CONCEPTUAL DESIGN OF CARBON/PROTON SYNCHROTRON FOR PARTICLE BEAM THERAPY

F. Noda, F. Ebina, H. Nishiuchi, T. Hae, M. Umezawa, S. Fujitaka,
K. Saito, H. Akiyama[1], K. Hiramoto
Energy and Environment Systems Laboratory, Hitachi, Ltd.
[1] Hitachi Works, Hitachi, Ltd.

Abstract

Slow cycle synchrotron system for cancer therapy is presented to realize the pencil beam scanning with carbon and proton beam. The designed synchrotron's circumference is 60m and the maximum beam energies are 480MeV/u for carbon and 250MeV for proton. In the treatment system using the presented synchrotron, the discrete spot-scanning scheme for lateral irradiation is employed using fast beam ON/OFF method. This beam switching method is one of the characteristics of the RF driven slow extraction (RFDE) from the synchrotron. On the other hand, distal dose distribution is controlled with energy stacking technique, which is superposition of various Bragg peaks. Bragg peaks are directly controlled by extraction energy from synchrotron.

INTRODUCTION

Hitachi has researched, developed and manufactured the proton beam therapy system [1, 2]. Recently, the needs of carbon beam therapy system have been rising with its high dose concentration, which is depended on small beam size and sharp Bragg peak, as well as its high biological effect. Hence, we have carried out the conceptual design of carbon/proton synchrotron for cancer therapy. Several key technologies in this conceptual design are based on the technologies of proton synchrotron for beam therapy that have been developed. The first is multiple-harmonic operation with un-tuned cavity loaded FINEMET cores. The second is RF driven slow extraction. The third is discrete spot scanning, which is realized by above two technologies, and energy stacking method. In the following sections, the overview of designed synchrotron and some notable issues of this synchrotron are described. Furthermore we wish to discuss about the evolved multiple-harmonic operation of RF for long-term slow extraction.

CARBON/PROTON SYNCHROTRON

Overview of Synchrotron

The designed synchrotron's circumference is 60m and the maximum beam energies are 480MeV/u for carbon and 250MeV for proton. These energies correspond to the beam range of 35cm in water. Figure 1 shows a schematic view of carbon/proton synchrotron, and Table 1 summarises the major parameters of synchrotron. The ring has a super-periodicity of 6. Each super-periodicity is composed of two dipole magnets and two quadrupole magnets. Long straight sections are used for beam injection (bump magnets and inflector), acceleration (RF cavity) and extraction (bump magnets, transverse RF, deflector and septum magnets). The beta and dispersion functions of this synchrotron are shown in Fig. 2. The maximum values of βx, βy and ηx are 12m, 13m, and 4.5m, respectively.

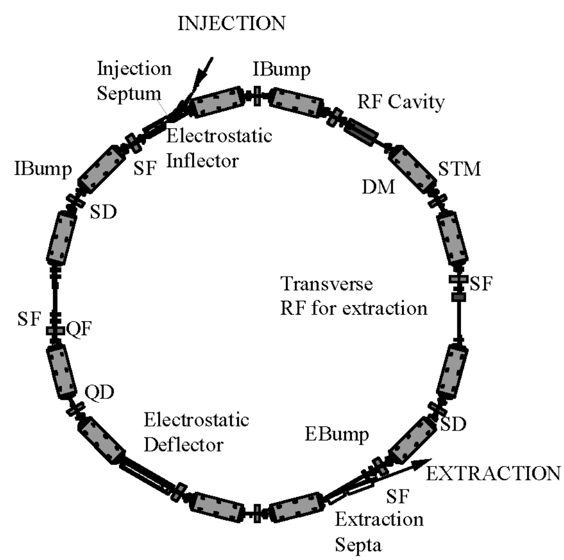

Figure 1: Schematic view of synchrotron. DM: Dipole magnet; QF, QD: Quadrupole magnet; SF, SD: Sextupole magnet; STM: Steering magnet; IBump/EBump: Injection/Extraction bump magnets.

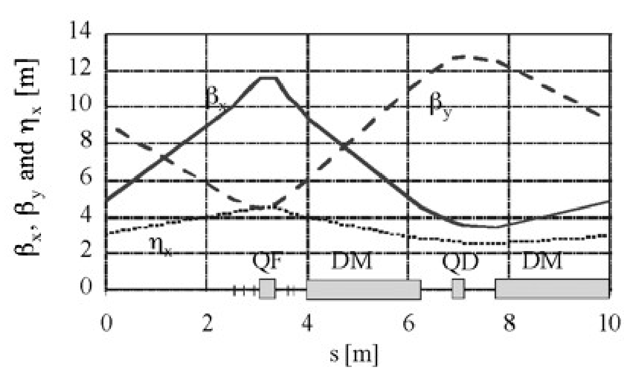

Figure 2: Beta and dispersion functions for one super-period.

Injection

Carbon or proton beam, which is pre-accelerated by linear accelerator, is injected into synchrotron by multi-turns injection method. Injection energy of 7 MeV/u is decided in consideration of space charge limitation for proton. The efficiency of injection is over 60% with 20-turns injection. Injection beam is painted around 200π.mm.mrad in horizontal phase space by sweeping of magnetic field of injection bump magnets. Injected beam is adiabatically captured into radio frequency buckets for acceleration. The capture efficiency is about 70-80%. At capture and early acceleration period, the multiple-harmonics are superimposed in order to mitigate the space charge force. In the case of proton therapy system, beam intensity was enhanced by a factor of 1.6-1.8 with multiple harmonics method using second and third harmonics.

Acceleration

Injected beam is accelerated by the un-tuned cavity loaded FINEMET cores. FINEMET is nano-crystalline soft magnetic material, which is patented by Hitachi Metal, Ltd. This cavity is suitable for a beam therapy system, because of following reasons. (i) It is unnecessary to control a resonant frequency of cavity in accordance with changing of revolution frequency. It makes control of RF significantly easier. (ii) Multiple harmonics operation is realized by only one cavity, so ring becomes compact and it is unnecessary to control the phase of radio frequency between several cavities. RF system for heavy ion synchrotron has been developed. The cavity length is 1.4m. The maximum accelerating voltage is 3kV. Operation frequency covers wide range from 1 to 10MHz that needed for acceleration of carbon/proton beam thoroughly. Solid-state power amplifier drives this cavity with multi-feed method [3]. The expected efficiency of acceleration is 80-90%.

Extraction

The accelerated beam is extracted by slow extraction scheme using a third order resonance ν_x=5/3 by transverse RF-driven slow extraction method (RFDE) [4]. Stabilities of extracted beam parameter, for example beam position, beam size and momentum deviation, are very important issue for particle beam therapy, especially for spot scanning irradiation system. In the RFDE method, the separatrix is kept constant whole extraction, so the control of extraction is very easy, and it makes extracted beam position more stable. In the case of proton beam therapy system, deviations of beam position in transverse and vertical direction are both within 0.5mm, and same stability for carbon/proton synchrotron system will be expected. Also the simulation code has been developed in order to analyze a mechanism of realistic RFDE [5] and to realize more precise control. The efficiency of extraction is over 90% in simulation.

Table 1: Major Parameters of Synchrotron

Circumference	60m
Injection energy	7MeV/u
Injection method	Multi-turns injection
Extraction energy	Proton : 70-250MeV carbon : 120-480MeV/u
Extraction method	RF driven slow extraction
Operation tune	ν_x=1.67-1.72, ν_y=1.23-1.43
Super-periodicity	6
Main magnets	Num. of Dipoles 12 Num. of Quadrupoles 12
Natural chromaticity	ξx=-0.4, ξy=-0.7
Transition gamma	1.76
Acceptance (A_x/A_y and $\Delta p/p$)	200/30π.mm.mrad and ±0.5%
Particle number	Proton : 1 x 10^{11} ppp carbon : 1.5 x 10^{9} ppp

SPOT SCANNING IRRADIATION

Discrete Spot Scanning

RF driven slow extraction is fit for a cancer therapy, as mentioned above. However a fast beam ON/OFF technology plays a vital role in discrete spot scanning. Fast beam switching is realised by the synchronized operation of the transverse RF for extraction and the RF for the acceleration [6]. The discrete spot scanning has already been realised by this technology at the University of Texas M.D. Anderson Cancer Center (MDACC), which is one of the world-famous center for cancer treatment and research. This beam switching system realises beam off in less than 150μs. In spot scanning irradiation method, it is unnecessary to prepare a bolus and collimator. It makes a preparation time of irradiation short. Therefore, improvement in the throughput of beam therapy can be expected. Also beam size will be kept small without bolus.

Energy Stacking

Distal dose distribution is controlled by energy stacking method. Energy stacking method means the superposition of various Bragg peaks that are directly controlled by extraction energy from synchrotron. In this method, it is unnecessary to prepare a range shifter. Therefore beam size will be kept small, and distal fall off will be kept sharp. The energy stacking method is also used at MDACC.

Combination of this energy stacking and discrete spot scanning method makes the most of characteristic of carbon beam with high dose concentration.

MULTIPLE HARMONIC OPERATION FOR LONG EXTRACTION PERIOD

Multiple-harmonics technology usually is used in a low energy in order to mitigate a space charge force. This method is also effective in mitigating a wake field, which is induced by circulating beam at high energy. This synchrotron has harmonic number of 2 (f_{rf}~7.5MHz), so frequency of second harmonics (h=4) is 15MHz at extraction. In this frequency region, impedance of cavity is low. However, it is possible that the same effect is realized by superimposing of the lower harmonic h=1(f_{rf}~3.75MHz). A typical voltage pattern is shown in Fig. 3. The voltage of harmonics h=2 is decreasing gradually from 600V to 300V at end of acceleration. At the same time the voltage of harmonics h=1 is increasing from 0V to 600V. Preliminary simulation results are shown in Fig. 4 and Fig. 5. Figure 4 shows longitudinal phase space plot (top) and projection (bottom) at start of extraction. In this case, harmonics is only h=2. On the other hand, Figure 5 shows one in the case of h=2 and h=1. The peak current of bunched beam is reduced by this method to about 70%. This method is effective for stability during a long extraction period in cases like a spot scanning irradiation, especially respiratory-gated irradiation, which involves a waiting time for irradiation.

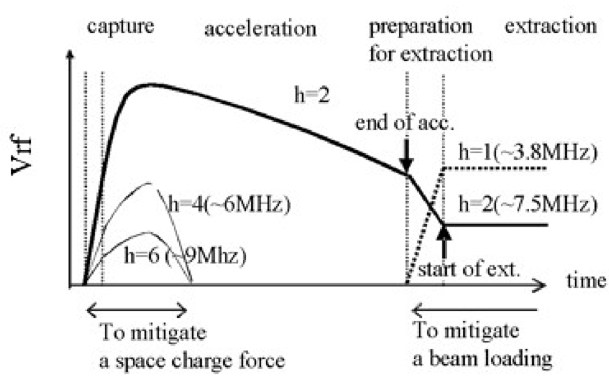

Figure 3: Schematic patterns of RF voltage for multiple harmonics operation.

SUMMARY

We presented the conceptual design of carbon/proton synchrotron for beam therapy system using a spot scanning irradiation. The multiple-harmonics operation is useful method for mitigation of space charge force. For this purpose, the RF acceleration system using un-tuned cavity has already been developed. For extraction, the RF driven slow extraction (RFDE) method and the fast beam switching method have already been developed and these are suitable for spot scanning irradiation. Also energy-stacking technique for depth control is ready. Furthermore, the idea for keeping a beam stability during long extraction period was presented. This synchrotron will be able to satisfy the requirement for carbon/proton and also carbon therapy system using a spot scanning irradiation.

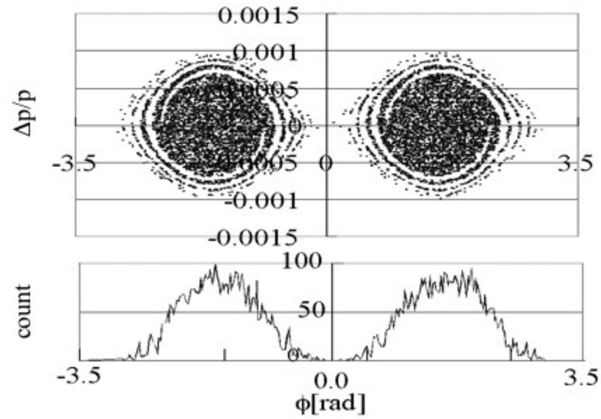

Figure 4: Longitudinal phase space plot (top) and projection (bottom) at extraction. Harmonic number h =2.

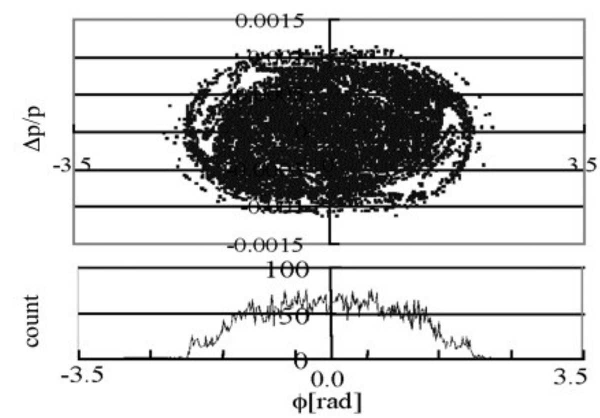

Figure 5: longitudinal phase space plot (top) and projection (bottom) at extraction. Harmonic number h = 2 and h = 1.

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