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COOLING DESIGN FOR THE FRIB RFQ CAVITY AT MICHIGAN STATE UNIVERSITY*

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Abstract

We present, in this paper, the cooling design for the Radio Frequency Quadrupole (RFQ) cavity of the Facility for Rare Isotope Beams (FRIB) at Michigan State University. The locations and radius of the cooling passages are optimized, which exist in the five-meter-long copper cavity, tuners, dipole-mode stabilizing rods and end-plates. A three-dimensional RF, thermal, and structural analysis by ANSYS has been performed to carry out the design and verify that the present design can meet the requirement for water velocity, stress, deformation and frequency shift.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) will be a new national user facility for nuclear science, funded by the Department of Energy Office of Science (DOE-SC), Michigan State University (MSU), and the State of Michigan [1]. As a part of the facility, the FRIB Radio Frequency Quadrupole (RFQ), which is 5-meter long and contains 5 segments, will operate at 80.5 MHz and accelerate stable ions with the charge-to-mass ratio of 1/7 to 1/3, from 12 to 500 keV/u [2]. The maximum power to be taken away by the cooling system accounts to about 100 kW. The layout of the cooling system is shown in Fig. 1. The 5-meter long RFQ is mechanically separated into five segments. The cooling-loops inside the vanes and wall are paralleled for each segment. There are 4 main manifolds (2 for supply and 2 for return) and 24 sub manifolds (12 for supply and 12 for return) for the whole RFQ accelerator.

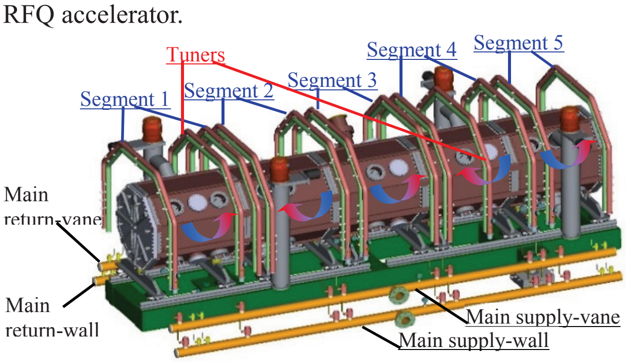

Figure 1: Cooling system layout of FRIB RFQ.

TECHNICAL REQUIREMENT

The design requirement for the cooling system of FRIB RFQ is described as the following.

1. Two water skids can be adopted for the cooling operating in parallel or separately.
2. Adequate cooling shall be ensured for the RFQ cavity, tuning slugs, dipole-mode stabilizer rods, end-plates, and RF coupler.
3. The RFQ structure shall operate at a nominal ambient temperature of 20 °C.
4. The cooling water skid supply pressure to the RFQ manifolds shall not exceed 10.3 bar (150 psi).
5. The total combined water flow rate available to the RFQ shall not be less than 300 gpm (19 l/s).
6. The frequency shift shall be controlled within 80.5 MHz ±0.5 kHz from 0 to full RF power.
7. The maximum equivalent stress of the RFQ cavity due to deformation shall be less than 50 MPa.

COOLING DESIGN

Parameters for Cooling Passages

There are totally 118 cooling passages for the FRIB RFQ: 100 passages for the main cavity (40 for vanes, 60 for the wall), 9 passages for tuners, 8 passages for end-plates and 1 passage for the RF power coupler. Each segment contains 20 passages in the vanes and wall with quadrupole-symmetric locations. Fig. 2 shows the optimized locations of passages in the vanes and wall at a fixed longitudinal position of the RFQ. In Fig. 2, A1 and A2 (8 passages per segment) are the cooling passages for the vanes while B1 and B2 (12 passages per segment) are the cooling passages for the wall.

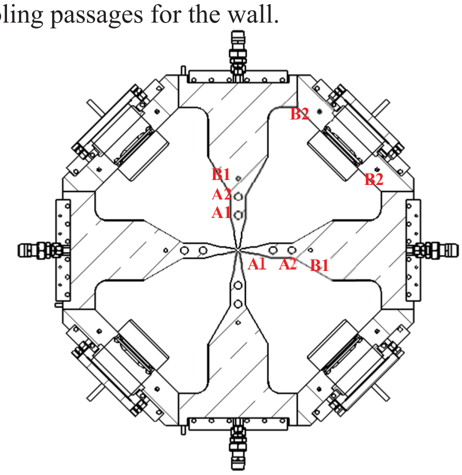

Figure 2: Locations of the passages in the vanes and wall.

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The diameters of cooling passages are not the same. The diameters of the A1 and A2 passages in segment 1 and segment 5 are 20 mm, and the diameters of other passages (including A1 and A2 of segment 2 to 4, all of B1 and B2, passages for tuners, end-plates and the RF power coupler) are 10 mm. Considering the structure of the RFQ and the layout of cooling system, the locations of cooling passages are shown in Fig. 3. The upper two figures show the passage locations in segment 4. The A1, A2 and B1 passages are shown in the upper left figure, and the entrance and the exit of B2 passages and tuner passages can be seen in the upper right figure. The locations of cooling passages in segment 2 and 3 are quite similar to those in segment 4. The location of cooling passages in segment 1 and 5 are different with those in other segments because of the existence of undercuts, dipole-mode stabilizer rods and end-plates. The lower two figures shows these passages in segment 5.

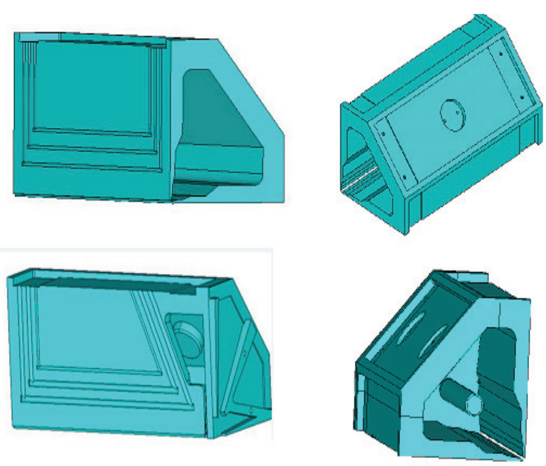

Figure 3: Locations of cooling passages in segment 4 (upper) and segment 5 (lower) (in one quadrant).

To control the frequency shift of each segment, the water velocity of each passage is set different, as shown in Table 1. The total flow rate is 288.8 gpm and the frequency shift is -0.4 kHz (simulated by ANSYS) in such velocity of water.

Table 1: The Water Velocity of Each Passage

Location	**Channel: Vane (m/s)**	**Channel: Wall (m/s)**
Segment 1 and 5	1.6	1.0
Segment 2 to 4	1.4	1.0
Tuner		1.0
End-plates		1.0
RF power coupler		1.0

Tune Steps and Design Strategy

The tune steps before RFQ operation are described in Fig. 4. We define the RFQ resonant frequency with full power is 80.5 MHz +Δf1 +Δf2. Δf1 is the frequency shift between the operation frequency without power and 80.5 MHz. It is affected by the passage locations, water temperature and water velocity. Δf2 is the frequency shift between full RF power and no power. It is affected by the passage locations and water velocity. Δf2 remains the same while the input water temperature is set different. The tune objective is Δf1 =0 and Δf2 <±0.5 kHz during RFQ operation.

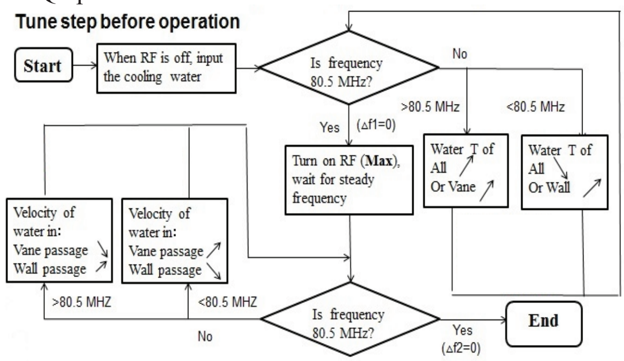

Figure 4: Tune steps.

The resonant frequency of the RFQ cavity changes linearly with the input power, if only the cooling exists in the wall or vanes. But if the cooling exists reasonably both in the wall and vanes, the RFQ can be operated with the resonant frequency not changing with the input power, that is, △f2 =0. The water velocity and passage locations shall be reasonably designed, and water velocity shall be adjusted before operation to achieve △f2 =0. So the tune steps are described as the following:

Firstly, adjust the water temperature to obtain the steady state operation frequency of 80.5 MHz with RF off (Δf1 =0);

Secondly, turn on the RF. The cavity frequency will change so wait for the steady state. Adjust the flow velocity in the vanes or wall until the steady-state operation frequency reaches 80.5 MHz (Δf2 =0).

The influence factors of the water temperature and velocity are given in the subsequent section.

3D THERMAL, STRUCTURAL AND RF SIMULATION

To provide a reference for tuning, the influence factors of the water temperature and velocity are analysed by the thermal, structural and RF simulation [3,4]. The simulation is carried out segment by segment.

Thermal and Structural Simulation

To carry out thermal and structural simulation, a former RF simulation is needed to determine the heat loads. As an example, the temperature, deformation and stress distributions of segment 3 and 5 simulated by ANSYS are shown in Fig. 5.

The main result of thermal and structural simulation is presented in Table 2. The maximum temperature of the whole cavity is 32.1 °C in segment 5, the maximum displacement is 136 μm in segment 4 and the maximum stress is 51.8 MPa on the end-plate in segment 1.

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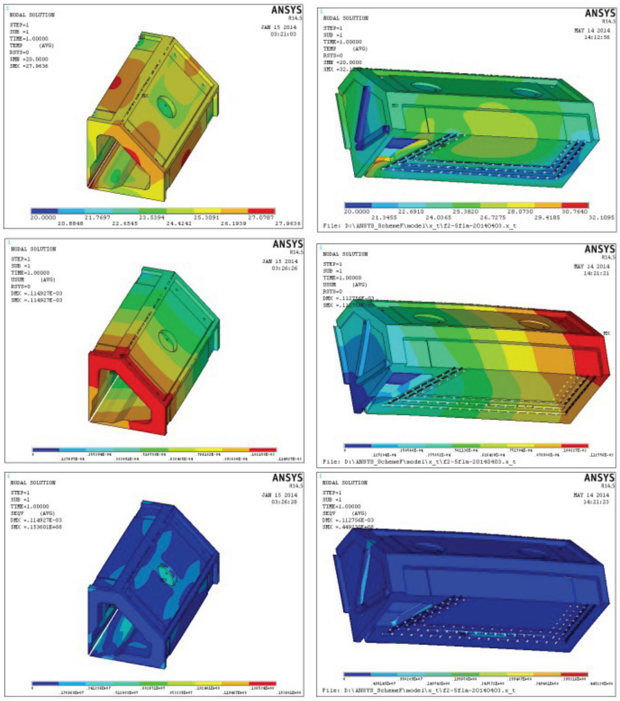

Figure 5: Temperature, deformation and stress distributions of segment 3 (left) and segment 5 (right).

Table 2: Result of Thermal and Structural Simulation

Segment	Temperature /max (°C)	Displacement /max (μm)	Stress /max (MPa)
1	30.0	76.6	51.8
2	28.4	92.6	11.1
3	28.0	115	15.4
4	29.8	136	17.6
5	32.1	113	44.9

RF Simulation

After the simulation of the displacement, the resonance frequency is simulated again in order to obtain the frequency shift. Table 3 and Table 4 shows the frequency sensitivity on the water temperature and velocity.

Table 3: Frequency Sensitivity on the Water Temperature

Segment	Channel: Vane (kHz/°C)	Channel: Wall (kHz/°C)	Channel: All (kHz/°C)
1	-12.9	10.1	-2.8
2	-9.6	7.0	-2.6
3	-8.9	6.4	-2.5
4	-8.3	6.0	-2.3
5	-9.3	6.6	-2.7
Total	-9.5	7.0	-2.5

Table 4: Frequency Sensitivity on the Water Velocity

Segment	Channel: Vane kHz/(0.1m/s)	Channel: Wall kHz/(0.1m/s)
1	1.7	-1.3
2	2.3	-1.6
3	2.4	-1.8
4	2.6	-2.0
5	1.8	-1.5
Total*	2.2	-1.7

* For tuners, the value is about -1.0 kHz/(0.1m/s).

It can be concluded in Table 3 and 4 that the frequency sensitivity on the water temperature is much larger than which on the water velocity. Therefore, if $\Delta f2$ is too large after the RF power is on (Fig. 4), the temperature of water have to be adjusted to obtain $\Delta f1+\Delta f2=0$.

CONCLUSION

With the cooling design for the FRIB FRQ, the diameters of cooling passages are 10 mm or 20 mm, whose water velocities range from 1.0 m/s to 1.6 m/s (Table 1). The frequency shift between the resonance frequency at full RF power and 80.5 MHz is expect to be close to zero. The temperature of the inlet water for the vanes and wall can both be adjusted if the operation frequency is not 80.5 MHz (-9.5 kHz/°C for Channel Vane and 7.0 kHz/°C for Channel Wall). The velocity of inlet water for both channels can also be adjust to obtain the zero frequency shift before operation (2.2 kHz/(0.1m/s) for Channel Vane and -1.7 kHz/(0.1m/s) for Channel Wall). During operation with the maximum RF power, the maximum temperature and stress of the RFQ cavity are predicted to be ~32 °C and ~50 MPa respectively.

ACKNOWLEDGMENT

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