loss effect, which is characterized by a sudden decrease in rf voltage above threshold level of input power under DC bias field. It gives wider variation of selecting ferrite material. Ni-Zn ferrite SY-20, newly developed by TDK co., is applied for the cavity, whose μQf value is several times larger than conventional Ni-Zn ferrite, e.g. SY-2. Since it greatly reduces power dissipation at ferrite cores, it can be thought that in the system power loss is almost drawn out to the external resistance and that only voltage remains on the cavity. It is the reason why the system can produce very high accelerating voltage.

Experimental research has performed with a prototype cavity, shown in Fig. 3, as a collaboration between Osaka University and Toshiba co.. Designed gap voltage up to 700V was obtained with 1kW input through frequency range from 1 to 8 MHz, even under 25ms frequency sweep. All the results show the new concept of tuning-free cavity is applicable to a rapid-cycling compact proton synchrotron.

These results show the feasibility of a 1.9m long tuning-free cavity for the synchrotron discussed in this paper, which produces accelerating voltage at frequency range from 0.85 to 6.4 MHz, up to 5.6kV peak with 8kW rf power.

3.4 Injection and Extraction for Synchrotron

The synchrotron applies a one-turn and on-axis injection method due to small current of the injected beam. The proton beam is injected by a kicker magnet at a long straight section. The injector kicker magnet is needed fast current fall-time as 200 nsec, so this magnet has to be distributed constant type[5]. The magnetic field is 0.052 T and the magnet length is 0.53 m. Magnets of the same type are operated at KEK booster synchrotron and SPring-8 synchrotron. A power supply is required about 50 kV, less than one for SPring-8.

The extraction is performed by a kicker magnet and a septum magnet with a bending magnet between. The magnet length and the field strength are 0.53 m / 0.071 T and 0.74 m / 1.0 T, respectively. With the fast extraction method, the kicked beam passes through the bending magnet only once. Thus the beam trajectory at extraction doesn't give any restrictions to the good field region, which can be very small.

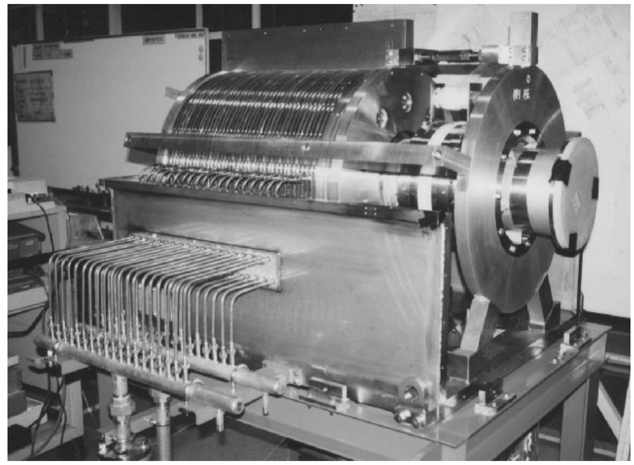

Figure : 3 The prototype of tuning-free ferrite loaded cavity

4 CONCLUSION

A rapid-cycling compact synchrotron with one-turn injection and fast extraction is proposed, which consists of distinctive elements such as combined function magnets and a new type of a tuning-free cavity. It is characterized by energy flexibility, easy application to breath synchronization and reduced price. High efficiency, high safety to surroundings and high beam quality can be achieved with the method because of small beam loss at extraction, absence of a degrader and conservation of its small beam emittance. Additionally a radiation shield system becomes simple. The beam energy of the synchrotron can be up to 250MeV for proton radiotherapy without any difficult problems.

After experimental and analytical research of these elements have been performed in order to verify the proposal, availability of the synchrotron for a hospital use has been confirmed.

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