DEVELOPMENT OF A NEW RF ACCELERATING CAVITY FOR J-PARC RING ACCELERATOR*

Y. Morita†, T. Kageyama, KEK, Ibaraki, Japan
J. Kameda, ICRR, University of Tokyo, Chiba, Japan
S. Yamashita, ICEPP, University of Tokyo, Tokyo, Japan

Abstract

We have proposed a multi-ring core structure suitable for magnetic-alloy-ribbon-wound cores operated at high power loss densities, especially applied to high gradient RF accelerating cavities for proton or ion beams. Our multi-ring core structure consists of three toroidal ring cores of different radial sizes concentrically arranged to form "a core module," which corresponds to a conventional disk-shaped toroidal core. We have developed a prototype RF cavity loaded with a single core module cooled by a low viscous, chemically inert and electrically insulating liquid. The prototype RF cavity has been successfully tested up to a power loss of 10 kW per core module.

INTRODUCTION

FINEMET is a Fe-based soft magnetic alloy (MA) with a nanocrystalline structure, developed by Hitachi Metals, Ltd.. FINEMET has characteristics of high complex permeability of $(\mu_r', \mu_r'') = (2.6\times10^3, 3.2\times10^3)$ around 1 MHz, high saturation flux density of 1.2 T, and high Curie temperature of 570 °C. These excellent magnetic properties have boosted the development of tuning-free, compact and high gradient accelerating structures for proton and ion synchrotrons. For example, a compact synchrotron with an RF accelerating cavity loaded with air-cooled FINEMET MA cores was first developed for medical use [1]. As another example, FINEMET MA cores have enabled tuning-free high gradient accelerating cavities [2] indispensable for the 3-GeV Rapid-Cycling Synchrotron (RCS) and the 30-GeV Main Ring of J-PARC.

However, it was reported that some MA cores being used in RCS suffered thermal stress damage [3]. The structure of the RCS core is a conventional disk-shaped toroid whose inner/outer diameter and thickness are 375 mm/850 mm and 35 mm, respectively. The core is first made by winding MA ribbon, and then impregnated with low-viscous epoxy resin. Moreover, the core surfaces are coated with glass cloths and epoxy resin for corrosion protection since the cores are operated at an average power loss of 6 kW per core in RCS and need to be directly cooled by water.

A series of thermal structural simulations and compressive strength tests showed that the thermal stress damage should be attributed to the low-viscous epoxy resin impregnation making an originally flexible MA-ribbon-wound core stiff [5]. From the view point of long-term operation, corrosive damage to the water-cooled Fe-based MA cores is our next concern since the durability of the waterproof coating is unknown.

In order to solve these problems, we have proposed a multi-ring MA core structure. The structure consists of three toroidal ring cores of different radial sizes concentrically arranged. Each ring core is directly cooled by a low viscous, chemically inert, electrically insulating liquid. Therefore, the ring cores are neither impregnated with epoxy resin nor waterproof coated, so that the core structure remains flexible and can survive the thermal stress expected in RCS.

MULTI-RING CORE STRUCTURE

Structure

- The core module (Fig. 1) consists of three ring FINEMET MA cores concentrically arranged and sandwiched between two glass epoxy plates with flow channel grooved.
- Each ring core is made by winding MA ribbon (35 mm in width), but the winding thickness is kept at 81 mm, which is about one third compared to the winding thickness 238 mm of the RCS core, Therefore, the tension control when winding MA ribbon can be more accurately controlled so that the magnetic properties are expected to be improved.
- Use properly structural and functional materials to keep every ring core stress-free. For example, the stainless-steel collars and glass-epoxy plates are structural materials, but FINEMET is a functional material.

No Impregnation

- MA-ribbon wound cores are flexible. Epoxy resin impregnation makes MA cores stiff, so that the thermal stress increases by two orders of magnitude compared with non-impregnated flexible MA cores [5].
- The operating temperature of the cores is not limited by the glass-transition temperature (around 100 °C) of the epoxy resin, which is much lower than Curie temperature (570 °C) of FINEMET.

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† yuichi.morita@kek.jp

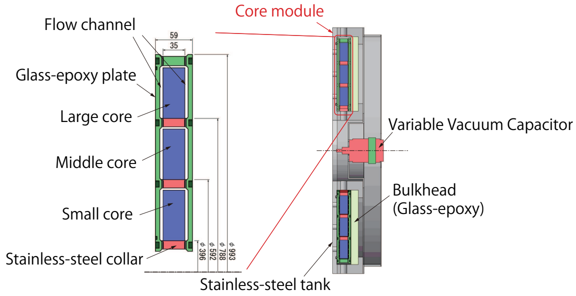

Figure 1: Cross-sections of the core module and the prototype cavity.

Fluorinert as a Cooling Liquid

A low viscous, chemically inert and electrically insulating liquid (Fluorinert FC-3283 supplied by Sumitomo 3M, Inc.) was chosen as a coolant to avoid corrosion of the cores. Properties of Fluorinert are shown in Table 1, together with those of water. Using Fluorinert as a coolant costs too much but would be reasonable when considering the price of the MA core.

Table 1: Properties of Fluorinert [4] and Water

Property	FC-3283	Water
Chemical formula	$(C_3F_7)N_3$	H_2O
Boiling point [°C]	128	100
*Density [kg/m^3]	1780	992.22
*Dynamic viscosity [10^{-6}m^2/s]	0.59	0.6532
*Specific heat [J/kg/K]	1076	4178.5
*Thermal conductivity [W/m/K]	0.0624	0.6305
Breakdown voltage [kV/2.54 mm gap](25°C)	43	-
**Relative permittivity	1.91	78.36
**Electric loss tangent	$<4\times10^{-4}$	$<1\times10^{-2}$
Price [JPY/Liter]	$\sim$ 19000	-

* at 40°C. ** at 25°C, 1 kHz.

The flow channels (81 mm width × 3 mm height) formed between the core and glass-epoxy plate surfaces (Fig. 1) are designed to enable turbulent flow of Fluorinert, so that the heat transfer coefficient can be increased to 750 W/m^2/K. As shown in Fig. 2, a number of sub-slots and small rudders are arranged to allow the smooth flow without stagnation.

PROTOTYPE CAVITY

Prototype Cavity

A cross-section of the prototype cavity is shown in Fig. 1. It is a half cell structure loaded with a single core module. A variable vacuum capacitor is used instead of an accelerating gap. The resonance frequency was tuned to 1.7 MHz.

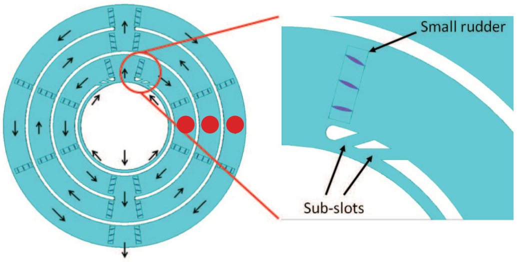

Figure 2: Flow control with sub-slots and small rudders arranged in the flow channels. Red closed circles represent spots where TSP was painted.

High Power Testing

RF Source A solid state broadband amplifier was used. The output power (CW), frequency, and impedance are 0 - 10 kW, 0.8 - 3 MHz, and 50 Ω, respectively. A matching box consisting of a capacitor and a inductor was placed between the RF source and the cavity whose input impedance is ∼140 Ω on resonance.

Cooing System The cooling system with Fluorinert consists of a magnetic pump (max 150 L/min), a heat exchanger with a capacity of 100 kW to transfer the heat from Fluorinert to the secondary cooling water, and a reservoir tank being always purged with nitrogen gas in order to avoid dew condensation. Additionally, the cooling system will be equipped with a circulating system with filters to remove water, organic substances, and hydrofluoric acid coming from disintegration of Fluorinert by radiation.

Measurement of Shunt Impedance

The shunt impedance of the prototype cavity was obtained by directly measuring the voltage across the capacitor (accelerating gap) and the power loss in the core module. The shunt impedance was 140 Ω within an error of 10 % and no deterioration was observed up to 10 kW per core module. According to the result, there seemed to be no unusual heating or discharge inside the cores. The power loss of 10 kW per core module is 1.7 times higher than that of the present RCS cavity.

Measurement of Temperatures on the Core Surfaces

Temperatures on the core surfaces were measured with a temperature-sensitive paint (TSP). We painted TSP at some spots (shown as red circles in Fig. 2) on the core surfaces. Only the color of the spot on the small core changed since its heat load is the highest among the three ring cores. The measurement results for the small core is shown in Fig. 3.

According to our calibration in advance, the color change of TSP started at the lower line of the green area and stopped at the upper line. Actually, the color began to change at 4 kW, and stopped at 7 kW. These values are

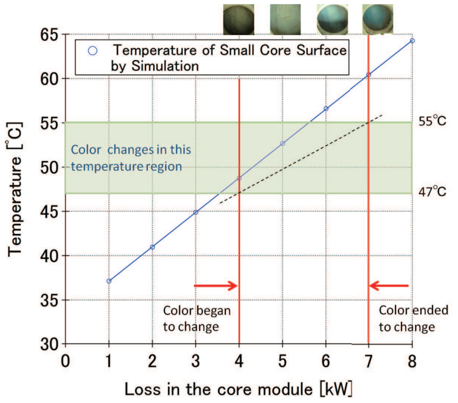

Figure 3: Graphical representation which relates the surface temperature measurement with the simulation result.

shown as red lines. The blue line represents the temperature at the spot on the small core, which was obtained by ANSYS CFX. The blue line is expected to diagonally cross the rectangular formed with the green area and the two red lines, as shown by the broken line in Fig. 3, if the measurement and the simulation are consistent with each other. The error of temperature measurement with TSP is approximately $\pm 10\,^\circ$C, so that we can conclude that the experimental result is consistent with the simulation.

Heat Transfer Coefficient

The effective heat transfer coefficient from the core volume to the Florinert coolant was estimated by measuring the time constant of the exponential decay of the coolant temperature after switching off the RF power. The effective heat transfer coefficient is expressed by

$$\frac{1}{h_{eff}} = \frac{1}{h_C} + \frac{1}{h} \tag{1}$$

where h_C is the heat transfer coefficient inside the core volume and h is the heat transfer coefficient from the core surface to the coolant. The time constant τ related to the effective heat transfer coefficient by

$$h_{eff} = \frac{\rho V C}{A\tau} \tag{2}$$

where ρ, V, and A are the density, volume, and surface ares of the core module, respectively. Figure 4 shows an agreement within the maximum error of 20 % between the measurement and simulation results (by means of ANSYS CFX), where the effective heat transfer coefficient is plotted as a function of the coolant flow rate.

The heat transfer coefficient h from the core surface to the coolant was also calculated with the simulation whose reliability was confirmed by the above experiment. The simulation shows that the heat transfer coefficient at the spot on the small core surface where TSP was painted is 750 W/m^2/K when the coolant flow rate per core module is 83 L/min, where the flow velocity and Reynolds number are 1.4 m/s and 1.4×10^4, respectively. The heat transfer coefficient of 750 W/m^2/s is about 1.5 times higher than that for the RCS core cooled by laminar flow of water.

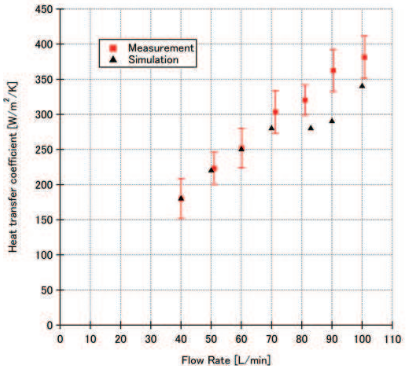

Figure 4: The effective heat transfer coefficient data obtained from the experiment and simulation are plotted as a function of the coolant flow rate.

Heat Load Test

The prototype cavity was also tested at 10 kW for 8 hours without interruption. The core module was disassembled after the high power test and no damage was observed anywhere on the core surface or on the glass-epoxy plate. The fluorinert coolant used for this test was also checked as for the dielectric strength, the concentration of fluorine ion, and the amount of water dissolution, and neither degradation nor contamination was detected.

CONCLUSIONS

We have proposed a multi-ring core structure suitable for MA-ribbon-wound cores. A prototype cavity loaded with a single core module cooled by Fluorinert was constructed and tested. The high power test has demonstrated good performance of the multi-ring core at power loss densities up to 10 kW per core module. As for the core cooling by turbulent flow of Fluorinert, the heat transfer coefficient of 750 W/m^2/K from the core surface to the coolant was achieved. The next prototype cavity with a single gap, loaded with six core modules, is being under design.

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