ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB051

MA RF CAVITY DESIGN AND SIMULATION FOR CSNS/RCS UPGRADE PROJECT*

Bin.Wu†, X. Li[1], H. Sun[1]
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[1] also at Dongguan Neutron Source Center, Dongguan, China

Abstract

The dual harmonic RF system will be adapted for China Spallation Neutron Source (CSNS) upgrade project. Limited locations in CSNS/RCS are reserved to install additional three 2nd harmonic cavities. The cavity loaded by magnetic alloy (MA) material would be used. Because of the low Q factor of the MA core, the cavity cooling becomes a very important issue in cavity design. Air-forced, indirect and direct cooling scheme were studied. The fluid thermodynamic of different cooling structure were simulated by ANSYS CFX which considered the anisotropy of thermal conductivity of MA core. The limitation of these cooling schemes were discussed in detail based on the simulation results. Indirect cooling experiment was done to assess the cooling efficiency and verify the simulation result. A high power test cavity cooled by water has been designed to estimate the property of the MA core and cooling effectiveness for CSNS/RCS.

INTRUCTION

RF cavity loaded by nanocrystalline soft magnetic alloy (MA) material has the advantages of high accelerating gradient and wide bandwidth which will bring great benefits in the length of cavity and avoiding complex tuning system [1]. It is best adapted for high power proton synchrotron accelerator. CSNS/RCS would adapt the MA cavity as the second harmonic cavity due to the finite space of CSNS/RCS tunnel. Together with the ferrite cavity already running in CSNS/RCS, the dual harmonic RF system will be formed to increase the bunch factor to promote the beam power up to 500kW. Due to the low Q factor of the MA core, the cavity cooling becomes a very important issue in cavity design. During the preliminary research stage of CSNS/RCS upgrade project, MA cavity with different cooling structure were studied with detail here.

Fluid Thermodynamic Simulation of MA Cavity

The MA toroid is fabricated by winding the nanocrystalline soft magnetic alloy ribbon (≈18um). SiO2 (≈2um) insulator layer need to be attached on the side of ribbon to reduce the ebby current loss of MA core in the high frequency. This kind of metal laminate structure contributes to the anisotropy of thermal conductivity in cylindrical coordinate system. The thermal conductivity along the radius of MA is smaller than the direction of the width of ribbon and the circumference. The main parameters are listed in Table 1. What's more, the heat loss in MA core is proportional to $1/r^2$, because the average power density distribution P_density (r) and the average power loss P_ave is defined by Eq. (1), Eq. (2).

$$P_{density}(r) = \left(\frac{V_{rf}}{2\pi f r_1 \ln(\frac{r_2}{r_1})\cdot len}\cdot\frac{1}{r}\right)^2\cdot\frac{2\pi f}{2\mu_0\mu' Q} \tag{1}$$

$$P_{ave} = \int_{r_1}^{r_2} P_{density}(r)\cdot 2\pi\cdot len\cdot r dr/V_{core} \tag{2}$$

Where V_{rf} is the voltage of the single MA core. Q and f is the Q value and resonator frequency of cavity. r_1, r_2 is the outer and inner radius of MA core. len and μ' is the length and relative permeability of MA core. V_{core} is the volume of a MA core. Figure 1 shows the average power density distribution when the average power loss is 0.03W/cc, 0.1W/cc and 0.3W/cc, the radius of MA core with the inner/outer diameter is 300/500mm and 25mm thick. It is noted that the high power loss focus on the area of the inner radius of MA core. This is the main consideration when it comes to the cooling structure design of MA cavity.

Table 1: The Thermal Conductivity of MA Core

Orthotropic Cylindrical Components [2]	
Axial Component	7.1 [W m^{-1} K^{-1}]
Theta Component	7.1 [W m^{-1} K^{-1}]
R Component	0.6 [W m^{-1} K^{-1}]

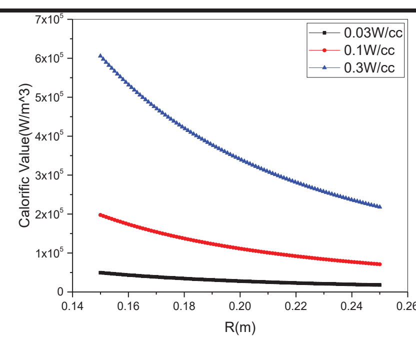

Figure 1: Power density distribution along the radius in MA core.

CFX is a module of ANSYS for fluid thermodynamic simulation. It has the function of transient and steady-state solver with custom material coordinate system [3]. We used CFX to design and simulate the cooling structure considering the anisotropy of thermal conductivity and the heat loss distribution in Table 1 and Figure 1. K-epsilon is choosing as the numerical algorithm in CFX which is useful for most engineering problems. Beside the default criteria to judge the convergence in CFX, other criteria are when the temperature of a solid point set by us in MA core is come to stable and the temperature rise in outlet meet the theory formula of temperature rise by Eq. (3).

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB051

$$\Delta T[k] = \frac{P[W]}{L[m^3/s]*\rho[kg/m^3]*C[J/kg/K]} \quad (3)$$

Where P is the power loss of heat plate, L is the water flow, ρ and C is the water density and the specific heat.

Air-forced Cooling Scheme

The easiest way to cool the MA core is air-forced cooling scheme. The heat is taken away by a cold air with a certain velocity which is constrained by the power of fan and the temperature of air. Liquefaction on MA core would be happened if the temperature of air is too low. The MA core treatment process is easy and the mechanical support to MA core is the main concern. J-PARC MR has adapted this kind of MA cavity as the second harmonic cavity and J-PARC RCS also considered this cavity as a back-up solution [4,5]. The big limitation of this cavity is the cooling efficiency of air. The air flow is hard to be uniform and depends on the position of air inlet and location of the core. An air-forced MA cavity was designed and simulated by CFX code which considered the anisotropy of thermal conductivity in Table 2 and the average power density is 0.03W/cc in Figure 2. The air flow is set as 354 m^3/hr and the inlet temperature is 30℃. The simulation results shown that the maximum temperature is up to 118℃ in Figure 3 (a) and focus on the outsider of MA core where the air flow is hard to achieve in Figure 3 (b). The location of air inlet can be adjusted to optimize the uniformity of air velocity, but the cooling efficiency is hard to be more than 0.03W/cc which is suit for the application of low power running.

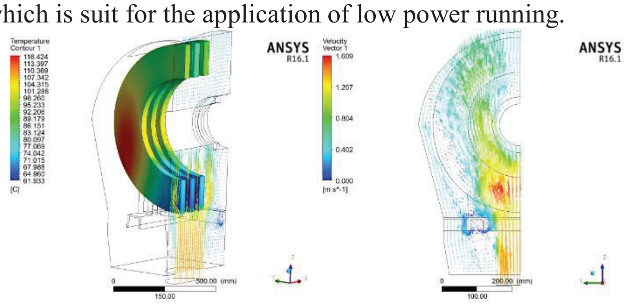

Figure 2: Distribution of temperature and air velocity on MA core in air-forced cooling structure.

Indirect Cooling Scheme

MA core can be cooled by a metallic cooling plate like the way to cool the ferrite cavity [6]. Theoretically, the cooling efficiency can be high as the simulation result in Figure 3. The power density is up to 0.1W/cc and the water flow is 3L/min with the temperature 25℃. The maximum temperature in MA core is just 40℃. But in fact, the cooling efficiency is less than the theoretical value. As the MA core is formed by winding the amorphous ribbon. The surface of MA core is uneven and need to be insulated when it attached with metallic cooling plate. The thermal interface material (TIM) with high thermal conductivity need to be used to fill the air gap within the interface of MA core and the cooling plate. We did a high power test experiment for MA core with different commercial TIMs and calculated the cooling efficiency by recording the temperature rising curve in the water outlet. The experimental results in Figure 4 indicated that the measured data are hard to close to the theoretical value which is simulated by CFX transient solver. It can be explained that the air pockets within the interface gap is not fully removed during the TIM handing process. As the Curie temperature of MA core is higher than 500℃ and the maximum temperature is far away from the glassy-transition temperature of the epoxy resin using for the moulding [4], it would not be a big problem if the power loss is around 0.1W/cc. The anti-radiation performance of TIMs should be confirmed if the MA cavity works in the heavy radiation environment.

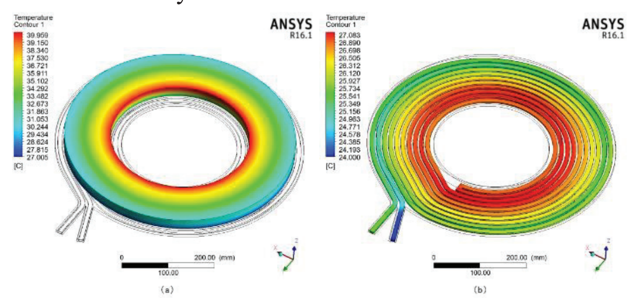

Figure 3: Distribution of temperature on MA core and water in indirect-cooling structure.

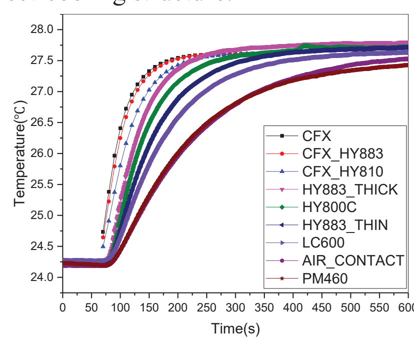

Figure 4: Temperature rising curve of different TIM in the flow outlet.

Direct Cooling Scheme

Direct cooling scheme has been adapted by J-PARC RCS and MR to cool MA core with the average power density more than 0.3W/cc [7,8]. The accelerating gradient is significantly improved as the cooling efficiency can be more than 500W/m^2/k. The MA core waterproof treatment is the key to avoid the deformation of MA core under a high thermal stress [9]. The cooling structure equipped with a guild flow is necessary because the diameter of the MA core can be more the 800mm. A cooling structure was designed for CSNS/RCS and simulated by CFX code, the result shows in Figure 5. Deflectors are inserted the gap between cores to guild the water flow and the water outlet is located on the inner diameter area because the power loss is heavy in this area shown in Figure 1. The maximum temperature is about 52℃ in Figure 5 (a) and the average power density is around 0.3W/cc. The accuracy of CFX simulation to direct cooling structure will be checked after finishing the manufacture of direct-cooling MA cavity on the second half of the year.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB051

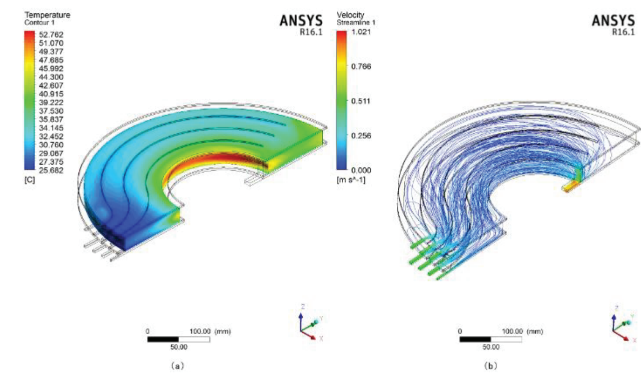

Figure 5: Distribution of temperature and water velocity on MA core indirect-cooling structure.

High Power Test Cavity

Based on the requirement of CSNS/RCS upgrade for high power loss MA cavity, a test MA cavity cooled by water has been designed for high power test to estimate the property of the MA core and cooling effectiveness. The main parameters are listed on Table 2. Nine thermal probes and two observation windows are installed to record the temperature of MA core surface and the water flow state. A water tank can cool three cores with the inner/outer diameter of 200/450mm and 25mm thick. The cross-section is listed in Figure 6.

Table 2: Single Gap Cavity

Main parameters	
Frequency range	0.5~10MHz
Cavity Length	0.768m
Number of cells	2
Number of cores	3/cell
Gap voltage	>2kV
O.D. of MA core	450mm
Power Dissipation / core	0.3W/cc
Coolant	Water

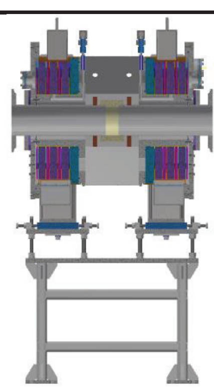

Figure 6: A cross-section of high power test cavity.

CONCLUSION

MA cavity with different cooling structures were studied with CFX code considering the anisotropy of thermal conductivity and the heat loss distribution. The best cooling scheme is depended on the average power density of MA core. When P_{ave} is around 0.03W/cc, air forced scheme for MA cavity can be used. The cooling efficiency of indirect scheme is restricted by the process of TIM coating when P_{ave} is around 0.1W/cc. Direct cooling scheme has the highest cooling efficiency but the structure is complex and the process of how to make MA core waterproof is the key . Some plug-ins for optimizing the state of fluid is need. A test cavity cooled by water was designed for high power test to estimate the property of the MA core and cooling effectiveness for CSNS/RCS upgrade project.

REFERENCES

[1] Saito K, Hirota J I, Noda F., “FINEMET-core loaded untuned RF cavity”, *Nuclear Instruments & Methods in Physics Research, Section A*, (Accelerators, Spectrometers, Detectors and Associated Equipment), 1998, 402(1):1-13.

[2] Y. Morita, T. Kageyama, M. Akoshima *et al.,* “Numerical analysis and experiment to identify origin of buckling in rapid cycling synchrotron core”, *Nuclear Instruments and Methods in Physics Research Section A*: Accelerators, Spectrometers, Detectors and Associated Equipment, 2013, 728:23-30.

[3] Wang Fujun, Analysis of compute fluid dynamics-CFD software theory and application, Tsinghua University Press, 2004:8-12.

[4] C. Ohmori *et al.*, “Design of Magnetic Alloy Resonant System (MARS) Cavity for J-PARC MR”, in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper THPPC005, pp. 3278-3280.

[5] C. Ohmori *et al.*, “Air-cooled Magnetic Alloy Cavity for J-PARC Doubled Rep.-rate Scenario”, in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 3869-3871. doi:10.18429/JACoW-IPAC2014-THPRI046

[6] X. Li, H. Sun, F. C. Zhao, and J. Y. Zhu, “Design of Rapid Tuning System for a Ferrite-Loaded Cavity with Heavy Beam Loading”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 4203-4206. doi:10.18429/JACoW-IPAC2017-THPIK048

[7] T. Uesugi *et al.*, “Direct-Cooling MA Cavity for J-PARC Synchrotrons”, in *Proc. PAC'03*, Portland, OR, USA, May 2003, paper TPAB021,

[8] M. Nomura *et al.*, “Condition of MA Cores in the RF Cavities of J-PARC Synchrotrons after Several Years of Operation”, in *Proc. IPAC'10*, Kyoto, Japan, *May* 2010, paper THPEA022, pp. 3723-3725.

[9] M. Nomura, M. Yamamoto, A. Schnase *et al.,* “The origin of magnetic alloy core buckling in J-PARC 3 GeV RCS”, *Nuclear Instruments and Methods in Physics Research Section A*: Accelerators, Spectrometers, Detectors and Associated Equipment, 2010, 623(3):903-909.