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COMPACT COTANGENTIAL ORBIT ACCELERATOR FOR PROTON THERAPY

T. Hae, T. Aoki, C. Hori, H. Nakashima, F. Noda, T. Seki, K. Hiramoto
Hitachi Ltd., Hitachi city, Japan

Abstract

A new type accelerator is being developed for the next generation particle therapy system. This accelerator utilizes a weak focusing DC magnetic field and a frequency modulated RF acceleration. Since a superconducting magnet is applicable to the main magnet, the accelerator can be compact. The accelerator characteristically has cotangential orbits to form an orbit-concentrated region. A beam is extracted from the region by using a new extraction method with the transverse RF kicker, peeler and regenerator magnetic fields. In this method an extracted beam energy can be controlled by applied time of the acceleration RF voltage without using an energy selection system (ESS). Intensity and pulse width of the extracted beam can be controlled by a voltage and/or a frequency pattern of the RF kicker.

INTRODUCTION

Currently, a cyclotron type accelerator (AVF cyclotron, synchrocyclotron) and a synchrotron are provided to practical use of particle therapy.

Since a superconducting magnet is applicable to a cyclotron type accelerator with a DC main magnetic field, it is a merit to be able to downsize the accelerator. However, it is necessary to install an ESS outside the accelerator in order to obtain various desired beam energy levels for treatments. A degrader in an ESS generates unnecessary radiation and reduces beam utilization efficiency. There is also a problem of fragmentation that makes it difficult to apply the cyclotron type accelerator to uses other than proton therapy.

On the other hand, a synchrotron has a merit to extract a variable energy beam without the ESS. In addition, transverse RF-driven slow extraction technology [1] has made it possible to control both the position and the intensity of the extracted beam with high accuracy. Thus, a synchrotron is advantageous for scanning irradiation. However, since the synchrotron requires an AC main magnetic field, it is difficult to adopt the superconducting magnet as a means to achieve a smaller body.

The cotangential orbit accelerator that combines the merits of both a cyclotron type accelerator and a synchrotron has been proposed as a next-generation accelerator for particle beam therapy [2]. This new accelerator uses the DC main magnetic field and the frequency-modulated RF acceleration. The accelerator body can also be downsized by applying the superconducting magnet. It is more nortable that a variable energy beam can be extracted without the ESS by the new method. The accelerator can be applied to both proton and heavy ion beam therapies. In particular, the result of the conceptual design study on the accelerator for proton therapy is described in this paper. The main specifications of the accelerator are listed in Table 1.

Table 1: Margin Specifications

Parameter	Value
Diameter of yoke	2.7 m
Total weight	60 t
Magnetic field	4.0 T at injection point, 3.94 T at max. energy orbit
Main coil	NbTi cable, conductive cooling
Magnetomotive force of main coil	1.8 MA
Harmonic number	1
RF frequency	61.0 ~ 48.5 MHz
RF voltage, required power	10 kV, 30 kW
Extracted beam energy	70 MeV to 225 MeV without degrader
Extraction method	Slow extraction, RF kicker + peeler regenerator
Pulse repetition rate	< 500 Hz

DISTRIBUTION OF ORBITS

The orbits are decentered as shown in Fig. 1 (a) to create the orbit-concentrated region with the radial width of about 10 mm. This region is located at orbits from 70 MeV to 225 MeV, and that corresponds to the extraction energy range needed for treatment. There are two reasons for forming the orbit-concentrated region.

- Extracting the beam from the orbit-concentrated region allows for reduction of the required radial displacement from the equilibrium orbit for each beam within the extraction energy range.
- Installing the RF kicker on the orbit-concentrated region makes it easier to apply the transverse RF electric field to each beam within the extraction energy range.

These two points are essential to realize the new extraction method. Figure 1 (b) shows the ideal main magnetic field distribution on the midplane that realizes such an orbital arrangement. The tune diagram is shown in Fig. 2. It has been confirmed that there is sufficient horizontal and vertical acceptance based on results of a tracking analysis with the ideal main magnetic field distribution [3].

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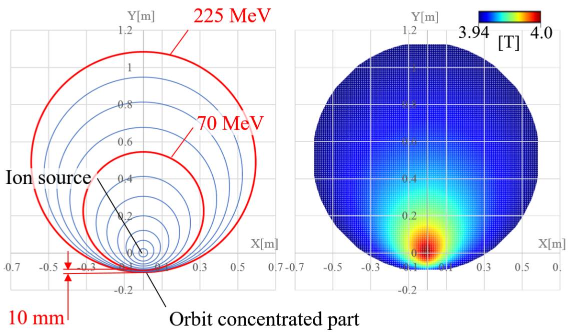


(a) Orbit distribution (b) Main magnetic field

Figure 1: Orbits and main magnetic field.

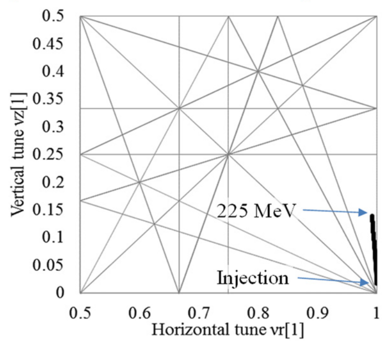
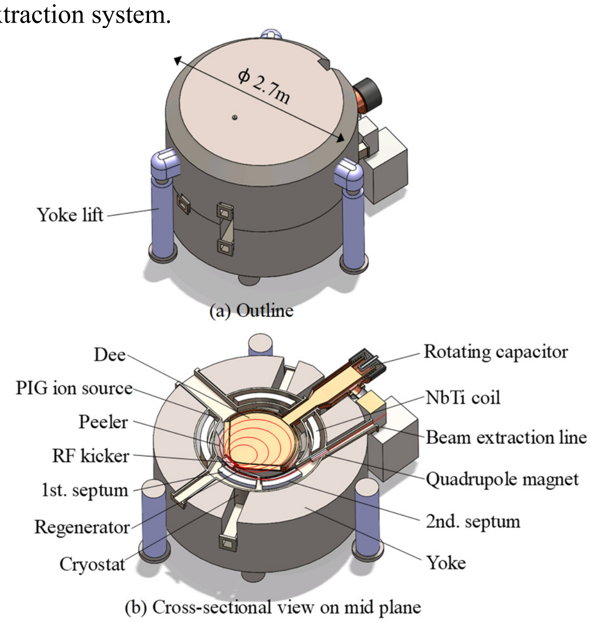


Figure 2: Tune diagram.

ACCELERATOR CONFIGURATION

Figure 3 shows schematic drawings of the accelerator. The main components of the accelerator include the main magnet, the ion source, the RF accelerating system and the extraction system.



(a) Outline

(b) Cross-sectional view on mid plane

Figure 3: Schematic drawings of the accelerator.

Main Magnet

A conduction-cooled superconducting magnet is applied to forms the ideal magnetic field by weak focusing. The shape of the magnetic pole has been obtained by singular decomposition calculation. NbTi wire is selected for the coil winding, based on its relatively low cost and satisfactory mechanical strength.

Ion Source

A compact PIG ion source is applied. Hydrogen gas is introduced into the chimney between the upper and lower cold cathodes. A plasma is generated by applying a DC high voltage and discharging the gas. An RF acceleration electric field formed by an accelerating cavity is used to extract the beam from the plasma.

RF Accelerating System

An accelerating cavity with λ/2 resonant mode is applied to the system. The resonant frequency of the cavity must be modulated because of the non-isochronous magnetic field. Hence either the inductance or the capacitance of the cavity must be varied in time. Thus, the resonant frequency is modulated at the cycle of 2 ms with a rotating capacitor that is attached at the open end of the accelerating cavity opposite the accelerating gap. The shunt impedance of the accelerating cavity was calculated by 3D electromagnetic field analysis, and as a result, the required RF power is about 30 kW. A solid-state amplifier is used for the RF power supply.

Extraction System

The new extraction method utilizes the system consisting of the RF kicker, the peeler and regenerator fields and septum magnets.

Figure 4 shows a schematic diagram explaining the extraction method. The RF kicker is the electrode pair having holes that the circulating beam passes through. Beam orbits of any energy within the extraction energy range are included between the electrode pairs. After the beam is accelerated to reach the extraction energy, the RF accelerating voltage is turned off, and then the RF kicker begins to apply a transverse RF electric field to the circulating beam so as to excite horizontal betatron oscillation. The frequency band of the transverse RF electric field is set to include $f_{rev} \cdot (1-\nu_r)$, where f_{rev} is the circulating beam frequency and ν_r is the horizontal tune of the beam. While the transverse RF electric field is turned on, the circulating beam eventually reaches the peeler and regenerator fields on the outer peripheral side of the equilibrium orbit of 225 MeV. As a result, half-integer resonance ($2\nu_r = 2$) is driven by the peeler and regenerator fields, and a large turn separation can be obtained that cannot be realized by the RF kicker only. The peeler and regenerator fields have been designed by trajectory analysis to obtain sufficient turn separation at the entrance of the septum magnet while keeping the vertical betatron oscillation stable for the beam of any energy within the extraction energy range. The extraction system utilizes several septum magnets whose excitation currents are changed according to the extraction energy.

An example of the timing chart regarding the beam extraction is shown in Fig. 5. The pulse width of the extracted beam is controlled by the application time of the RF kicker

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in order to match the requirement of spot scanning irradiation. The beam current is controlled by the amplitude and/or the frequency of the transverse RF electric field. The RF captured and accelerated beam can be effectively utilized by this slow extraction, which can contribute to a higher dose rate for proton therapy.

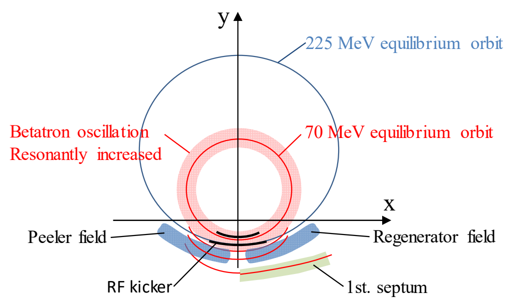


Figure 4: Schematic drawing explaining the extraction method.

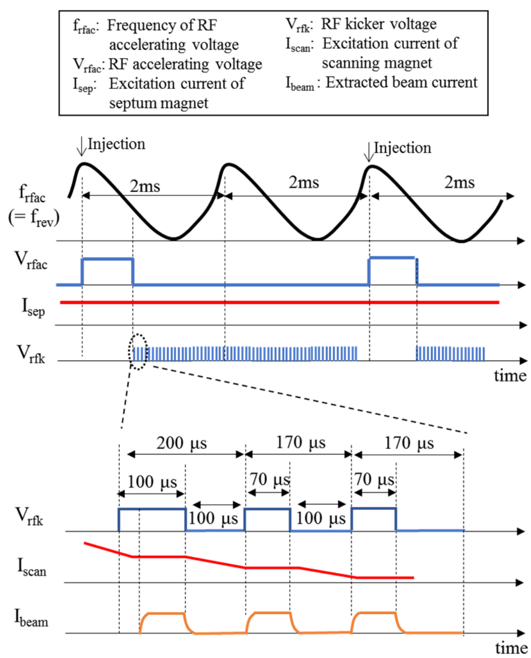
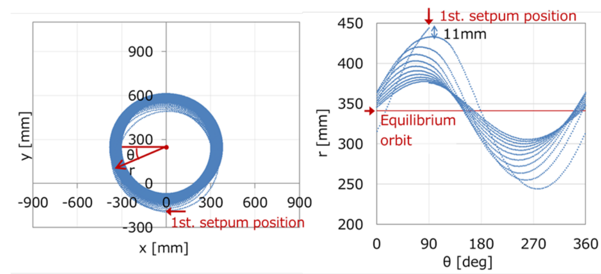


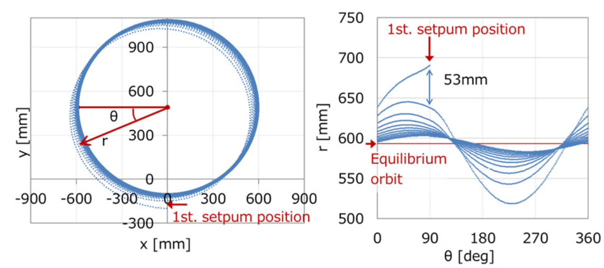
Figure 5: Timing chart of beam extraction.

BEAM EXTRACTION SIMULATION

Figure 6 shows the simulation results of single particle tracking by using the analysis code GPT [4]. In these results, only the RF kicker voltage V_{rfk} = 2 kV is applied without the RF acceleration. And the trajectory is calculated from each initial position to the septum entrance. The initial position is set to the place displaced +1 mm horizontally from each equilibrium orbit. In these conditions, for the lowest extraction energy of 70 MeV, the minimum turn separation of 11 mm can be obtained and it exceeds the septum conductor thickness of 7.5 mm. The turn separation becomes larger as extracted beam energy increases. Because the higher energy beam is more affected by the peeler and regenerator fields in this extraction method. For the highest extraction energy of 225 MeV, the turn separation reaches 53 mm, and the beam utilization efficiency is maximized.



(a) 70 MeV extraction trajectory. (b) 70 MeV last 10 turns.



(c) 225 MeV extraction trajectory. (d) 225 MeV last 10 turns.

Figure 6: Tracking simulation result of beam extraction.

CONCLUSION

The conceptual design has been done for the cotangential orbit accelerator using the DC main magnetic field and the frequency modulated acceleration. And the new extraction method utilizing combination of cotangential orbits, RF kicker, and peeler and regenerator magnetic fields has been proposed. The tracking simulation indicated the possibility to extract proton beam of the energy range of 70 to 225 MeV without an ESS. The new extraction method enables slow beam extraction, therefore both a high beam utilization efficiency and high-accuracy dose control suitable for a scanning irradiation can be realize.

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