MULTI-HARMONIC RF ACCELERATION SYSTEM FOR A MEDICAL PROTON SYNCHROTRON

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Abstract

We have developed an RF acceleration system for a medical proton synchrotron. The RF cavity is a tuning-free wideband type, loaded with FINEMET cores, and it is driven by a solid-state RF power amplifier with an operation frequency range between 1MHz and 10MHz. A multi-harmonic RF acceleration scheme has been realized with the RF control system to reduce beam loss by space-charge effects in the low energy region. Original techniques for high-speed digital signal processing and high-precision RF signal processing have been applied to achieve feedback control of the frequency, phase and amplitude of the second and third harmonic RF signals as well as the fundamental RF signal. Beam acceleration tests were carried out to confirm the performance of the developed system.

INTRODUCTION

In recent years, particle beam therapy has made rapid progress and attracted great attention as the least invasive treatment method for tumors. Various types of particle beams have been investigated, with the newest focus on the use of proton beams and carbon beams. Hitachi has developed one of the most advanced proton beam therapy systems. This system has been installed at the Proton Medical Research Center (PMRC) at the University of Tsukuba [1]. Hitachi is also building a proton beam therapy system at the University of Texas M.D. Anderson Cancer Center, which is one of the world's largest cancer treatment and research centers.

The accelerators employed at hospital-based small facilities have to be managed by a few operators who are non-experts regarding accelerators. Therefore, simple operation and easy maintenance are required along with compactness and low cost. In order to make the accelerator system compact and inexpensive, injection energy of the synchrotron should be as low as possible, e.g. below 10MeV in the case of proton beams. The beam dynamics is, however, strongly affected by space-charge effects, because a relatively high intensity of the extraction beam (16nC/pulse) is required for irradiation of a large volume of tumor in the case of a passive scattering method. The resulting tune shift leads to emittance growth and beam loss through some betatron resonance. One method to mitigate the space-charge effects is "multi-harmonic RF acceleration" with a sophisticated RF control system and a wideband RF cavity producing a high accelerating voltage. Three years ago, we succeeded in enhancing the beam intensity by 40% by using dual-harmonic acceleration with our previous system [2]. In this paper, we describe an even more sophisticated system for triple-harmonic acceleration.

SYSTEM CONFIGURATION

Figure 1 shows the configuration of the RF acceleration system developed for a medical proton synchrotron. It is necessary to change the frequency of the accelerating voltage applied to the RF cavity according to the magnetic field strength of the bending magnets. A search coil inserted in the magnetic pole gap of a bending magnet detects a change of the magnetic field strength, and a B-clock signal is generated based on this detected signal. Programmed data of the frequency and phase for digital synthesizers are updated in the RF control system in synchronization with the B-clock signal. After feedback control of the frequency, phase and amplitude, all the harmonic RF signals are combined. The combined signal is amplified with an RF power amplifier, and it is transmitted to the RF cavity.

Timing signals required for operation of the RF acceleration system are generated by timing generating equipment of the central control system. The programmed data of the frequency, phase and amplitude are also created with a server of the central control system, and transmitted to the RF acceleration system by communication via Ethernet before operation of the synchrotron.

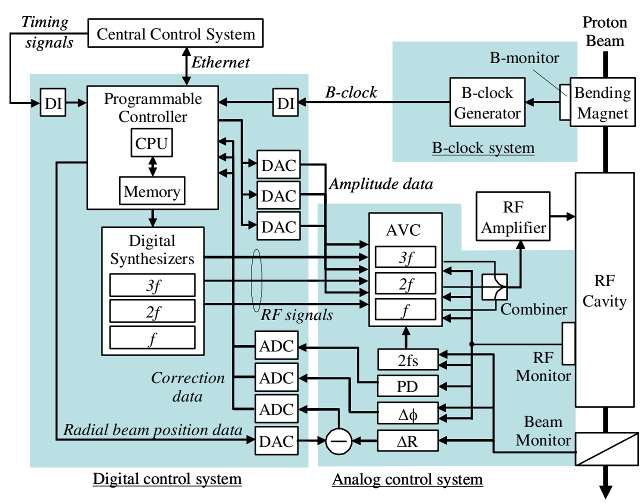

Figure 1 System configuration

RF CAVITY AND AMPLIFIER

Figure 2 shows a photo of the fabricated RF cavity. Typical design specifications and performances are summarized in Table 1. The RF cavity can produce a gap voltage higher than 1.5kV with the supplied RF power of 2.4kW over the operation frequency range between 1MHz and 10MHz.

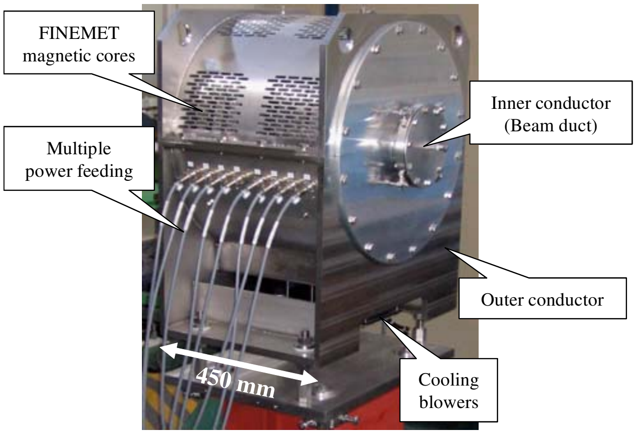

Figure 2 Photo of fabricated RF cavity

Table 1 Design specifications and performances of RF cavity

operation frequency	1 - 10 MHz	
gap voltage	> 1.5 kV	
resonance control	untuned type (Q < 0.5)	
cavity impedance	545 ± 95 Ω (68 ± 12 Ω /core)	
cavity structure	Reentrant coaxial resonator	
	cavity length (flange to flange) outer conductor diameter inner conductor diameter	580 mm 580 mm 140 mm
accelerating gap	gap length installed number	40 mm 1
core material	FINEMET (FT - 3M)	
core shape	toroidal ring	
	outer diameter inner diameter width	500 mm 300 mm 26 mm
core number	8	
dissipated power (core loss)	< 2.4 kW (Solid-state Amp.) < 300W/core	
core cooling	forced air-cooling	
power feeding	multiple power feeding	

Nanocrystalline FINEMET Cores

FINEMET is a Fe-based soft magnetic alloy with an ultra fine grain structure, developed by Hitachi Metals, Ltd. It has characteristics of high complex permeability of (800, 1800) around 3MHz, high Curie temperature of 570 °C, and high saturation flux density of 1.35T. We first applied FINEMET as the material for magnetic cores nine years ago, and have since demonstrated its excellent stability against excitation and heat-up by high RF power [3-4]. Advantages of the RF cavity loaded with FINEMET cores are summarized as follows. (1) Because the FINEMET cores have a low-Q value of <0.5 and high impedance, they are well suited to a tuning-free wideband cavity, for which resonant frequency control is not required. The control system of the RF cavity is simplified and an expensive power supply for a bias current to adjust permeability of the magnetic cores is unnecessary. Since complicated bias windings around the magnetic cores are also dispensable, the RF cavity itself becomes simple and compact. (2) Cooling of the magnetic cores can be realized by forced air cooling, further simplifying and downsizing the RF cavity, and the maintenance load can also be reduced.

Multiple Power Feeding

The developed "multiple power feeding" [5-6] effectively generates a high accelerating voltage with a solid-state RF power amplifier. A coupling loop is provided for each magnetic core, with which the RF cavity is excited by RF power supplied from a multi-channel amplifier through each transmission line. By adjusting the size of the magnetic core so that the impedance should be set to about 50Ω, the cavity impedance can be matched with the output impedance of the RF power amplifier and the characteristic impedance of the transmission line. Advantages of the multiple power feeding are summarized as follows. (1) A solid-state RF power amplifier can be adopted. Therefore, the system becomes much simpler and maintenance load can be reduced, compared with a vacuum-tube RF power amplifier. A driver amplifier and DC power supplies for the vacuum-tube RF power amplifier are not necessary. (2) Power combiners and impedance transformers working at a high RF power level are not necessary, although they are required for a conventional system using a solid-state RF power amplifier. (3) The multi-channel amplifier can be operated even when one or more modules are missing; furthermore, if any module should fail, system downtime can be minimized. (4) The multi-channel amplifier can be modularized, and all the modules are interchangeable. Therefore one module is sufficient as a spare.

RF CONTROL SYSTEM

Multi-harmonic RF Acceleration

The multi-harmonic RF acceleration scheme has been realized with the RF control system, in which three harmonics from the fundamental to the third one are generated with digital synthesizers. The digital synthesizers can generate stable and reproducible RF signals with low FM noise. High-speed digital signal processing by FPGA technology has been applied to RF frequency and phase controls for the digital synthesizers. Programmed data of frequency, phase and amplitude for all the harmonics are stored in a 16MB SRAM module. Sequence control synchronizing with external timing signals is performed by the programmable controller employing a CPU SH-4. Timing control such as feedback on/off is managed with the programmable controller.

High-precision RF signal processing has been developed to detect the amplitude and phase of each harmonic voltage generated at the RF cavity. A heterodyne detection scheme provides both precise separation and conversion of the harmonic components to individual RF signals with the same frequency of 30MHz, at which amplitude and phase detections can easily be done. The heterodyne detection scheme has also been employed for beam position and phase detections necessary for frequency feedback control. RF signals required for the heterodyne detection (31-40MHz) are generated with single sideband mixers, in which the output RF signals of the digital synthesizers (1-10MHz) are mixed with local RF signals of 30MHz crystal oscillators.

Frequency Control

Output RF frequencies of the digital synthesizers are set based on the summation of programmed data and feedback compensation values. The programmed data are updated by B-clock signal with resolution of 0.2G, which is generated by a V-F converter with a maximum clock rate of 200 kHz. The analog processing unit inputs signals detected with a beam monitor and a cavity RF-voltage monitor, and outputs the radial displacement of beam orbit (ΔR) and the phase oscillation of a bunched beam to the cavity RF-voltage (ΔΦ). The digital processing unit determines the feedback compensation values from the ΔR and ΔΦ values so that they can be suppressed enough to prevent beam loss. The programmed data can easily be optimized by learning control using the feedback compensation values. The total delay time of ΔΦ feedback processing is 5μs, which is short enough to damp the phase oscillation (synchrotron oscillation) of 5 kHz completely.

Phase Control

Output RF phases of the digital synthesizers are set based on the summation of two kinds of programmed data. One is the data dependently programmed on the RF frequency and updated by the B-clock signal during operation. This kind of phase data is necessary to compensate for frequency-dependence of transfer characteristics of individual components. The other is the time-series data dependently programmed on the synchronous phase of the accelerated beam; these data are updated by the T-clock signal with a constant period of 20μs. The phase of each harmonic voltage generated at the RF cavity is measured in the analog control unit, and the deviation from the desired value can be compensated for in the digital control unit. The precision of phase control is within an error of ±3°.

Amplitude Control

Amplitude control for each harmonic voltage is performed with the Automatic Voltage Controller (AVC) in the analog control unit. Each harmonic signal from the digital synthesizer is amplitude-modulated with the AVC, so that the measured amplitude corresponds to the desired value by feedback. The desired amplitude value is programmed for each harmonic and saved in the digital control unit. During operation, the programmed data are updated by the T-clock signal and transferred to the AVC. The precision of amplitude control is within error of ±3%.

BEAM ACCELERATION TEST

The performances of the new RF control system were examined in the PMRC synchrotron at the University of Tsukuba. The energy of the proton beam injected into the synchrotron was 7MeV, and the flattop (extraction) energy was set at 200MeV during this series of experiments. Synchrotron oscillations of 1-4 kHz were observed and successfully suppressed by the ΔΦ feedback as shown in Figure 3. The radial beam position could be controlled by the ΔR feedback as well. Figure 4 shows a typical beam bunch shape in the case of the triple-harmonic acceleration. Compared with the dual-harmonic acceleration, a 20% higher beam intensity was obtained at the extraction by flattening the bunch shape further in the low-energy region.

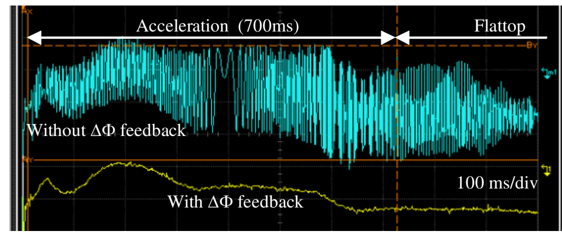

Figure 3 Suppression of synchrotron oscillation by ΔΦ feedback

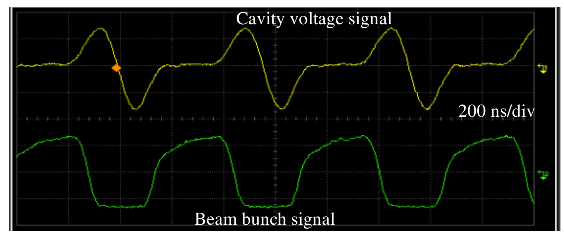

Figure 4 Bunch shape in the case of triple-harmonic acceleration

FUTURE PLANS

The present system can be easily applied to medical carbon-ion synchrotrons by doubling the accelerating voltage with two sets of the RF cavity and amplifier. Hitachi is now designing the RF accelerating system for the HICAT synchrotron. We are also developing a high-gradient RF cavity for medical carbon-ion synchrotrons (>3kV/0.6m) by further advanced power-feeding with solid-state RF power amplifiers (5kW).

ACKNOWLEDGEMENT

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