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Thermal Analysis of CSNS RFQ

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Abstract Water-cooling serves two functions in an RFQ. One is to take away the power dissipated on the inside surface of the RFQ by the RF field to maintain the thermal stability and to limit the deformation of RFQ. The other is to be used to tune the RFQ basically without effecting the field distribution when the RFQ is out of resonance, since the beam transmission of RFQ is very sensitive to the field profile, the ordinary frequency tuning method by the movable tuners is no more adopted in an RFQ operation. The cooling water channel position and number, as well as the optimum cooling water temperature are determined through thermal analysis. In addition, the tuning method by adjusting the cooling water temperature is determined when the RFQ is out of resonance.

Key words RFQ, water-cooling, heat transfer coefficient, frequency shift

1 CSNS RFQ and the power dissipation

The China Spallation Neutron Source (CSNS) is an accelerator-based high power project currently under planning in China[2)]. Due to the advantage of bunching, focusing and accelerating beams simultaneously, Radio Frequency Quadrupole (RFQ) accelerator is the important and extensively adopted accelerating structure after the ion source to raise the low beam energy in a linear accelerator (Linac) especially in the Linac with intense beam currents. The four-vane type RFQ of CSNS[1] is structurally similar to the one previously developed at IHEP for the Accelerator Driven Subcritical (ADS) program[2, 3]. In comparison, the RF frequency is chosen to be 324MHz instead of 352.2MHz, and the input and output energy are lowered to 50keV and 3MeV respectively to facilitate pre-chopping at low energy beam transport (LEBT) and further chopping at medium energy beam transport (MEBT). The pulsed beam current is 40mA and the beam duty factor is 1.05%. The chopped beam with up to 50% chopped ratio, which is pre-chopped by modulating its energy at LEBT, will lose in the RFQ. The 3.62m long RFQ cavity is divided into two resonantly coupled segments with each consisting of two technological modules. Some relevant parameters of the RFQ are listed in Table 1.

Table 1. CSNS RFQ design parameters.

input energy/keV	50
output energy/MeV	3
RF frequency/MHz	324
pulsed beam current/mA	40
beam duty factor	1.05%
RF duty factor	1.3%
power dissipation/kW	279 (got by SUPERFISH)
transmission	97%
total RFQ length/m	3.62
structure	4-vane

As listed in Table 1, the power dissipation got by the 2-dimension code SUPERFISH is about 279kW. The real power dissipation is always larger than that got by SUPERFISH, as a rule of thumb, it generally needs to be multiplied by a factor of 1.2—1.4. In the thermal analysis of RFQ, the optimization of water-

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cooling channel position and water temperature is based on the factor of 1.4. In the meantime, comparison between different factors is also performed to examine how much influence of the factor on the results. Certainly, the RF duty factor and beam loss power should also be taken into account in the thermal analysis.

2 Heat transfer coefficient and water temperature rise

The heat transfer coefficient h is used in calculating the convection heat transfer between a moving fluid and a solid in thermodynamics. In our case, it is used to calculate the heat transfer between the cooling water and the water-cooling channel surface. Indeed, there also exists convection heat transfer between RFQ cavity surface and the ambient air. However, since the heat transfer coefficient h between the RFQ cavity surface and the ambient air is very small (about $10\mathrm{W/(m^2{\cdot}K)}$, and the difference in temperature between RFQ cavity surface and the ambient air is generally small in the mean time, so the heat transfer between them is negligible. The transfer power Q between the water-cooling channel surface and the water is described by the equation

$$Q = h\cdot A_{\mathrm{s}}\cdot \Delta T\,, \tag{1}$$

where A_{s} is channel side surface area, ΔT is the temperature difference between the channel surface and water. The heat transfer coefficient is often calculated from the Nusselt number Nu. One of the earliest equations developed to compute the heat transfer coefficient valid for fully developed turbulent water flow in a circular pipe is the Dittus-Boelter equation[4]

$$h = \frac{\kappa_{\mathrm{w}}\cdot Nu}{D}\,, \tag{2}$$

with

$$Nu = 0.0243\cdot Re^{0.8}\cdot Pr^{0.4}\,, \tag{3}$$

where κ_{w}=0.63W/(m·K) is the thermal conductivity of water, D is the diameter of water pipe, Re is the Reynolds number defined as:

$$Re = \frac{v\cdot D\cdot \rho}{\mu}\,. \tag{4}$$

Here v is the velocity of water flow, μ is the absolute viscosity of water. ρ is water density. Pr is the Prandtl number defined from

$$Pr = \frac{C_{\mathrm{p}}\cdot \mu}{\kappa_{\mathrm{w}}}\,, \tag{5}$$

with C_{p} the specific heat of water at constant pressure. The coefficient 0.0243 in Eq. (3) is afterwards changed to 0.023 by McAdams[5], so Eq. (3) becomes

$$Nu = 0.023\cdot Re^{0.8}\cdot Pr^{0.4}\,. \tag{6}$$

A more accurate formulation recommended by Petukhov is as follows[6]

$$Nu = \frac{(f/8)Re\cdot Pr}{1.07+12.7\sqrt{f/8}(Pr^{2/3}-1)}\,. \tag{7}$$

Where the friction factor f for smooth pipe is given by

$$f = \frac{1}{(1.82\log_{10}Re-1.64)^2}\,. \tag{8}$$

The water temperature rise ΔT_{w} per meter long along the channel may be obtained from

$$\Delta T_{\mathrm{w}} = \frac{q}{\dot{m}\cdot C_{\mathrm{p}}}\,. \tag{9}$$

Here q is the exchange power per meter long along the channel between the channel and the cooling water, $\dot{m}$ is the mass flow rate of water defined as

$$\dot{m} = v\cdot \rho\cdot A_{\mathrm{t}}\,. \tag{10}$$

Where A_{t} is the transverse section area of the water-cooling channel.

In our RFQ thermal analysis, the optimization of water-cooling channel position and water temperature is based on Eq. (6). Simulations based on Eq. (7) are also carried out to test how much difference between them. For our pervious ADS RFQ, the design philosophy of water-cooling system is aimed at a high beam duty factor from 6% to the continuous wave (CW) working mode. So the inlet and outlet of every module is directly connected with the water manifold. For CSNS RFQ with a lower duty factor, the cooling water from the first module will continuously go through the second module in the same segment, and then back to the water manifold. The diameter of the water channel, mainly determined mechanically by the transverse structure of RFQ, is chosen to be 11mm. To ensure the fully turbulent water flow, the velocity of water flow is chosen to be 1.0m/s. With this velocity, the temperature rise at the exit of water channel is less than 0.5℃. The simulations show that the resonant frequency shift of RFQ caused by the temperature rise is within the range of 20kHz required by the beam dynamics.

3 Design with 16 water-cooling channels

As shown in Fig. 1, due to the symmetry in the structure, only 1/8 cross section of RFQ needs to be simulated. There are totally 16 water-cooling channels distributed on the cross section of the RFQ. In Fig. 1, the temperature and deformation map of the cross section of RFQ given by program ANSYS is shown. From the figure, one can see that the difference in temperature in the RFQ is less than 0.3℃, and the maximum deformation, which is located at the outside of RFQ wall, is less than 2.9μm. To be emphasized here is that the deformation of the RFQ is based on the reference temperature of 25℃, which should be the same as the RFQ machining temperature. By adjusting the locations of the water-cooling channels and the water temperature, not only could one limit the maximum deformation of RFQ as small as possible, but also ensure the resonant frequency shift of RFQ to be zero or nearly zero. From Fig. 2, one can see that the resonant frequency shift is zero when the water-cooling temperature is chosen to be 23.2℃. The frequency shift sensitivity to the temperature is about −5kHz/℃ when the water-cooling temperature is away from the optimum water-cooling temperature of 23.2℃.

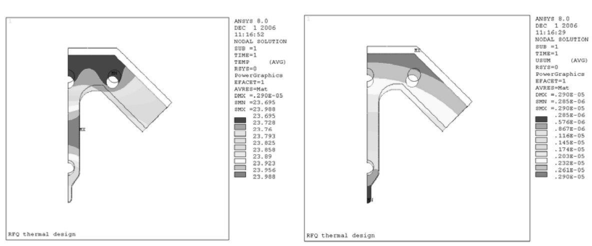

Fig. 1. Temperature and deformation map of the cross section of RFQ for the cases of 16-channel.

As mentioned in Section One, for our present beam-chopping scheme, up to 50% of the chopped beam ratio will be lost in the RFQ, so the power contributed from the beam loss must be taken into account in the thermal analysis. In simulations, the beam loss power is homogeneously loaded on the vane tip curved surface along the RFQ. The frequency shift due to the beam loss and the optimum water-cooling temperature of the vane to cancel the frequency shift are shown in Fig. 3. From the figure, one sees that the frequency shift due to the beam loss could be easily cancelled by slightly adjusting the water-cooling temperature of the vane while keeping the water-cooling temperature of the wall $T_w = 23.2$℃ unchanged.

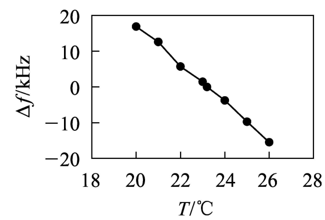

Fig. 2. The frequency shift versus the water-cooling temperature without beam loss.

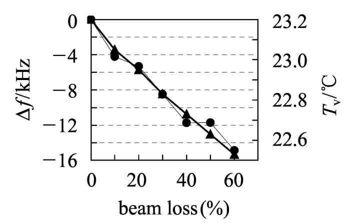

Fig. 3. The frequency shift (dot) and the optimum water-cooling temperature (triangle) of the vane versus the beam loss at T_w=23.2℃.

The water-cooling also serves to tune the RFQ without effect on the field profile when the RFQ is out of resonance. Fig. 4 and Fig. 5 give the relationships between the frequency shift and the water-cooling temperature of the wall and the vane, respectively. Fig. 4 shows that, the frequency shift is basically linearly decreased with the water-cooling temperature of the vane while keeping the water-cooling temperature of the wall $T_w = 23.2$℃ unchanged, and the frequency shift sensitivity to the temperature is about −22.1kHz/℃. However, the frequency shift is basically linearly increased with the water-cooling temperature of the wall while keeping the water-cooling temperature of the vane $T_v = 23.2$℃ unchanged, and the frequency shift sensitivity to the temperature is only 16.7kHz/℃, which is less than that got in the case of varying the water-cooling temperature of vane. So, in the real RFQ operation, when the RFQ is out of resonance, it is preferable to tune the RFQ by adjusting the water-cooling temperature of the vane rather than by adjusting the water-cooling temperature of the wall.

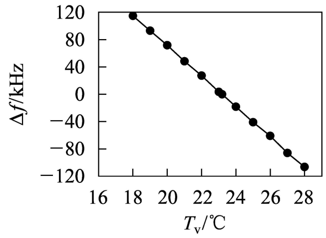

Fig. 4. The frequency shift versus the water-cooling temperature of the vane at T_w=23.2°C.

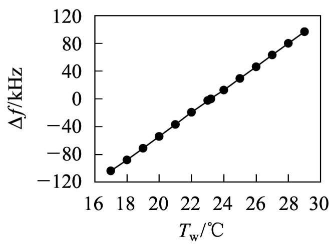

Fig. 5. The frequency shift versus the water-cooling temperature of the wall at T_v=23.2°C.

4 20 water-cooling channels design

Instead of just one water-cooling channel in every vane of the RFQ, there are two water-cooling channels drilled in every vane of the RFQ, as shown in Fig. 6. There are totally 20 water-cooling channels instead of 16 channels distributed on the cross section of RFQ. Comparing to the case with 16 channels, the difference of temperature in the RFQ is only 0.2℃, which is less than 0.3℃ for the case of 16 channels. The maximum deformation, which now is located at the vane tip and the inside surface of the wall, is about 0.05μm, much less than 2.9μm for the case of 16 channels.

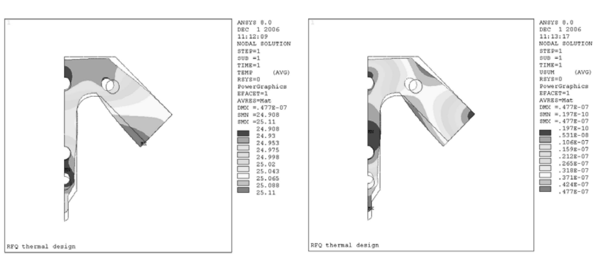

Fig. 6. Temperature and deformation map of the cross section of RFQ for the case of 20-channel.

The optimization of the location of the water-cooling channels is also carried out, and the optimum water-cooling temperature, at which the frequency shift is zero, is got to be 24.5℃. As shown in Fig. 7, when the water-cooling temperature is away from this optimum temperature, a frequency shift will be produced. The frequency shift sensitivity to the temperature is also about −5kHz/℃, which is almost the same as that got in the case of 16 channels. As shown in Fig. 8, comparing to the case of 16 channels, the frequency shift sensitivity to the beam loss is lower, and the variation of water-cooling temperature of the vane needed to cancel the frequency shift is also less than that for the case of 16 channels. In Fig. 9 and Fig. 10, the relationships between the frequency shift and the water-cooling temperature of the vane and the wall are shown, respectively. The frequency shift sensitivity to the water-cooling temperature of the vane is about −28.8kHz/℃ in the case of T_w = 24.5℃, while the frequency shift sensitivity to the water-cooling temperature of the wall is about 23.4kHz/℃ in the case of T_v = 24.5℃. Like the case with 16 channels, the frequency shift sensitivity to the water-cooling temperature of the vane is still higher than to the water-cooling temperature of the wall.

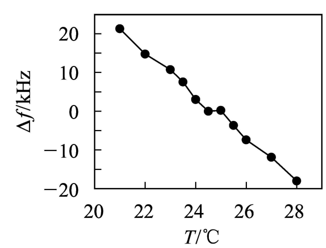

Fig. 7. The Frequency shift versus the water-cooling temperature without beam loss.

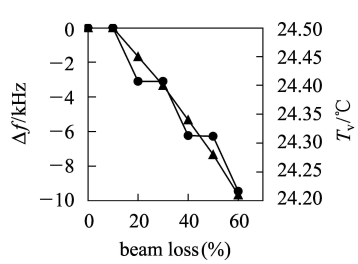

Fig. 8. The frequency shift (dot) and the optimum water-cooling temperature (triangle) of the vane versus the beam loss at T_w=24.5°C.

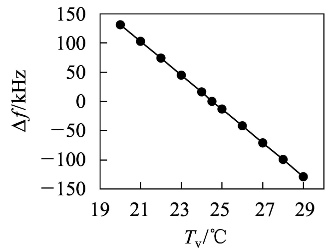

Fig. 9. The frequency shift versus the water-cooling temperature of the vane at $T_{\rm w}$= 24.5°C.

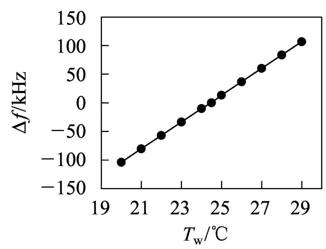

Fig. 10. The frequency shift versus the water-cooling temperature of the wall at $T_{\rm v}$=24.5°C.

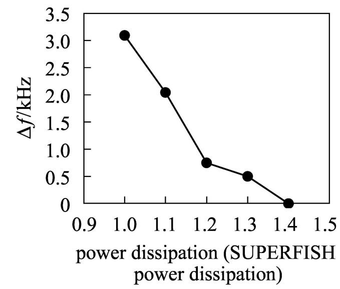

Fig. 11. The frequency shift versus the power dissipation in case of 16 channels.

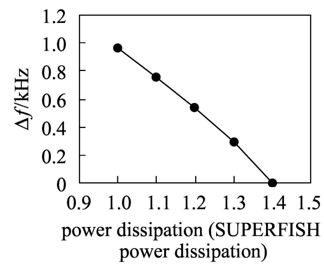

Fig. 12. The frequency shift versus the power dissipation in case of 20 channels.

5 Discussions

In the above simulations, the program ANSYS is just used to perform thermal-structural analysis, while the program SUPERFISH, which is proved to be highly accurate and extensively used in high frequency electro-magnetic field, is used to calculate the resonant frequency of RFQ. To connect the above program, a code is written to read and edit the deformation results of ANSYS and to out-put the results as a form of SUPERFISH input. In addition, the heat flux loads (i.e., the power dissipation of RFQ on the unit area) required by the program ANSYS in thermal-structural analysis is also provided by the program SUPERFISH. So, whether the heat flux loads are in accordance with the real case, or if not, what errors will be produced, is very important. As mentioned in Section 1, the above simulations are based on the load of SUPERFISH power dissipation multiplied by a factor of 1.4. Simulations are performed to examine the effect of the factor, and the results are shown in Fig. 11 and Fig. 12. From the figures, one sees that the frequency shift produced by different factors is small both for the 16-channel and 20-channel cases. Especially for the case of 20-channel case, the frequency shift is less than 1kHz.

Besides the power dissipation of RFQ, the heat transfer coefficient is another uncertain factor that has an effect on the thermal analysis results. The above simulations are based on the Macdams equation, i.e., Eq. (6). In comparison, Table 2 and Table 3 list the frequency shift got by different calculating equations for the heat transfer coefficient. Obviously, the difference in the results produced by the calculating equations for the heat transfer coefficient is very small and negligible.

Table 2. The frequency shift versus different heat transfer coefficient calculating equation at T=23.2°C for the case of 16 channels.

	McAdams Eq.	Dittus-Boelter Eq.	Petkhov Eq.
frequency shift/kHz	0	0.39	0.52

Table 3. The frequency shift versus different heat transfer coefficient calculating equation at T=24.5°C for the case of 20 channels.

	McAdams Eq.	Dittus-Boelter Eq.	Petkhov Eq.
frequency shift/kHz	0	0.2	0.3

The above thermal analysis shows that both the 16-channel and 20-channel design schemes satisfy the requirement from RFQ dynamics. Comparing to the

16-channel design, the 20-channel design scheme is a little better in the following aspects such as the temperature difference in the RFQ body, the maximum deformation and the frequency shift sensitivity to the power dissipation and the calculating equation for the heat transfer coefficient, etc. The price is that, firstly, there are additional 4 channels needed to drill in every RFQ module mechanically; secondly, the total cooling water flow rate increases by 25%.

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中国散裂中子源RFQ的热分析

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摘要 射频四级场(RFQ)加速器的水冷具有以下两种功用：首先它可以把射频场发热带走，维持RFQ腔的热稳定性及限制RFQ强体形变幅度；其次，当RFQ失谐时，它还可以用来进行RFQ的调谐，而同时又基本不影响RFQ的射频场分布. 由于RFQ粒子的传输效率对射频场的分布极其敏感，在RFQ的运行中不再采用传统的用调谐器对RFQ进行调谐的方法. 本文通过热分析，确定了RFQ加速器的水冷管道的数量和布局及最佳工作水温；确定了RFQ失谐时，如何利用水温变化来对RFQ进行调谐的方法.

关键词 射频四级场(RFQ)加速器 水冷 热交换系数 频率漂移

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