Heat-structure analysis of a 432-MHz RFQ for the JHP

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Abstract

A radio-frequency quadrupole (RFQ) linac with an accelerating energy of 3 MeV and a resonant frequency of 432 MHz is being developed. In order to find the optimum method of cooling this RFQ a variety of heat-structure analyses were performed by using a numerical-calculation code ISAS2. The frequency changes were obtained from the results of the heat-structure analyses, where the dependence of the resonant frequency on the deformation of a cavity was derived by using a code SUPERFISH. The advantages and disadvantages of various cooling methods are discussed.

Introduction

A 1-GeV proton linac, an injector of the Japanese Hadron Project (JHP), is now under development[1]. Our group is developing a 432- MHz RFQ linac as a preinjector[2].

The resonant frequency and the accelerating energy of this RFQ are 432 MHz and 3 MeV, respectively. Since its accelerating energy is high, the cavity length about four times as long as the rf wavelength. Then, the difference between the resonant frequencies of the accelerating mode and the higher-order mode becomes small, and the mixture of the higher-order mode due to the thermal deformation becomes unstable. Moreover, since the duty of rf power is pretty high (3 %), the cooling must be optimized in order to operate the RFQ stably and its influence on the frequency should be well understood.

In general, it is expected that the cooling efficiency is improved and the thermal deformation is decreased by boring a channel near the location with the high power dissipation. So, channels bored near the vane side and the inside wall in parallel to the beam axis are probably effective in a four-vane type RFQ like this machine. In this occasion, the variation in the thermal deformation or the frequency due to the water-temperature rise along the beam axis must be precisely evaluated.

In this paper, we describe the optimization method of the number, the positions and the flow rates of cooling channels based upon the result of a two-dimensional heat-structure analysis.

Conditions of Heat-structure Analysis

The present heat-structure analysis uses a general structure analysis system ISAS2(Integrated Structure Analysis System 2)[3]. In this analysis,we supposed that heat conduction was steady and linear and ignored its pressure drop. The temperature of the cooling water at the entrance was held fixed to 25℃. We did not consider the reduction in the heat transfer coefficient due to the deposit on the cooling-channel wall surfaces. The material of a cavity is oxygen-free copper containing 0.2 % silver. The power dissipation and its distribution were calculated by supposing that the Q value is 60 % as large as the result of the SUPERFISH[4]. The time-averaged total power dissipation is 19.7 KW.

Among various locations with the high power dissipation we cannot bore a cooling channel near the cavity wall, since a tuner and a coupler must be installed in these places. Thus, we bore channels in the vanes as shown in Fig. 1. Since the water enters at both ends of each vane and exits at the center, the channel in the longitudinal direction is a half as long as the vane (1.35 m). The radius of a channel must be more than 6 mm in order to bore the 1.35 m channel.

We only analyzed a quarter of the cavity using its symmetry. We started the analysis from the occasion of one channel per one-quarter cavity. From now on, the number of channels is counted per one-quarter cavity. By the analysis of one channel we could already understand the effect of the channel position and the flow rate on the deformation and resonant frequency. We then attempted to decrease the frequency deviation due to the thermal deformation by increasing the number of channels and the flow rates.The positions and the diameters of channels thus studied are shown in table 1 together with Fig. 1. Here, the velocity of water flow was held fixed to 2 m/s in order to avoid the erosion. As can be seen from Fig. 1 the diameter of a channel in the vane is restricted by the size of the vane, and that outside the vane by the contact surface. The distance between the channel and the boundary was made 5 mm by considering the accuracy of manufacturing.

The effect of the deformation on the resonant frequency was evaluated from the variation $\Delta G(\mu m)$ in the shortest distance among the vane tips and that $\Delta R(\mu m)$ in the cavity inside radius as

$$\Delta f=(df/dR)\Delta R+(df/dg)\Delta G$$
$$=-7.5745\Delta R+34.079\Delta G \quad [KHz] \qquad (1)$$

For comparison we show the change in the resonant frequency of a 432-MHz cavity, when the temperature is uniformly changed by an amount of ΔT, as

$$\Delta f_{Uni}=f\times\alpha\times\Delta T$$
$$=7\times\Delta T \quad [KHz] \qquad (2)$$

,where the resonant frequencies of cavities with various ΔG's and ΔR's were calculated by using SUPERFISH.

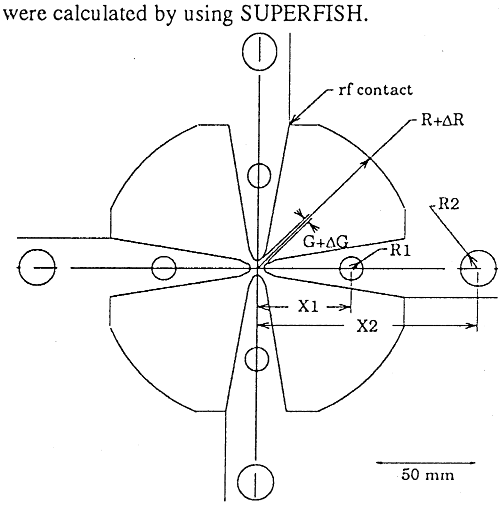

Fig. 1. Cross sectional view of the RFQ cavity and definitions of cooling channel positions X1 and X2, cooling channel radii R1 and R2, cavity radius R+ΔR and gap length G+ΔG.

Table 1
Parameters of each models.

Models with one cooling channel	flow rate [Liter / min]
Model A (X1=47,R1=6)	13.56
Model B (X1=58,R1=8)	24.10
Model C (X1=85,R1=10)	37.68
Models with two cooling channels	
Model 1 (X1=46.8,R1=6 : X2=85,R2=10)	51.24 (13.56+37.68)
Model 2 (X1=47.0,R1=6 : X2=110,R2=9)	44.08 (13.56+30.52)
Model 3 (X1=58.0,R1=8 : X2=106.5,R2=8.5)	51.34 (24.12+27.22)

Results and Discussion

Models with one cooling channel

First, we analyzed the Model A , the channel of which was bored as closely as possible to the vane tip with a radius of 6 mm. Then, we analyzed the Model B and C , the channels of which were located farther from the vane tip. In these cases the diameters of the channels were made as large as possible. Figure 2 shows the relationship between cooling water temperatures and cavity maximum temperatures in the entrance and exit. The frequency deviations Δf are shown in Fig. 3, where these values are obtained by substituting the thermal deformation into Eq. 1.

It is seen from Fig. 2 that water temperature at the exit is approximately in inverse proportion to flow rate. It is noted that the cavity maximum temperature of the Model B is the smallest of three, although its flow rate is the second-highest. In the Model B the channel is located halfway between the cavity wall and the vane side , being most effective in cooling. In the Model C with the highest flow rate the channel is kept away from the vane tip, where the temperature is increased. In the Model A with the lowest flow rate the channel is located nearest to the vane tip, but farthest from the cavity wall, where the temperature is increased.

For the same reason, the deviation in the resonant frequency of the Model B is smaller than that of any other models. Since the Model A is cooling the vane tip most effectively, the extension of the vane is relatively small as compared with expansion of the inside diameter of a cavity. As a result the gap G in Eq. 1 is increased beyond the uniform deformation due to the average temperature rise of a cavity, giving rise to the increase in the resonant frequency. In contrast the extension of the vane of the Model C is relatively large as compared with the expansion of the inside diameter,and ΔG becomes negative, resulting in the large decrease in the resonant frequency. The frequency of the Model A varies by an amount of 24 KHz along the beam axis,while those of the Model B and C 10 KHz. The Model B can be one of possible candidates, since its cooling channel is most effective with the small deviation in the resonant frequency.

Models with two cooling channels

We did not take into account the possible heat resistance at the contact surfaces in a cavity, being hard to estimate. It is expected that the effect of the resistance on the present analysis is minimized by keeping the temperature rise of the cavity as low as possible. For this purpose we examined the case of two channels and large flow rates. It is expected that the frequency deviation similar to that of the model B is obtained by locating one channel more closely to the vane tip and adding the other channel outside, while keeping the temperature rise lower than that of the model B.

In the two channels version we flow the water through two channels in the same direction rather than the opposite direction for the following reason. In the RFQ the effect of the thermal extension of the vanes is cancelled by that of the thermal expansion of the cavity diameter. If the water flows through the two channels in the opposite direction, the condition of the cancellation is broken, resulting in the large frequency deviation.

In the case of two closely-located channels, the heat-exchange between the channels must be considered in principle. We have analyzed one case by taking into account the heat exchange. The effect of the heat exchange was negligibly small, probably because the water flows in the same direction through the two channels. For this reason we neglect the heat exchange from now on.

Typical examples of the analyzed results with different positions and diameters of two channels are shown below. Figure 4 shows the water temperatures and the cavity maximum temperatures at the entrance and the exit. The variation of the resonant frequency along the beam axis is shown in Fig. 5 for each model. The water temperature and the cavity maximum temperature are lowered as compared with the occasion of one channel, since the total flow rate is increased. However, the frequency deviation becomes significantly larger than that of the Model B with one channel, since the cavity inside wall is cooled excessively as compared with the vane tip side.

Thus, we searched for the optimum solution by varying the water velocity of the two channels. Among several models with two channels the Model 1 is the most effective in cooling. However, the outside channel(R2) in the Model 1 is too closely located to the bolts used for the cavity contact. In order to secure the sufficient rf contact we made the parameter search on the Model 2 rather than the Model 1. In the beginning, we varied the velocity of the outside channel, holding the inside channel fixed to 2 m/s. Figure 6 shows the results for the cavity temperature and water temperature, while Fig. 7 the frequency deviation. It is seen that the frequency deviation is improved by an amount of 20 KHz by decreasing the velocity in the outside channel to a half. However, the total flow rate of this case is almost the same as that of the Model B, losing the advantage of the two channels version over the one channel version.

Thus, we next varied the velocity in the inside channel, holding that in the outside channel fixed to 2 m/s. Figure 8 shows the velocity dependence of the water temperature at the exit and those of the cavity maximum temperatures at the entrance and the exit. The velocity dependences of the frequencies at the entrance and the exit are shown in Fig. 9. It is seen that these temperatures and the frequency deviations are approximately inversely proportional to the velocity, since the heat transfer coefficient is approximately proportional to the velocity. Although the frequency deviation is significantly decreased by increasing the velocity, we have to seriously consider the effect of erosion in order to use the high velocity water flow.

Conclusion

The frequency of an RFQ cavity is very sensitive to both the thermal extension of the vane and thermal expansion of the cavity inside diameter, since the electric field is concentrated on the vane tip. In the case of one channel per one-quarter cavity (a radius of 8 mm, a velocity of 2 m/s) the deviation in the resonant frequency was +22~+6 KHz, and the temperature rise in the cavity was less than 8 ℃. In the case of two channels (radii of 6 mm and 9 mm, a velocity of 2 m/s) the deviationwas KHz and the temperature rise was less than. Thus, the one-channel version is advantageous over the two-channel version with respect to the frequency deviation due to the thermal deformation, if we hold the velocity fixed.

Varying the velocities of the water flows through two channels, we obtained the similar result to that of the one-channel version. Thus, we bored two channels in the high-power model of the RFQ for the following practical reason. The small frequency deviation of the one-channel version arises from the delicate cancellation of the vane extension by the diameter expansion. The theoretical prediction may not be sufficiently accurate for predicting the this kind of results. On the other hand, if we have two channels, we can adjust the water flows empirically in order to find the optimum result, although this result may not be better than the theoretically obtainable optimum result for the one-channel version.

Reference

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[4] K. Halbach et al., Part. Accel. 7(1976)213.

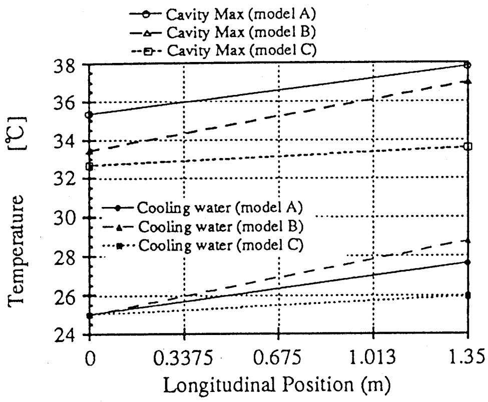

Fig. 2. The relationship between cooling water temperatures and cavity maximum temperatures in the entrance and exit with one cooling channel.

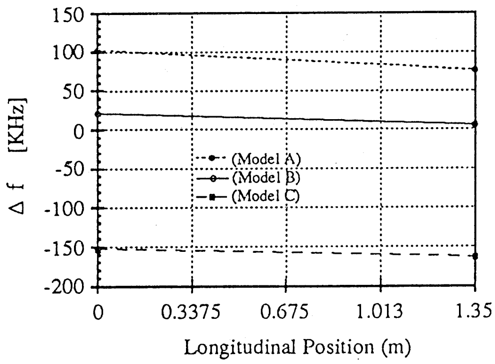

Fig. 3. The frequency deviations Δ f with one cooling channel.

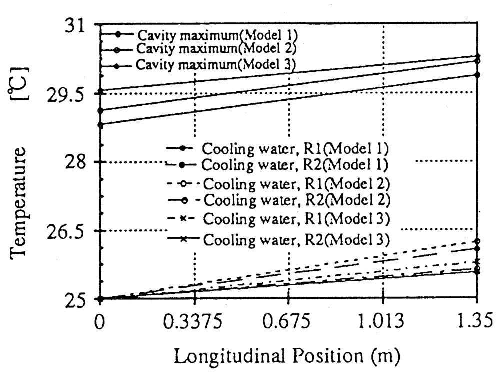

Fig. 4. The water temperatures and the cavity maximum temperatures at the the entrance and the exit with two cooling channel.

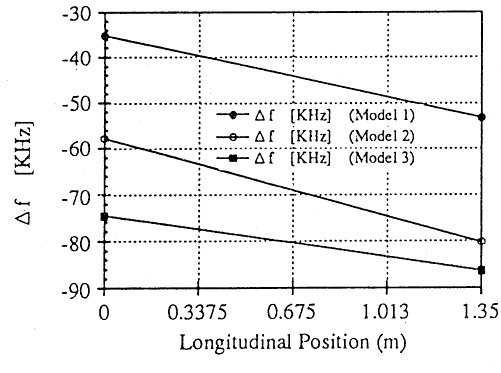

Fig. 5. The variation of the resonant frequency along the beam axis for each model with two cooling channel.

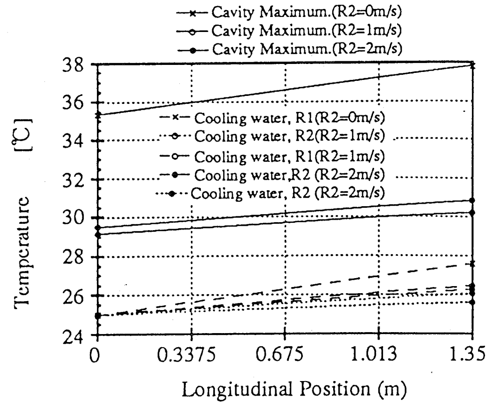

Fig. 6. The results for the cavity temperature and water temperature with models were varied the velocity of the outside channel, holding the inside channel fixed to 2 m/s.

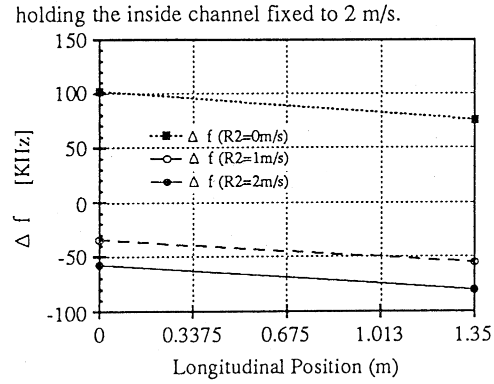

Fig. 7. The results for the frequency deviation with models were varied the velocity of the outside channel, holding the inside channel fixed to 2 m/s.

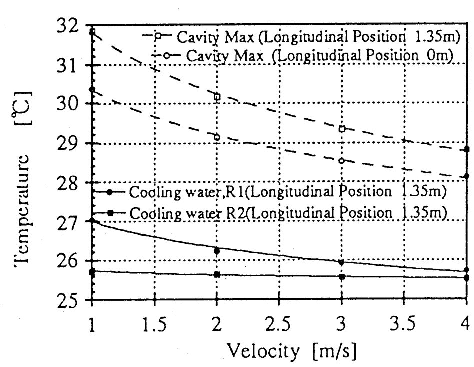

Fig. 8. The velocity dependence of the water temperature at the exit and those of the cavity maximum temperatures at the entrance and the exit with models were varied the velocity in the inside channel, holding that in the outside channel fixed to 2 m/s.

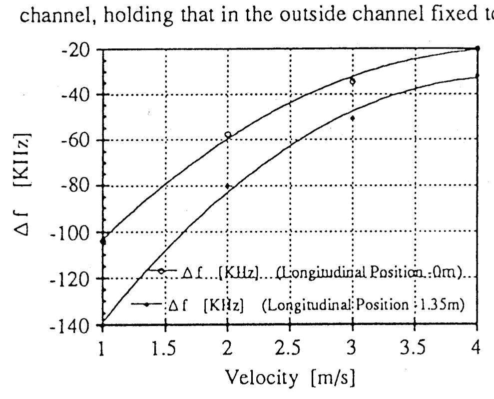

Fig. 9. The velocity dependences of the frequencies at the entrance and the exit with models were varied the velocity in the inside channel, holding that in the outside channel fixed to 2 m/s.