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DEVELOPMENT OF CO-BASED AMORPHOUS CORE FOR UNTUNED BROADBAND RF CAVITY

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Abstract

We have developed a cobalt-based amorphous core as a new magnetic-alloy (MA) core for the loaded RF cavity. Because of its permeability found to be approximately twice as high as that of FINEMET, this MA core is an excellent candidate for constructing a compact broadband RF cavity with less power consumption. In this report, we present our recent studies of the Co-based amorphous core's physical properties, performance, and development.

INTRODUCTION

Demand for low-cost compact accelerators is increasing, especially in the field of ion-beam radiotherapy. We have recently carried out various studies on compact carbon-beam machines to be widely used for cancer therapy. In compact accelerator designs[1], as the primary accelerator component the rf accelerating cavity requires high field-gradient and broadband characteristics. Furthermore, the length of drift space for placing rf cavities is limited to 1-2 m per cell. Thus, constructing compact high-field gradient cavities with low rf power consumption is essential.

To achieve compactness and ease of use, a low-Q high-permeability magnetic alloy (MA) core is suitable for constructing a high field-gradient rf cavity, which requires no bias windings and reduces the system complexity. As a good choice of a MA material to be used for the core, FINEMET (manufactured by Hitachi Metal Co.), which possesses excellent soft magnetic properties such as high permeability and low quality factor, has been widely used.

As an excellent alternative to FINEMET, we have recently developed a Cobalt-based amorphous core (manufactured by Toshiba Materials Co.) to further reduce the rf power consumption and increase the shut impedance of the cavity. In this report, we briefly discuss the advantages of MA-loaded cavity and the impedance properties of our new amorphous core.

MA-LOADED RF CAVITY

First, the core material exhibits inductance as well as core loss due to hysteresis and eddy currents. We therefore represent the magnetic permeability of a core in complex form,

$$\mu = \mu' - j\mu'', \tag{1}$$

where the real and imaginary parts of Eq. 1 measure the increase in inductance and core loss, respectively.

The core impedance is therefore expressed as

$$Z = j\omega\mu \ L_0 = \mu''\omega L_0 + j\mu'\omega L_0 \equiv R + j\omega L. \tag{2}$$

Here, L_0 is the inductance of air-core.

When this core inductance is connected across a gap capacitance, a resonant circuit, see Fig.1, is realized as a cavity whose shunt impedance Z_0 is given by

$$Z_0 = \frac{R^2 + (\omega L)^2}{R} = R\left(1 + Q^2\right) = 2\pi L_0\left(\overline{\mu}Qf\right) \tag{3}$$

with quality factor $Q = \mu' \ / \mu'' = \omega L / R$ and $\overline{\mu} \equiv \mu''(1/Q + Q)$. The $\overline{\mu}Qf$ factor in the above equation is often used as a measure of the cavity performance.

Due to low-Q values (less than 1 for both FINEMET and our Co-based amorphous) of a MA core, the MA-loaded cavity shows a broadband feature as shown in Figure 2. This feature removes a complexity of tuning loop and achieves a simple structure of untuned broadband cavity.

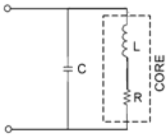

Figure 1. Core-loaded cavity with gap capacitance C as a parallel resonant circuit.

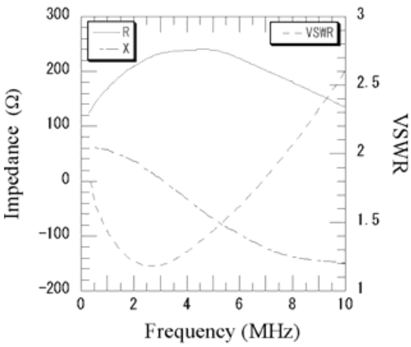

Figure 2. Typical impedance properties ($Z = R + jX$) of a FINEMET-loaded cavity.

PROPERTIES OF HIGH-PERMEABILITY AMORPHOUS CORE

We chose a Cobalt-based amorphous as an effective alternative to FINEMET, since it has been known to possess the high-permeability feature for commercial frequency (less than 100 kHz). Desirable core-loss and permeability characteristics can be developed by further heat treatment in a magnetic field. The heat treatment typically consists of heating the material to a temperature of around 420 °C in an inert atmosphere for certain time interval. The magnetic field is applied during annealing in order to improve its permeability. Optimum annealing conditions may depend on the processing of the material and the size and shape of the core.

At present, the core permeability using a thin amorphous tape of thickness 15 mm is found to be approximately twice as high as that of FINEMET, doubling the $\overline{\mu}Qf$ values, see Figure 3. Here, roughly the half-size test cores (thickness of 25 mm, outer radius of 230 mm and inner radius of 89.1 mm) compared to actual core were used for measurements, see Figure 4. The high values of core permeability guarantee a more compact cavity and reduce rf power consumption.

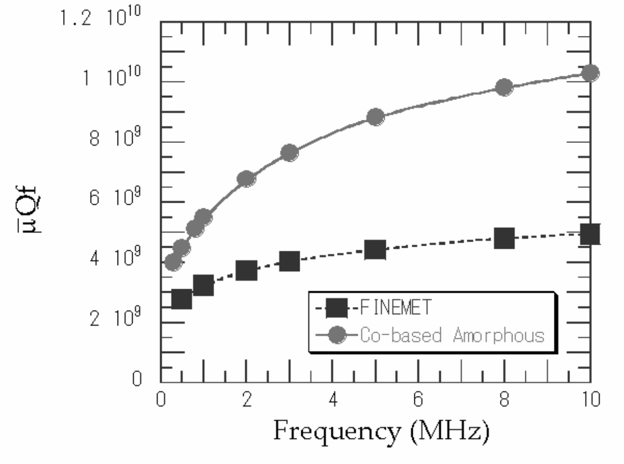

Figure 3. Comparison of $\overline{\mu}Qf$ values between Co-based amorphous core and FINEMET.

As explained earlier, manufacturing procedures of the amorphous core have not yet been established for accelerator application in the frequency of a few MHz region, the core impedance still depends appreciably on core size and annealing/manufacturing parameters. We plan in another study to optimize these parameters for actual large-size cores.

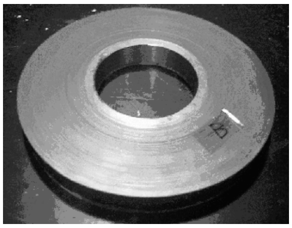

Figure 4. Half-size Co-based amorphous core.

Although a high-permeability feature of the newly-developed Co-based amorphous core is promising, there are many concerns regarding its stability against temperature, rf power, radiation, and so on. In this report, we discuss the results for temperature and rf-power dependences, the influence on core permeability due to metallic cooling plate, and the development status of actual large-size cores.

Temperature Dependence

Since the maximum surface temperature of a core with a metallic cooling plate attached to one side is expected to become as high as 90 °C at actual operation (average rf power density of 0.2 W/cm^3), the core impedance must remain stable below 100 °C. To investigate the stability against temperature we exposed the medium-size core (outer radius 300 mm, inner radius 150 mm, thickness 30 mm) to a constant 100 °C environment for 388 hours and measured its impedance deviation. In Figure 5, constant heating of the core resulted 4 – 6 % decrease in its $\overline{\mu}Qf$ values (depending on frequency). After 388 hours of heating, we cooled down the surrounding environment to room temperature to check whether such heating causes permanent degradation in core permeability. Such permanent degradation was not observed. Considering the moderate impedance reduction during the exposure to high temperature and the recovery of the $\overline{\mu}Qf$ value when the surrounding environment returns to room temperature after 388 hours, the observed deviation in core permeability due to heating has a little effect on beam acceleration and thus considered negligible.

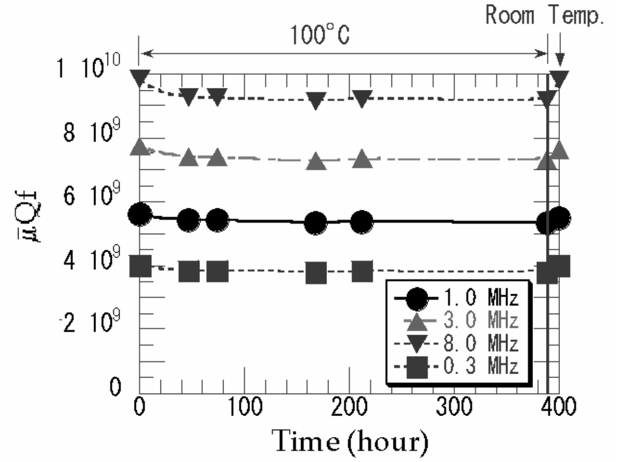

Figure 5. Temperature dependence of $\overline{\mu}Qf$ values for several frequencies. A Co-based amorphous core was placed in a constant 100 °C environment for 388 hours and then cooled down to room temperature.

RF-power Dependence

Based on compact medical accelerator designs, the average rf power density inside a core becomes approximately 0.2 W/cm^3. The stability of core permeability against rf power must be verified. In order to measure the rf power dependence of the $\overline{\mu}Qf$ factor, we supplied a maximum power density of 10.0 W/ cm^3 to the small-size core, which is roughly 1/10 in size (thickness of 25 mm, outer radius of 50 mm and inner radius of 30 mm) compared to actual size. As shown in Figure 6, the $\overline{\mu}Qf$ values are considerably stable against the change in rf power density below the actual operational density of 0.2 W/cm^3, while they tend to decline above a few W/cm^3. In Figure 7, the variation in the $\overline{\mu}Qf$ value is also plotted as a function of average rf filed, B_{rf}. The $\overline{\mu}Qf$ value at 1 MHz is found to decrease slowly for higher values of B_{rf} , noting that the saturation magnetic flux density of Co-based amorphous core is approximately 0.5 T.

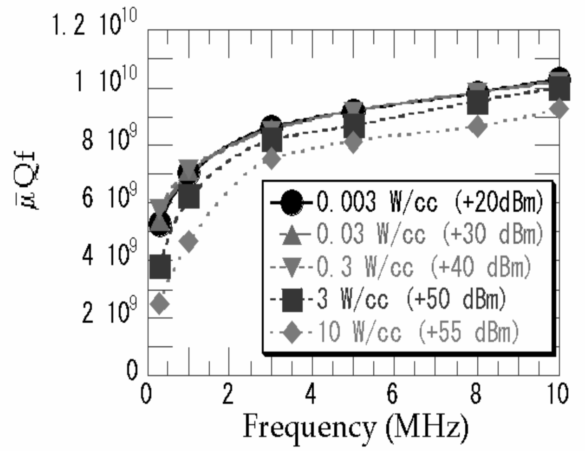

Figure 6. $\bar{\mu}Qf$ values for a small-size core as a function of rf power density. For an actual operation of 0.2 W/ cm^3, the core permeability is stable.

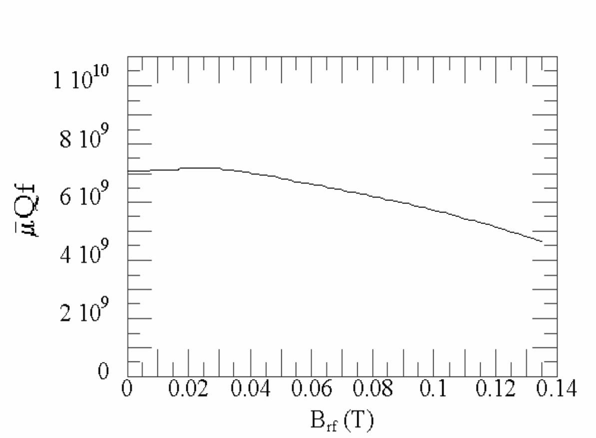

Figure 7. Variation in $\bar{\mu}Qf$ value at 1 MHz for a small-size core as a function of average rf field.

Impedance Reduction due to the Presence of Metallic Cooling Plates

For the present discussion of cavities operating at relatively high power dissipation of 0.2 W/cm^3, cooling by water is a suitable choice. In a water-cooling scheme, one efficient way to cool MA core is to dip it into a water tank. However, such direct water cooling method causes the core to oxidize and reduces cavity impedance due to the large dielectric constant of water[2].

An alternative way is to cool the core with metallic cooling plates. As we have previously reported[3], our impedance measurements using FINEMET cores revealed that the impedance reduction is severe for the case of a core sandwiched with metallic cooling plates. In order to suppress such reduction, we introduced the indirect "one-side" cooling method in which a metallic cooling plate is attached to only one side of the core.

According to the "one-side" cooling scheme, we carried out the impedance measurements of a medium-size amorphous core attached to metallic plate. While the change in the $\bar{\mu}Qf$ value by attaching a metallic plate for the case of FINEMET is within a few percent, the reduction of the $\bar{\mu}Qf$ value becomes approximately 13 % at 10 MHz for the case of the amorphous core. The cause of this reduction is not exactly determined, but we expect that the insulation material coated on coiled thin amorphous ribbon may be coarse so to induce electrically shorten circuits around oscillating magnetic field.

Development Status of Actual Large-size Cores

So far, our discussion has been limited to the impedance properties of rather smaller size cores. For actual accelerator use, larger size cores are needed. Thus, we prepared 12 actual large-size amorphous cores (outer radius 555 mm, inner radius 310 mm, thickness 30 mm) and measured their $\bar{\mu}Qf$ values. We found large variations of roughly +/- 27 % in $\bar{\mu}Qf$ values, indicating that the annealing/manufacturing procedures for large-size cores may not be well controlled. We are currently investigating the cause of this inconsistency in quality. However, even among all 12 cores, the core with the lowest $\bar{\mu}Qf$ values still exceeds the typical $\bar{\mu}Qf$ values of FINEMET.

SUMMARY

We developed a high-permeability MA core using Co-based amorphous tape as an effective alternative to FINEMET for a compact rf cavity design. The $\bar{\mu}Qf$ values of our newly-developed MA core are found to be twice as high as that of FINEMET. We are currently investigating the optimal annealing/manufacturing parameters to further improve the core properties.

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