RF CAVITY WITH CO-BASED AMORPHOUS CORE

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Abstract

A compact cavity for acceleration has been developed with cobalt-based amorphous cores. This core has high permeability that enables the cavity length to be made short, and its low Q-value of about 0.5 permits an RF system without tuning control of the cavity. In the frequency range from 0.4 to 8 MHz, an acceleration voltage of more than 4 kV can be obtained with a total input RF power of 8 kW. In this paper the structure of the cavity, the obtained core impedance, and their performances under high-power test are presented.

INTRODUCTION

In the HIMAC synchrotron, the present acceleration system[1] with a ferrite core cavity has many feedback loops, which make the operation complicated. The tuning system makes the cavity structure complicated with bias winding [2], which requires extra cost. Further, this complexity causes a parasitic resonance in the cavity, which practically requires techniques of its own to remove or suppress it. Considering these problems, the untuned property of the cavity is very attractive. This type of cavity with an amorphous core[3] was proposed, and was realized by utilizing a Fe-based amorphous core (FINMET FT-3M) [4,5]. The cavity without a tuning system has a simple structure and can be easily constructed at low cost. These properties of the cavity come from the low Q-value of about 0.5. Considering the recent R&D, we have developed a new RF high power system with the following characteristics:

1. The Co-based amorphous core[6] is used for an acceleration cavity, which has high permeability with a low Q-value of about 0.5. Especially, this core has about a 1.5-times higher $\overline{\mu}Qf$ value than the FINMET FT-3M, as shown in Fig.1. This is a very attractive point to realize a compact RF cavity with the required high shunt impedance.
2. The transistor amplifier is adapted to achieve the required acceleration voltage instead of the commonly used tetrode. This choice makes the acceleration system simple, and we have no need to exchange from the old tetrode to the new one after a certain period of operation.
3. With sufficient acceleration voltage, a beam with a large momentum spread can be accelerated without a debuncher cavity in the injection line.
4. The last merit of this system comes from the utilization of mixed harmonic waves in a same cavity with its broad band feature, and we can suppress the momentum spread, and enlarge the bunching factor[7]. These manipulations are important in a compact synchrotron to increase the beam intensity.

In this paper, we present the development and testing of an acceleration cavity, having high-power performances.

CO-BASED AMORPHOUS CORE

The fabricated core is made of 15 μm thick amorphous tape with 1.5 μm SiO_2 electric insulator. The filling ratio of the amorphous is around 75% with this insulator thickness. To determine the core size in the cavity, we have measured the impedances of the test core, which has a similar size as a final value. Based on the obtained property of the test core, the inner diameter, outer diameter, and thickness of the core are determined as 310 mm, 550 mm, and 30 mm, respectively. With this dimension, twelve cores were fabricated and checked regarding its $\overline{\mu}Qf$ values, which are shown in Fig. 1.

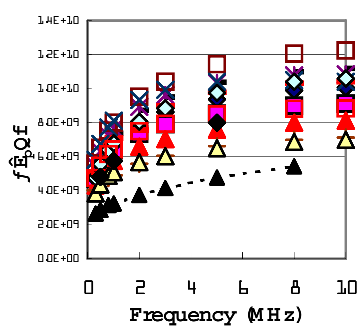

Figure 1: $\overline{\mu}Qf$ values of twelve cores in the required frequency range. The symbol of ▲ show the values of FINEMET FT-3M.

Though there are large differences of ±30% in the measured values of twelve cores, the mean value is still higher than the estimation with the test core. In each core, we must select the gluing side for a cooling plate to keep the core impedance high. To glue the copper cooling plate on the core, we have selected an epoxy resin with a mixture of alumina, which improved the thermal conductivity. In one resonator, three cores were installed. To have similar impedances in each resonator, we selected the cores among them. Though the fabricated twelve cores have large deviations, the mean $\overline{\mu}Qf$ values of each group have small deviations, as in Fig. 2.

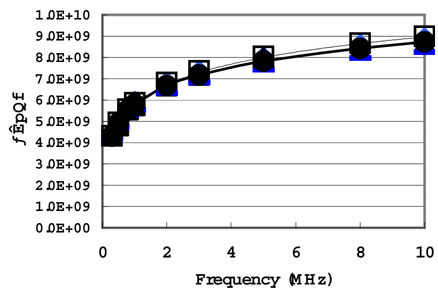

Figure 2: $\overline{\mu}\,Qf$ mean values of cores in each group with three cores.

RF CAVITY

A cavity is composed of two acceleration gaps, and both sides of the gaps consist of quarter-wave resonators. The acceleration gap is made of an alumina ceramic whose length is 60 mm. The outer diameter is 272 mm with 9 mm thick, and the designed capacitance is 29 pF. This small value of capacitance is important to have high impedance at a higher frequency region. The vacuum chamber is made of SUS316L with a conflat frange of ICF253, and the inner diameter is 190 mm φ with a chamber thickness of 4 mm. One resonator has been loaded with three cores. The amorphous tape was wound on a ring of SUS304 with an inner diameter of 280 mmφ. Each core is attached a cooling copper plate directly onto the one side of the core[8], and spacers of GFRP (Glass Fiber Reinforced Polymer) are inserted on the other side. The thickness of the copper and the GFRP are 15.6 mm and 20 mm, respectively. In the one resonator, three stacked cores were also held mechanically.

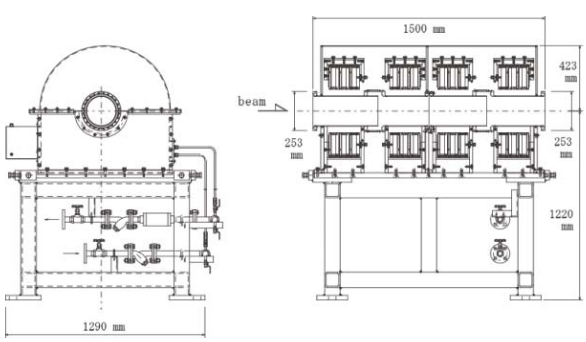

Figure 3: Left figure is cavity view from upstream, and the right figure is the cross-section of the cavity.

The impedances of this stacked core unit were measured to estimate the cavity impedance. The cross-section of the cavity is shown in Fig. 3, and the total cavity length is 1.5 m. To supply rf power from the transistor amplifier with an output impedance of 50 Ω, a transformer of 1:9 is attached to each resonator.

The quarter-wave resonator of the cavity can be considered as a parallel circuit of the capacitor of the half gap and the coaxial transmission line with a shorted end. The resonator impedance (Z) can be written as,

$$Z \quad 1/\left(i\omega C_g + \frac{1}{iZ_0 \tan(\gamma\ell)} \right). \qquad (1)$$

Here, C_g is the capacitance due to an acceleration gap, Z_0 is the characteristic impedance of the transmission line, ℓ is the length of the line, and γ is the phase constant. The calculated impedances are shown in Fig. 4.

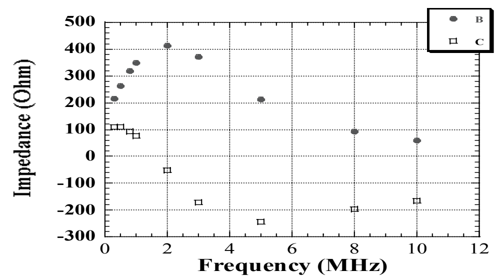

Figure 4: Cavity impedances of the quarter wave resonator as a function of the rf frequency. The real part (●) and the imaginary part (□) of the impedances are shown together.

HIGH-POWER OPERATION

The gap voltage of V can be expressed with the cavity reflection coefficient and the forward travelling wave voltage of V_f, as follows:

$$V = V_f + \Gamma_R V_f = (1+\Gamma_R)V_f. \qquad (2)$$

V_f can be estimated with the forward RF power of the amplifier. As shown in Fig. 5, the measured voltages are well expressed with the calculation, though we have assumed an ideal impedance transformer in Eq. (2). This fact shows that the power loss in the transformer is small.

Under the maximum power operation of 2 kW, the maximum RF field in the core was calculated to be about 24 mT at 1 MHz, and its peak power consumption was 0.13 W/cm^3. This maximum RF field and the power density are below the values with which the core permeability decreases, which is about 50 mT at 1 MHz[6].

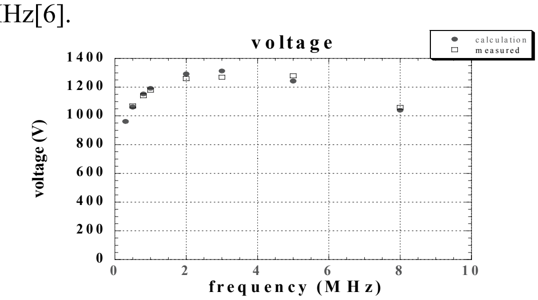

Figure 5: Obtained acceleration voltages (□) with input-power of 2 kW. The calculated values (●) are shown also.

BEAM TEST

To test its performance in beam acceleration, the cavity was installed in a HIMAC synchrotron as shown in Fig. 6. The transistor amplifier was set at the separated room, and the rf power was supplied with 50 Ω coaxial cable that is about 50 m long. The acceleration is from 6 MeV/u to 400 MeV/u, and corresponding acceleration frequencies are from 1.04 MHz to 6.6 MHz. In Fig. 7, accelerated beam intensity is shown, which is DCCT (Direct Current Current Transformer) signal divided with acceleration frequency. The gap rf signal is shown in the middle, and acceleration frequency is in the bottom. As seen in the figure, we could accelerate beam well. In this case, beam was extracted after acceleration as seen in the figure. In the case of no knock-out rf voltage to extract the beam, beam can be decelerated to reduce the radiation level as shown in Fig. 8. This beam deceleration is required in our dedicated synchrotron for cancer therapy.

Figure 6: Acceleration cavity installed in the HIMAC synchrotron.

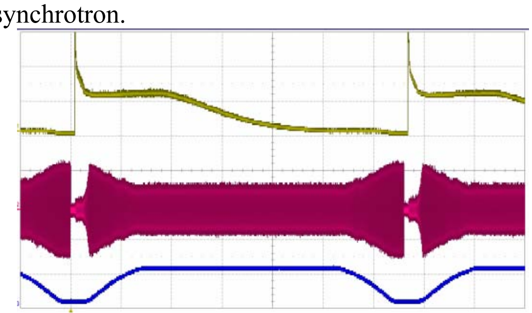

Figure 7: DCCT signal divided with acceleration frequency (upper), gap rf signal (middle), and level signal of acceleration frequency (lower). Horizontal scale is 0.5sec/div.

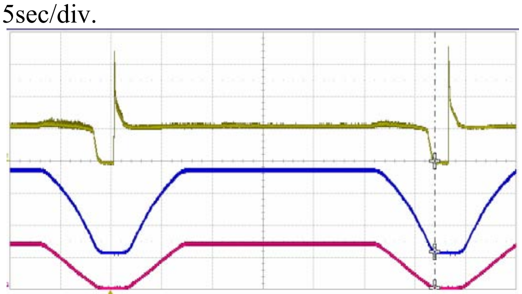

Figure 8: DCCT signal divided with acceleration frequency (upper), level signal of acceleration frequency (lower), and current pattern of dipole magnets. Horizontal scale is 0.5sec/div.

SUMMARY

For a dedicated synchrotron of carbon ion radiotherapy, we have developed a high-power acceleration system. In the developed acceleration cavity, Co-based amorphous cores were used, which have high permeability in the required frequency range. Utilizing this Co core, we could obtain a compact cavity for acceleration with the high shunt impedance of 400 Ω at maximum in one resonator, which is attached with three cores. There are four resonators in the cavity, and each resonator can be excited by a solid-state amplifier with output impedance of 50 Ω through 1:9 impedance transformer. With the maximum output power of 2kW in the continuous mode, an acceleration voltage above 4 kV can be obtained over a wide frequency range from 0.4 to 8 MHz, which is a sufficient voltage for the compact dedicated synchrotron for cancer therapy. The obtained cavity impedance and voltage have good agreement with simplified calculations by use of the measured core permeability's. To confirm the beam acceleration, the constructed new cavity was installed in the HIMAC synchrotron. In the beam test, the new high power system showed good acceleration performances.

ACKNOWLEDGEMENTS

The authors would like to thank engineers of Thamway co., ltd for their skilful fabrication of the RF amplifier, and Yamauchi for his good support in the beam tests. They are also grateful to the Dr. Y.Sato and Dr. Fujisawa for excellent advice and encouraging discussions.

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