Indirect “one-side” cooling method of a magnetic-alloy–loaded rf cavity

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For magnetic alloy (MA) loaded rf accelerating cavity, we have developed an indirect cooling system, which is effective for retaining its shunt impedance by cooling only one side of the MA cores. Because of its low- Q high-permeability property, MA cores are suitable for constructing untuned broadband accelerating systems. Since these same cores are made of wound thin tape, the key to establishing an untuned broadband cavity with effective indirect cooling method is to suppress the reduction of core impedance when attaching metallic cooling plates to the core and keeping a good thermal contact between them. We have employed indium bonding to thermally connect both cores and cooling plates. Both cooling and endurance tests have demonstrated its successful results.

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I. INTRODUCTION

Particle accelerators are becoming powerful tools for curing localized cancer because they can accurately deliver the appropriate doses of ion beam to the cancer cells and eradicate them with little damage to adjacent normal cells. The Heavy Ion Medical Accelerator in Chiba (HIMAC) has been one of the world’s leading facilities in demonstrating the effectiveness of carbon-beam radiotherapy, especially for treating critically localized tumors near vital organs such as the brain or spinal cord [1]. In order to promote the widespread adoption of heavy-ion radiotherapy, these medical accelerators must be designed and developed with essential features such as compactness, low cost, ease of use, and low maintenance.

According to the recent design studies [2] of compact medical accelerators undertaken at our institute, the size of medical carbon-beam accelerators can be as small as one-half the size of the HIMAC synchrotron. With such compact designs, the length of drift space for placing rf cavities and injection/extraction elements is limited to approximately 1 m per cell. Therefore, the demand for compact rf accelerating cavities is increasing.

To achieve compactness and ease of use, magnetic alloy (MA), which is a soft magnetic material composed of nanoscale crystalline, is considered for the untuned broadband rf cavity. As a good choice of a MA material to be used for the core, FINEMET (Hitachi Metal Co.) possess a high saturation magnetic flux density and excellent soft magnetic properties such as high permeability and low quality factor. Recently, rf accelerating cavities loaded with MA cores have been fabricated at a number of research facilities and demonstrated their wideband and high-field gradient features. However, the cooling methods for MA-loaded cavities operating at intense power dissipation are not yet established.

If the power consumption of a rf cavity is low, cooling by air can be considered without imposing a burden on the air conditioning apparatus. For the present discussion of cav-

ities operating at intense power dissipation, cooling by water is a more suitable choice.

In a water-cooling scheme, the efficient way to cool the MA core is to dip it into a water tank. However, this direct water-cooling method causes the core to oxidize and reduces cavity impedance due to the large dielectric constant of water [3].

An alternative way is to cool the core with metallic cooling plates. Since the MA core is made of coiled thin tape (thickness of $18\ \mu\text{m}$ for FINEMET) coated with insulation material (thickness of $2\ \mu\text{m}$ for FINEMET), one needs to consider retaining the insulation in the case of using the indirect cooling method. For this reason (a detailed explanation is given in Sec. III), the previously reported examples [4] of indirectly cooled rf cavity position the thick insulation material between the MA core and the metallic cooling plates in order to reduce the capacitance effect. Another consideration for using an indirect cooling method is achieving a good thermal contact between the core and the cooling plate because of the uneven surface of the core.

In this paper we report an efficient indirect cooling method that achieves a good thermal contact between the core and the cooling plate without the use of thick insulation material, while maintaining a high shunt impedance of the cavity by lowering the capacitance effect.

II. 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,

$$\mu = \mu' - j\mu'', \quad (1)$$

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

FIG. 1. A circuit diagram of a resonant cavity. A MA core is represented by R and L . The gap capacitance C is connected across the core.

The core impedance is therefore expressed as

$$Z = j\omega\mu L_0 = \mu''\omega L_0 + j\mu'\omega L_0 \equiv R + jX. \quad (2)$$

Here, L_0 is the inductance of air core.

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

$$\begin{aligned} Z_0 &= \frac{R^2 + X^2}{R} = R(1 + Q^2) = 2\pi f\mu''L_0(1 + Q^2) \\ &\equiv 2\pi L_0(\bar{\mu}Qf), \end{aligned} \quad (3)$$

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

FIG. 2. An example of the cavity impedance loaded with the MA cores. Eight or four FINEMET cores (inner diameter, 290 mm; outer diameter, 650 mm; thickness, 25 mm) are loaded in a cavity with a gap capacitance assumed to be 30 pF. Solid and open marks correspond to real and imaginary parts of the cavity impedance, respectively.

Because of low- Q values (less than 1 for FINEMET) of a MA core, the MA-loaded cavity shows a broadband feature as shown in Fig. 2, for example, and this feature removes a complexity of tuning loop and achieves a simple structure of untuned broadband cavity.

For a given accelerating voltage, the power density dissipated in a core can be determined. For example, the average power density based on the design study [2] of the medical fixed-field alternating-gradient (FFAG) accelerator is estimated as 0.1 W/cm³, while that of the 50 GeV proton synchrotron for the JAERI-KEK joint project is about 0.8 W/cm³ [4].

Since a compact design of rf cavity often leads to a high-field gradient with intense power density, one needs to establish the efficient cooling techniques.

III. IMPEDANCE MEASUREMENT OF MA CORES WITH COOLING PLATES ATTACHED

The direct contact of metallic cooling plates to the MA core from both sides of the core leads to null shunt impedance, as shown in Fig. 3. The cause of this null shunt impedance can be understood as due to the presence of electrically shorted circuits around the input oscillating magnetic field; see Fig. 4. To avoid the reduction of shunt impedance, one may install insulation material between the cores and the cooling plates. In Fig. 5, the core impedances for the case of installing polypropylene sheets of 0.5, 1, and 2 mm thickness are shown. Here, polypropylene sheets

FIG. 3. Impedance property of a MA core attached with metallic cooling plates. Real and imaginary parts of the core impedance are indicated in solid and open marks, respectively. Attachment of metallic plates to the core from both sides leads to the null impedance (triangles). If one metallic plate is removed, such reduction can be avoided (rectangles).

FIG. 4. Schematic description of the impedance reduction. Cross sectional views of (a) a FINEMET core in which every FINEMET ribbon is electrically insulated and (b) a core attached to two metallic plates inducing electrically shorted circuits are shown.

were attached to both sides of the core and then they were sandwiched with metallic plates. Such installation can recover the core impedance, but its reactance becomes capacitive above a few MHz (5 MHz for the case of a 2 mm thick polypropylene sheet). This indicates that thick insulation material is required to keep a core reactance inductive when cooling a core from both sides. To improve further, we attach a metallic cooling plate to only one side of the core (“one-side” cooling method), instead of sandwiching it with two plates. In this case, no insulation material is required to retain its impedance, as shown in Fig. 3, and thus conducting materials of high thermal conductivity can be used to thermally connect both cores and cooling plates.

IV. INDIRECT ONE-SIDE COOLING METHOD

The results shown in Fig. 3 indicate that no insulation material is required to retain the cavity impedance, and conducting materials of high thermal conductivity can be used to thermally connect both cores and cooling plates, when applying the one-side cooling method as mentioned earlier.

Several nonconducting and conducting filler materials have been considered, namely, (i) silicon rubber sheet, (ii) polyimide resin, (iii) silicon grease, and (iv) solder joint.

When the core becomes large in diameter, one would expect it to warp with an uneven surface, and thus the filler material must fill this irregularly spaced volume between the core and the cooling plate. Most of the soft silicon rubber sheets can only be compressed by about 30% of their thickness at most, implying that thick silicon rubber sheets are needed for large-size cores. Since the thermal conductivities of insulation materials are low (a few W/mK at most), it is desirable to keep the insulation material thickness thinner. Therefore, silicon rubber sheets cannot be considered for practical use because of their large thickness.

Another material, an organic matter of polyimide resin, was tested as a filler material. Although polyimide resin itself has low thermal conductivity of 0.34 W/mK, it is considered a radiation-proof material and can increase its thermal conductivity by being mixed with aluminum nitride (AlN) powder. In this paper the cooling experiment was done with raw polyimide resin of low thermal conductivity instead.

As one of the silicon greases, we have also considered a thermally conductive silicone room temperature vulcanizing (RTV) rubber as a good thermal conducting material

FIG. 5. Core impedances for the case after installing polypropylene sheets of 0.5 mm (triangles), 1 mm (squares), and 2 mm (diamonds) thickness. Polypropylene sheets were attached to both sides of the core and then sandwiched with metallic plates. Core impedances without metallic cooling plates are indicated by a circle.

FIG. 6. Shunt impedance of the core before (solid circles) and after (open circles) indium bonding.

(0.95 W/mK). Although the advantage of silicone RTV rubber is that it is cheap and easy to apply, its long-term degradation is yet unknown.

Since conducting materials can be used as filler material, we also prepared a metal-bonded core; one side of a FINEMET core was ion plated with copper of 10 μm thickness, and then a cooling plate and the Cu plated

core were bonded together by indium metal of about 0.5 mm thickness. Regarding this solder joint, the insulation role of SiO_2 may have been partially destroyed during the bonding process. Therefore, we measured the impedance property of the indium-bonded piece. The shunt impedance of Eq. (3) obtained from measurements is shown in Fig. 6, and the shunt impedance is successfully retained within 3.5% deviation after the bonding process.

V. COOLING EXPERIMENTS

With the above filler materials, we carried out the cooling experiments to check their thermal contacts and cooling efficiencies; see the experimental setup in Fig. 7. In Fig. 8 the results of cooling experiments are shown for the case of polyimide resin as an example at the feeding power density of 0.2 W/cm³.

Since magnetic flux density B at radius r is given by

$$B = \frac{d\Phi}{dS} = \frac{\mu N^2 I}{2\pi r}, \quad (4)$$

its magnetic energy U_m per volume V can be determined as

$$\frac{dU_m}{dV} = \frac{B^2}{2\mu} \propto \frac{1}{r^2}. \quad (5)$$

This implies that the magnetic power density dU_m/dV at radius r is inversely proportional to r^2 . Indeed, after 15 min of power feed, the cooling-free side of the MA core shows radial distribution of temperature increase due to dense

FIG. 7. Cooling experiment setup.

FIG. 8. (Color) The surface temperature distribution for the polyimide-resin-adhered core as an example at the feeding power density of 0.2 W/cm^3 . (a) Irregularly distributed hot spots were observed at first, indicating a loose adhering process. (b) A nice radial temperature distribution is seen after improving the adhering process. Top and bottom figures correspond to the temperature distributions after 15 min of power feed and 2 min of power cut, respectively. Disk-shaped area corresponds to the surface of FINEMET core. Three strip shape objects of (a) and a thick square object seen at the right side of the figures are the support materials and a power feeding loop, respectively.

magnetic flux density near the central region, as displayed in Fig. 8(b).

If the thermal contacts are partially broken, the surface temperature will show some irregular hot spots. In fact, there appeared some hot spots for the case of polyimide resin at first, and they remained in existence even after 2 min of power cut, see Fig. 8(a), indicating the poor thermal contacts. The adherence procedure of applying equally thin viscous material of polyimide resin onto the surface of the core was assumed to be the cause of these poor contacts. After reassembling the polyimide resin attachment by applying larger amount of polyimide resin near the inner surface region of the core, this problem was solved. Nice radial temperature distributions were observed for the rest of two cases.

The time dependence of maximum and average surface temperatures of the core and the average temperature of the cooling plate for the case of indium-bonded, RTV-rubber-adhered, and polyimide-resin-adhered cores were measured and are demonstrated in Fig. 9. Here, the power consumption of cores is 0.4 W/cm^3 . The “relative temperature,” which correspond to the average temperature differences between the cooling-free side of the core and the cooling plate, is roughly 10° for indium-bonded, 16° for RTV-rubber-adhered, and 24° for polyimide-resin-adhered cores. Because of the very large thermal conductivity of indium, the temperature difference within indium

is negligible. Since the power consumptions are the same for all three cases, the temperature differences within RTV rubber and polyimide resin can be estimated to be approximately 6° and 14° , respectively.

According to Fourier’s law of heat conduction, i.e., $P/A = k(\Delta T/\Delta x)$, the temperature difference ΔT can be roughly estimated, if the values for thermal conductivity k , thickness Δx of filler material, power consumption P of the core, and heat flow area A are given. In our experiments, the power dissipation of 400 W, the heat flow area of 0.036 m^2 , and thickness of filler materials of about 0.5 mm lead to the rough estimates of temperature differences within RTV rubber and polyimide resin as 5.9° and 16.3° , respectively. Considering the uncertainty in material thickness and the assumption of no heat transfer out to the surrounding air, these simple estimates are roughly consistent with our measured values. As expected, the indium-bonded core clearly depicts the most efficient cooling characteristics.

Although the above cooling experiments illustrate the successful bonding results for efficiently removing the power consumption of the core by water, there still remains a technical concern whether or not the cooling-plate-attached cores can maintain their good thermal contacts for a long period of time, considering the fact that their thermal conductivities and adhesion powers differ. Therefore, we have further carried out the endurance tests

FIG. 9. Time dependence of the maximum (square) and the average (circle) surface temperatures of the core and the average temperature (triangle) of the cooling plate for the case of (a) indium-bonded, (b) RTV-rubber-adhered, and (c) polyimide-resin-adhered cores. Cross marks correspond to the relative temperature explained in this study.

FIG. 10. Cyclic pattern of endurance test: 10 min of power on and 10 min of power off were repeated for 200 times. Only the first few cycles of endurance test for the case of a polyimide-resin-adhered core are shown.

for all three bonding types by repeating 10 min of power on and 10 min of power off in cycle for 200 times; see Fig. 10.

Figure 11 shows the comparison of the surface temperature distributions before and after the endurance tests. Both indium-bonded and polyimide-resin-adhered cores show no clear influence of heat cycle tests, while locally heated areas were observed for the RTV-rubber-adhered one, indicating the loose thermal contact.

VI. SUMMARY

Efficient methods to cool MA cores in untuned broadband cavity operated at intense power dissipation were studied. Considering the capacitance effect expected for direct cooling method, the present work was limited to the discussion of the indirect cooling method.

FIG. 11. (Color) Surface temperature distributions before (top) and after (bottom) the endurance tests for (a) indium-bonded, (b) - polyimide-resin-adhered, and (c) RTV-rubber-adhered cores. A RTV-rubber-adhered core shows two localized hot spots as indicated by dashed circles.

Our impedance measurements revealed that the impedance reduction is severe for the case of a core sandwiched with metallic cooling plates, and this reduction can be suppressed by employing the indirect one-side cooling method.

According to the one-side cooling scheme, we carried out the cooling experiments of three types of cores. They were bonded with metallic cooling plates by the filler materials, namely, solder joint, polyimide resin, and silicon grease. As expected, the indium-bonding scheme showed its effectiveness by demonstrating the lowest surface temperature. On the other hand, a polyimide-resin-adhered core has shown the highest surface temperature due to its low thermal conductivity of 0.34 W/mK. So, increasing its thermal conductivity is highly desired and can be achieved by mixing with AlN powder. For instance, 65% mixing of AlN powder can improve the thermal conductivity up to about 1 W/mK. However, its viscosity becomes too low to apply it to the surface of the core. By replacing silica (one of the composing elements of polyimide resin) with AlN instead of mixing them, we were recently able to improve its thermal conductivity to 1.6 W/mK.

Although the cooling tests with all three types of filler material have shown their effectiveness in achieving good thermal contacts, the endurance tests indicated that a long-term degradation cannot be neglected for the case of the self-supported RTV-rubber-adhered piece. We therefore conclude that the indirect one-side cooling method is ef-

fective and practical to be employed for MA-loaded cavities operated at intense power dissipation, and indium bonding is proven to be one of the most efficient and reliable bonding techniques.

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- [1] S. Yamada, in *Proceedings of the 2nd Asian Particle Accelerator Conference, Beijing, 2001*, edited by W. B. Liu *et al.* (Institute of High Energy Physics Chinese Academy of Sciences, Beijing, 2001), p. 829.
 - [2] T. Misu *et al.*, in *Proceedings of the 8th European Particle Accelerator Conference, Paris, 2002*, edited by T. Garvey *et al.* (EPS-IGA and CERN, Geneva, 2002), p. 599.
 - [3] C. Ohmori *et al.*, in *Proceedings of the Particle Accelerator Conference, Chicago, 2001*, edited by P. Lucas and S. Webber (IEEE, Piscataway, NJ, 2001), p. 888.
 - [4] C. Ohmori *et al.*, in *Proceedings of the 8th European Particle Accelerator Conference, Paris, France, 2002* (Ref. [2]), p. 257.