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RF Acceleration System for Medical Synchrotron

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Abstract

We have developed a FINEMET-core loaded untuned RF cavity using multifeed coupling. The operation frequency range was widened to 0.5-8.5 MHz, where the voltage standing wave ratio (VSWR) was lower than 2. The accelerating gap voltage higher than 1.5 kV was achieved with the cavity length of 550 mm and a supplied RF power of 2.4 kW. We have also developed an RF control system using a direct digital synthesizer (DDS). The performance of the RF control system was checked with a signal generator to simulate beam motions such as radial displacement of the central orbit, dipole and quadrupole oscillations of the bunch.

1. Introduction

Recently, the need for cancer treatments has been increasing more and more, reflecting the situation that more than one fourth of all deaths in Japan are due to various kinds of cancers. We have been developing a medical synchrotron for cancer therapy which accelerates proton and heavy ion beams. The medical synchrotron is operated in a hospital by a few operators who are non-experts on accelerators. Compactness, low cost and simple operation are therefore required. One of the complexities in its operation comes from control of the RF cavity. We selected an untuned RF cavity, since its resonant frequency does not need to be tuned to the frequency of supplied RF power. The control system of the RF cavity is therefore simple and an expensive power supply for a bias current to adjust permeability of loaded magnetic cores is unnecessary. Because complicated bias windings around the magnetic cores are also dispensable, the RF cavity becomes simple and compact.

The untuned RF cavity requires a Q-value low enough (Q<1) to cover a wide revolution frequency range of 0.5-8.5 MHz and an accelerating gap voltage higher than 3 kV to accelerate heavy ions up to 400 MeV/u. We selected FINEMET[1)] as the material employed for the magnetic cores to realize the wide operation frequency range and the high accelerating gap voltage. FINEMET is a Fe-based soft magnetic alloy composed of ultrafine grain structure, developed by Hitachi Metals, Ltd. It has high complex permeability of (800,1500) around 3 MHz, high Curie temperature of 570 °C and high saturation flux density of 1.35 T. Excellent stability against excitation and heat-up by a high RF power has already been confirmed with a testing cavity [1].

In this paper, results of performance tests are presented of a fabricated untuned RF cavity dedicated to medical synchrotron, together with those of RF control system using a direct digital synthesizer (DDS).

2. RF Cavity

A photograph of the fabricated untuned RF cavity is presented in Fig. 1. The design specifications are summarized in Table 1. The RF cavity has a single accelerating gap structure which consists of two quarter-wavelength coaxial resonators loaded with 12 FINEMET cores. The length of the RF cavity is 550 mm. The cavity impedance is designed as 700±150 Ω in the operation frequency range of 0.5-8.5 MHz.

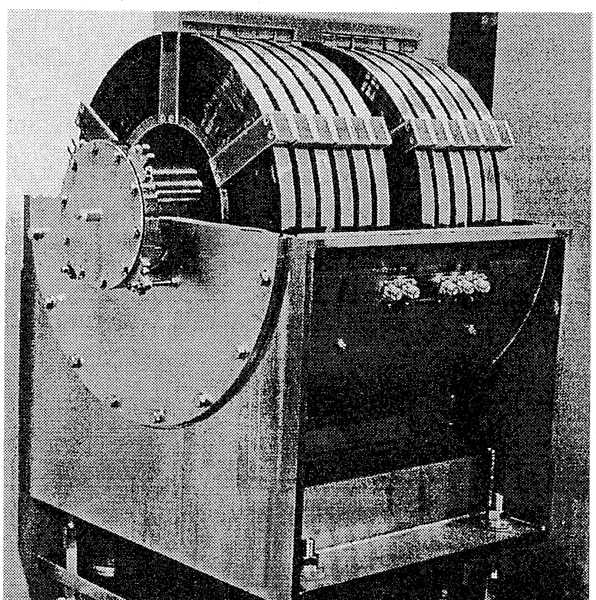


Figure 1 Photograph of the untuned RF cavity.

Table 1 Design specifications.

operation frequency	0.5 - 8.5 MHz	
gap voltage	> 1.5 kV ((> 3 kV))	
cavity impedance	700 ± 150 Ω (58 ± 13 Ω/core)	
cavity structure	quarter wavelength coaxial resonator × 2	
	cavity length	550 mm
	outer conductor diameter	580 mm
	inner conductor diameter	150 mm
accelerating gap	gap length	50 mm
	installed number	1
core material	FINEMET (FT - 3M)	
core shape	toroidal ring	
	outer diameter	500 mm
	inner diameter	280 mm
	width	26 mm
core loaded number	12	
core power loss	200 W/core ((800 W/core)) total 2.4 kW ((9.6 kW))	
core cooling	forced air-cooling	
power feeding	multifeed coupling	

((...)) means the possible value.

A solid-state amplifier is employed as an RF power source instead of a vacuum tube amplifier to reduce the burden of maintenance. Impedance matching between the cavity, feeding line and the power source is indispensable to produce a high voltage at the accelerating gap. Although the impedances of the power source and the feeding line are 50 Ω, the cavity impedance is designed as about 700 Ω to moderate dissipated RF power. Multifeed coupling [2,3] has been adopted to realize impedance matching between the cavity and feeding line. The cavity is coupled to the feeding lines with magnetic loops, each of which is wound around one FINEMET core. The cavity impedance is set to about 50 Ω per one FINEMET core to match the impedance of individual feeding lines.

Figure 2 shows the frequency dependence of the voltage standing wave ratio (VSWR) measured by the reflection method with a network analyzer. The VSWR was lower than 2 in the frequency range from 0.5 to 8.5 MHz. This meant power reflection from the cavity was less than 10 % and the cavity impedance matched well the impedance of individual feeding lines over the operation frequency range. On the other hand, a ferrite-loaded untuned RF cavity did not give such a good impedance matching over the wide frequency range without a parallel resistor across the accelerating gap [4].

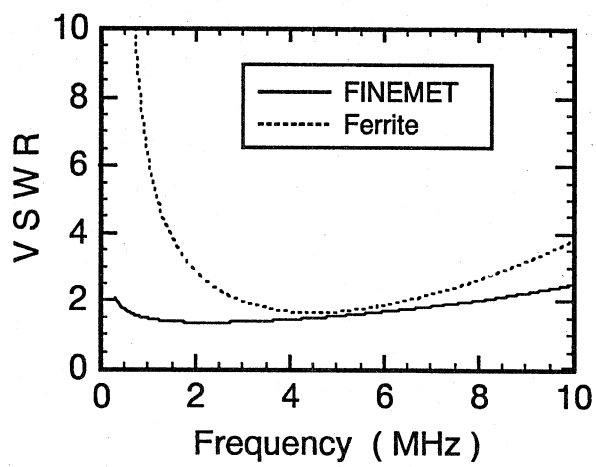


Figure 2 Result of the low power test. Comparison with a ferrite-loaded untuned RF cavity is shown.

Figure 3 shows the frequency dependence of the accelerating gap voltage measured with two voltage dividers connected to both sides of the gap. The wide operation frequency range was also confirmed in the high power test. The accelerating gap voltage higher than 1.5 kV was attained with a supplied RF power of 2.4 kW (200W/core). Surface temperatures of the FINEMET cores were monitored with thermocouples. There should be little differences between the measured surface temperatures and the internal temperatures, because of good thermal conductivity of the FINEMET cores. The maximum temperature rise was 25 °C from the room temperature of 20 °C. Therefore the effectiveness of air cooling with two blowers was confirmed. The accelerating gap voltage is now limited only by the available RF power. Based on the experimental results of the testing cavity [1], the operation at the supplied RF power of 800 W/core should be possible, owing to the stability of the FINEMET cores against excitation and heat-up by a high RF power. Then, the accelerating gap voltage higher than 3 kV can be obtained.

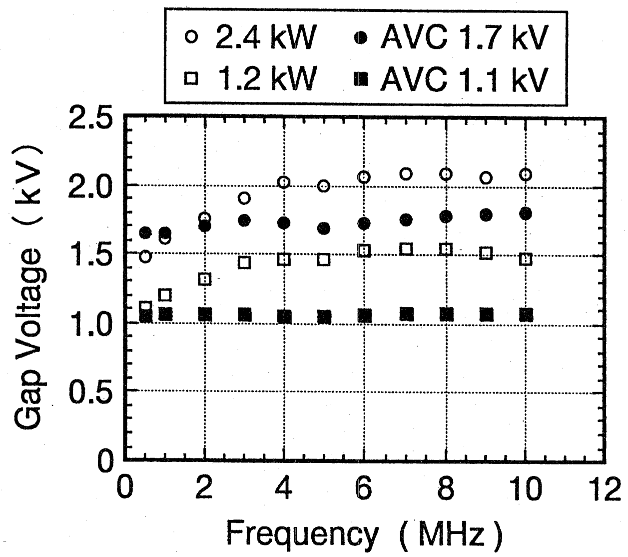


Figure 3 Result of the high power test. The test was carried out by constant power feeding and also under AVC operation.

3. RF Control System

We have developed an RF control system employing a DDS as the reference signal generator for the RF voltage applied to the cavity, to realize stable and reproducible operation of the synchrotron. The excellent performance of the RF control system was already reported at HIMAC [5]. The DDS realizes the RF control system operating in a wide frequency range with low FM noise and highly stable and accurate center frequency. RF frequency can be set with such resolution that the frequency error at the injection energy becomes $\sim 10^{-6}$, which is small enough compared with the momentum spread of the injection beam of $\sim 10^{-3}$. The injection beam can be captured stably in the RF bucket with high efficiency.

The RF control system employs the following four feedback loops: automatic voltage control loop (AVC loop), radial beam position control loop (ΔR loop), dipole and quadrupole bunch-oscillation suppression loops (ΔΦ, 2fs loops). The AVC loop adjusts the cavity gap voltage so as to follow the designed value. The RF frequency is corrected with the ΔR and ΔΦ loops so as to reduce displacement of the beam orbit and to damp the dipole oscillation. The cavity gap voltage is slightly modulated with 2fs loop for the suppression of the quadrupole oscillation.

The performance of the feedback loops was checked with a signal generator to simulate the beam motions: radial displacement of the central orbit, dipole and quadrupole oscillations of the bunch. The signal generator realized the beam transfer function from the cavity gap voltage to the output of beam monitor, and closed the feedback loops even without a real beam and a beam monitor. Results of the performance tests were shown in Figs. 3-6, in which each

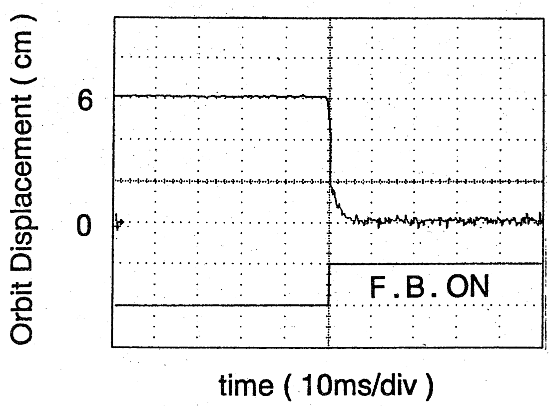
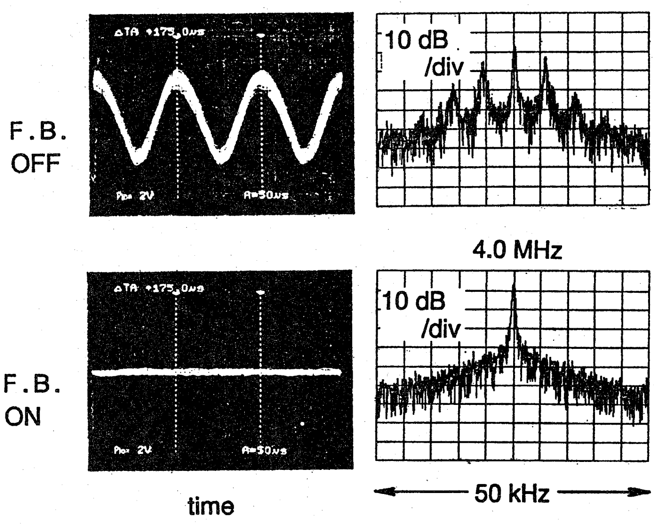


Figure 4 Performance of ΔR feedback loop.



(a) Output Signal of Phase Detector

(b) Frequency Spectrum of Beam Intensity Signal

Figure 5 Performance of ΔΦ feedback loop. The upper and lower figures show the signals when the feedback was OFF and ON, respectively.

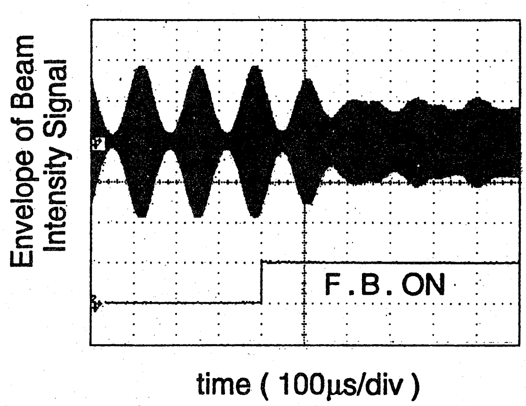


Figure 6 Performance of 2fs feedback loop.

feedback loop was independently examined, although a combination test was possible. (1) The AVC loop realized the voltage regulation within 5 %. (2) The ΔR loop reduced the orbit displacement from 60 mm to lower than 1 mm. (3) The ΔΦ loop suppressed the dipole oscillation of 5.7 kHz completely. (4) The 2fs loop damped the quadrupole oscillation of 8 kHz rapidly. These results meet the specifications required for the RF control system of a medical synchrotron.

4. Discussion

We have confirmed the performance of a FINEMET-core loaded untuned RF cavity using multifeed coupling. For a heavy ion synchrotron, two cavities should be installed to produce the accelerating gap voltage higher than 3 kV with the cavity length of 1.1 m and the supplied RF power of 4.8 kW. For a proton synchrotron, only one cavity should be installed to generate the accelerating gap voltage of 1 kV without suffering beam loading effect during debunching process. If a rapid-cycling synchrotron is adopted, the circulating beam current is much lower although the required accelerating gap voltage is rather higher. Several cavities should then be installed. For example, four cavities give the accelerating gap voltage higher than 6 kV with the cavity length of 2.2 m and the supplied RF power of 9.6 kW.

Acknowledgment

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1) FINEMET is a registered trademark of Hitachi Metals, Ltd.