Thermal analysis and water-cooling design of the CSNS MEBT 324 MHz buncher cavity

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Abstract At least two bunchers are needed in the 3 MeV H^- Medium Energy Beam Transport (MEBT) line located between RFQ and DTL for the CSNS (China Spallation Neutron Source). A nose-cone geometry has been adopted as the type of buncher cavity for its simplicity, higher impedance and lower risk of multipacting. By making use of the results got from the simulations on the buncher with two-dimension code SUPERFISH, the thermal and structural analyses have been carried out, the process and results to determine the resulting frequency shift due to thermal and structural distortion of the cavity are presented, the water-cooling channel position and the optimum cooling water temperature as well as the tuning method by adjusting the cooling water temperature when the cavity is out of resonance are also determined through the analyses.

Key words buncher cavity, thermal and structural analysis, water-cooling frequency shift

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1 Introduction

The China Spallation Neutron Source is an accelerator-based high power project currently under planning in China. The MEBT line, which is one of the key parts of CSNS linac, consists of a series of quadrupoles, RF cavities and beam diagnostic elements. In order to longitudinally match the beam from RFQ into DTL and control the longitudinal beam envelope, at least two bunchers should be used in the 3 m long MEBT. The aperture and voltage required by beam dynamics for the two bunchers are different, and the maximum aperture and voltage are 25 mm and 148 kV, respectively. In spite of the different requirements of the two bunchers, the same geometry is chosen for simplicity of manufacture processing. The buncher cavity power dissipation is expected to be less than 20 kW and be powered by a series of solid-state amplifiers. The designed aperture and voltage of the bunchers are chosen to be 32 mm and 156 kV considering the difference between the reality and simulation case. We have adopted the nose-cone geometry for its simplicity, higher impedance and lower risk of multipacting compared with other cavity types, such as the quarter-wave cavity and the pill-box with quadrupoles inside nose-cones. The simulation studies on the buncher start from 2D cylindrical symmetric geometry by 2-dimension code SUPERFISH. Then by making use of the power dissipations got from SUPERFISH, the thermal and structural distortion of the cavity is calculated by ANSYS. According to the results given by ANSYS, the optimum cooling water temperature is determined. In addition, the tuning method by adjusting the cooling water temperature is also determined when the buncher cavity is out of resonance.

2 Optimization of the buncher cavity

The buncher cavities maintain the longitudinal focusing as the beam proceeds through the MEBT. In designing the cavities, the following factors have to be considered[1]:

1) A high shunt impedance is desirable to reduce power consumption, to simplify the cooling and thus reduce the design complexity.

2) Electrical discharge (sparking) must be avoided by limiting the peak surface electric field. A maximum accepted value of 1.5 for the Kilpatrick limit has been chosen.

3) The cavity has to fit inside the mechanical limits imposed by the MEBT optical design, leading to a more compact structure.

The chosen nose-cone CCL buncher cavity structure with higher shunt impedance and lower risk of sparking is shown in Fig. 1.

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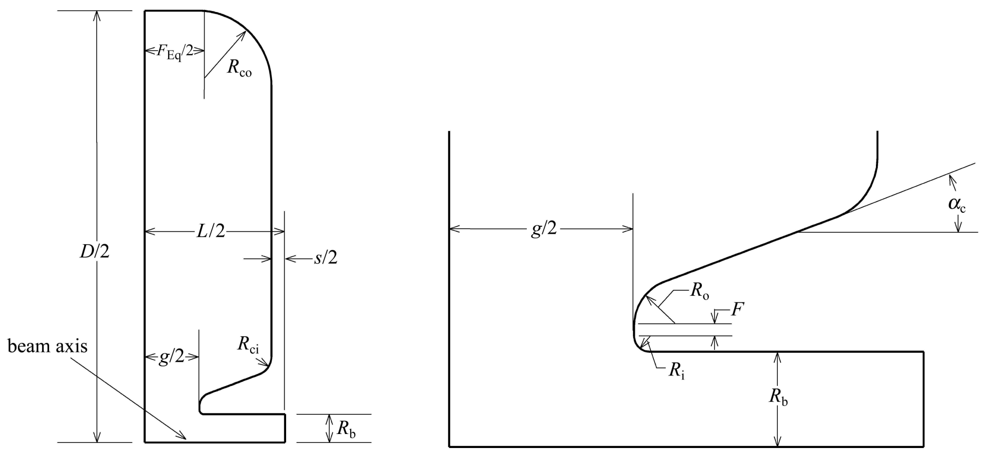

Fig. 1. The CCL type cavity.

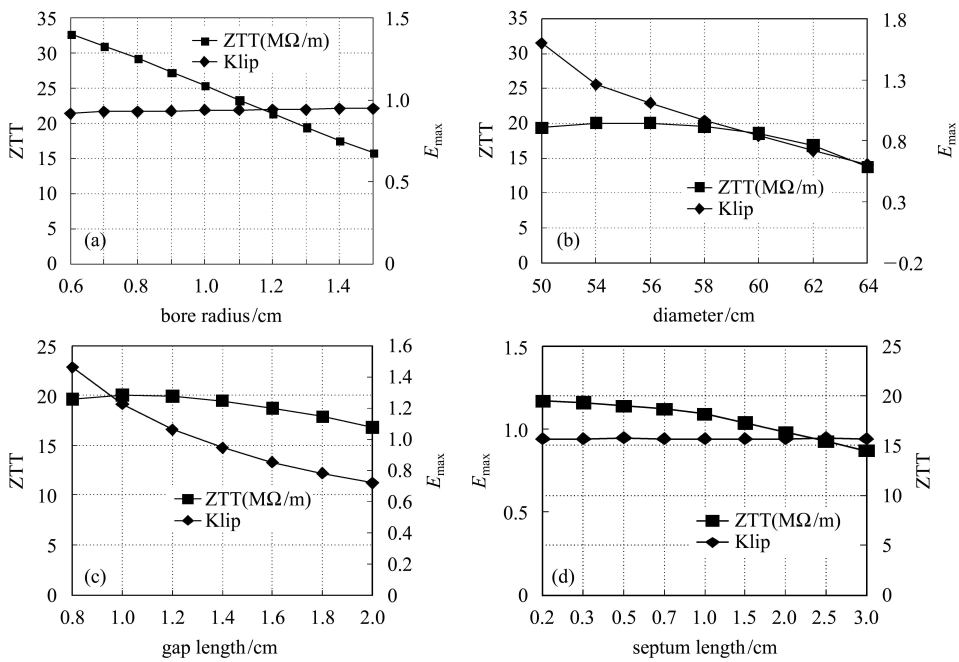

Fig. 2. (a) Bore radius (cm) versus shunt impedance (MΩ/m) and Kilpatrick limit; (b) Diameter (cm) versus shunt impedance (MΩ/m) and Kilpatrick limit; (c) Gap length (cm) versus shunt impedance (MΩ/m) and Kilpatrick limit; (d) Septum length (cm) versus shunt impedance (MΩ/m) and Kilpatrick limit.

By a series of simulations, the relationship between the main parameters of buncher cavity and shunt impedance and Kilpatrick limit is found, which is shown in Fig. 2.

Based on the results given by the above figures, the nose-cone CCL-cavity with 32 mm aperture and 156 kV voltage is finally chosen. While the values of the aperture and voltage are required by beam dynamic design, the values for the other parameters are the results of the buncher geometry optimization. Some relevant parameters of the buncher cavity are listed in Table 1.

The power dissipation got by SUPERFISH is about 11.53 kW, but 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 buncher, the optimization of water-cooling temperature is based on the factor of 1.3. Certainly, the RF duty factor should also be taken into account in the thermal analysis.

3 Thermal and structural analyses

In the thermal analysis, the heat flux loads required by ANSYS are provided by the program SUPERFISH as a format of power dissipations. To ensure the fully turbulent water flow, the velocity of water flow is chosen to be 1.0 m/s in the inlet pipe.

Table 1. Buncher parameters of CSNS MEBT.

beam kinetic energy/MeV	3.026
RF frequency/MHz	323.5
beam chamber aperture diameter/mm	32
reserved longitudinal space/mm	162
inner cavity diameter/mm	569
nose-cones separation/mm	15
Q value/computed	27915.2
transit time factor	0.596
shunt impedance/MΩ(linac convention)	2.28
$R/Q/\Omega$	40.964
nominal voltage/kV	156
peak dissipated power/kW	11.53
duty cycle	1.3%
peak electric field on nose cones/(MV/m)	26.107
ratio peak field to Kilpatrick limit	1.47

With this velocity, the mass flow rate is m = 0.095 kg/s. With an expected heat load of 179.8 W (1.3% RF duty factor) the temperature rise across the cavity is:

$$\Delta T=\frac{Q}{mC_{\mathrm{p}}}=0.22℃. \tag{1}$$

Here, the specific heat capacity of water C_{p} = 4200 J/kg. Calculating the heat transfer coefficient h between the cooling water and the water-cooling channel surface is complex, but an approximation can be obtained by the Dittus-Boelter equation[2]:

$$h=\frac{Nuk}{D}, \tag{2}$$

With

$$Nu=0.023 \cdot Re^{0.8} \cdot Pr^{0.4}, \tag{3}$$

where k = 0.58 W/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 the absolute viscosity of water, ρ the water density, Pr the Prandtl number defined from:

$$Pr=\frac{C_{\mathrm{p}} \cdot \mu}{k}. \tag{5}$$

In the buncher thermal analysis, the water-cooling channel layout is inspired by the similar construction of Spallation Neutron Source project (SNS). Eight water-cooling channels including 2 inlets and 2 exits are symmetrically distributed in the cavity. The diameter of the water channel, mainly determined mechanically by the thickness of buncher cavity, is chosen to be 11 mm. It is worthwhile noticing that the largest power dissipation is around the nose-cone part, however, in reality, the water-cooling pipe is hard to extend inside the nose-cone areas due to mechanical difficulty. During the simulation process, we are more concerned about whether the buncher cavity can be effectively cooled when water-cooling pipe does not extend inside the nose-cone.

Both conditions of using stainless-steel and copper materials were considered in our analyses. The temperature distribution for these two materials with water-cooling is shown in Fig. 3.

As shown in Fig. 3, the difference in temperature in the buncher cavity is about 7℃ for stainless-steel but less than 0.35℃ for copper when the water-cooling temperature is 25℃. After thermal analysis, ANSYS allows the thermal elements to be converted directly to the structural elements in order to obtain the stress and displacement solutions. The thermal distortion of the cavity is based on the coefficients of the cavity materials and the nodal temperature data obtained from the thermal solution, which are applied as a load on the structural model. Based on the above results of thermal analysis, the calculated maximum deformation of buncher cavity for stainless-steel and copper is 10 μm and 4 μm respectively as shown in Fig. 4. The unsymmetrical structural distortion is perhaps caused by the density of grids. In the case with high density mesh, ANSYS will produce a mistake during the structural analysis process. A better symmetrical distortion of the structure can be achieved for copper than for stainless-steel due to the higher thermal conductivity of copper.

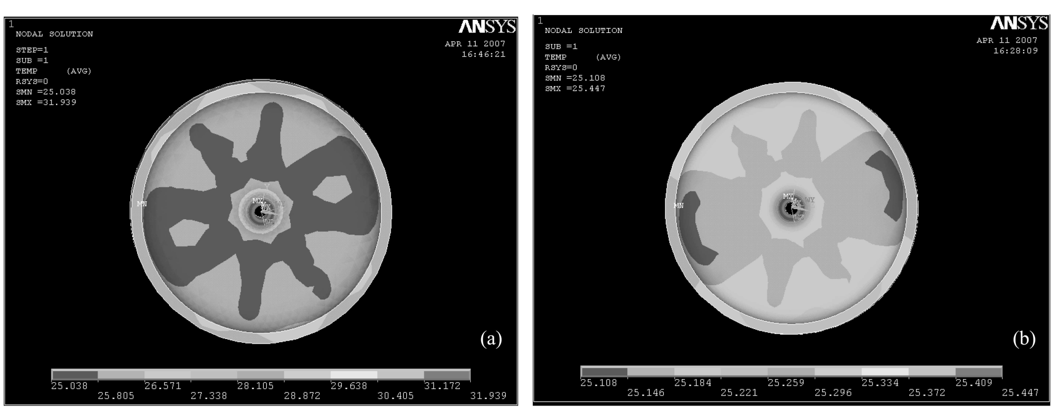

Fig. 3. Temperature distribution with water-cooling, (a) Stainless-steel; (b) Copper.

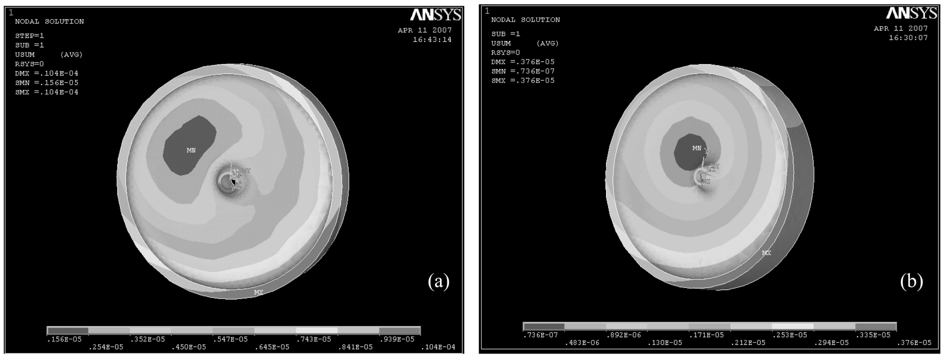

Fig. 4. Structural distortion for (a) Stainless-steel; (b) Copper.

4 Frequency shift and the optimum water-cooling temperature

For calculating the frequency shift, we should establish the model with solid cavity geometry and vacuum volume[3], as shown in Fig. 5. The initial resonance frequency of the buncher is firstly calculated by meshing the vacuum model and using the ANSYS high frequency electromagnetic analyses mode. Then by making use of the ANSYS Thermal-Structural analyses mode, we got the nodal solutions of the cavity model. It is important that the vacuum volume should share its outer boundary with the inner boundary of the cavity, otherwise, the meshes between the two volumes will not be associated. The nodal displacements at the cavity-to-vacuum interface are added to the original nodal locations and a new RF model based on this profile is obtained to determine the frequency shift caused by structural distortion.

Without water-cooling, the structural distortion due to RF power dissipation results in −106 kHz and −75 kHz frequency shift of the cavity for stainless-steel material and copper material, respectively. It is almost intolerable for the buncher with so high a frequency shift in reality. So, we just intend to use the buncher with cooling water. Fig. 6 shows the relationship between frequency shift and water-cooling temperature for stainless-steel and copper respectively with no cooling inside nose-cone.

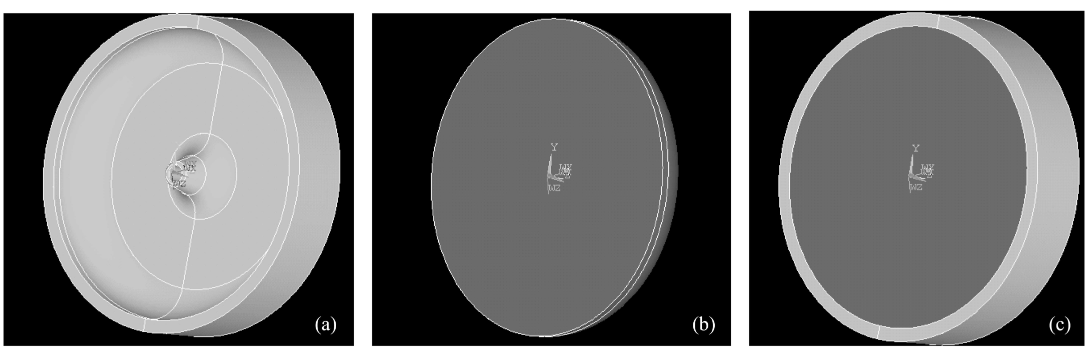

Fig. 5. (a) Cavity model; (b) Vacuum model; (c) Integrate model.

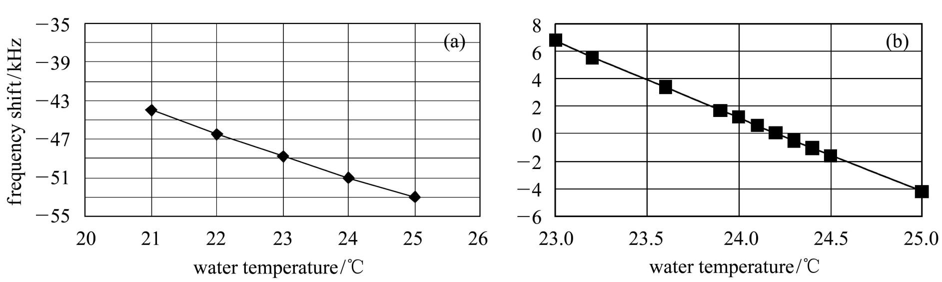

Fig. 6. Frequency shift versus water-cooling temperature. (a) Stainless-steel; (b) Copper.

From Fig. 6, one can see that due to the lower thermal conductivity of stainless-steel compared with copper, the frequency shift sensitivity to the temperature is about −2.3 kHz/℃ for stainless-steel and −5 kHz/℃ for copper. By adjusting the cooling-water temperature, the frequency shift due to structural distortion can be minimized .The minimum frequency shift obtained is about −0.076 kHz for copper at 24.2℃ water temperature, while the frequency shift is about −51.5 kHz for stainless-steel at the same water temperature.

As mentioned in Section 3, we have attempted to extend the water-cooling pipe into the nose-cone and do the same simulations again. Fig. 7 shows the simulation results in the case when the water pipe extends to the nose-cone areas.

As shown in Fig. 7, the frequency shift sensitivity to the temperature for stainless-steel and copper is −2.6 kHz/℃ and −5.4 kHz/℃, respectively. The minimum frequency shift obtained is about −0.092 kHz for copper at 24.5℃ water temperature, while the frequency shift is about 20.6 kHz for stainless-steel at the same water temperature. Compared with the case without water-cooling inside nose-cone, one can not find any differences for copper material, but if we choose stainless-steel material, we must insert the water-cooling pipe inside the nose-cone area, otherwise large frequency shift can not be controlled.

Besides the above discussions, the effect of RF duty factor should also be taken into account, especially in the RF conditioning. Considering the change of duty factor between CSNS phase Ⅰ and phase Ⅱ, simulations are performed to examine the effect of RF duty factor. Table 2 shows the optimum temperature and the maximum thermal deformation versus the RF duty factor for copper material:

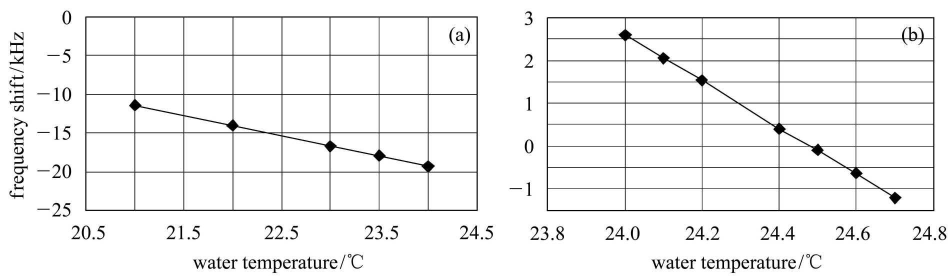

Fig. 7. Frequency shift versus water-cooling temperature with nose-cone cooling. (a) Stainless-steel; (b) Copper.

Table 2. The effect of RF duty factor.

RF duty factor	optimum cooling water temperature/℃	frequency shift/kHz	maximum thermal deformation/μm
0.5	24.7	−0.013	4
0.7	24.6	−0.126	5.6
1.0	24.4	−0.0254	8.4
1.3	24.2	−0.076	11.1
1.5	24.1	−0.038	12
2	23.8	−0.039	50

5 Conclusion

In the above simulations, the physical design of the main parameters of buncher cavity has been accomplished. In order to take away the power dissipated on the inside surface of the buncher cavity by RF field to maintain the thermal stability and to limit the deformation which results in undesired frequency shift, thermal and structural analyses have also been carried out. Due to our simulations, a scheme of eight water-cooling channels is proposed, and the optimum water-cooling temperature is determined. We also find the frequency shift sensitivity to the water-cooling temperature for tuning the cavity when it is out of resonance. It is noticed that copper is more efficient than stainless-steel for water-cooling, and that the disadvantage is lower mechanical strength.

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