Chinese Physics C Vol. 38, No. 10 (2014) 107005

Multi-physics analysis of the RFQ for Injector Scheme Ⅱ of C-ADS driver linac*

WANG Jing(王静)[1,2;1)] HUANG Jian-Long(黄建龙)[1] HE Yuan(何源)[2] ZHANG Xiao-Qi(张小奇)[2]
ZHANG Zhou-Li(张周礼)[2] SHI Ai-Min(石爱民)[2]
[1] Lanzhou University of Technology, Lanzhou 730000, China
[2] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

Abstract: A 162.5 MHz, 2.1 MeV radio frequency quadruples (RFQ) structure is being designed for the Injector Scheme Ⅱ of the China Accelerator Driven Sub-critical System (C-ADS) linac. The RFQ will operate in continuous wave (CW) mode as required. For the CW normal conducting machine, the heat management will be one of the most important issues, since the temperature fluctuation may cause cavity deformation and lead to the resonant frequency shift. Therefore a detailed multi-physics analysis is necessary to ensure that the cavity can stably work at the required power level. The multi-physics analysis process includes RF electromagnetic analysis, thermal analysis, mechanical analysis, and this process will be iterated for several cycles until a satisfactory solution can be found. As one of the widely accepted measures, the cooling water system is used for frequency fine tunning, so the tunning capability of the cooling water system is also studied under different conditions. The results indicate that with the cooling water system, both the temperature rise and the frequency shift can be controlled at an acceptable level.

Key words: frequency shift, multi-physics analysis, finite element method, ANSYS code

PACS: 29.20.Ej **DOI:** 10.1088/1674-1137/38/10/107005

1 Introduction

The China Accelerator Driven Sub-critical System (C-ADS) project under the management of the Chinese Academy of Sciences was launched in 2011, and as one of the three important parts of C-ADS, a 1.5 GeV, 10 mA continue wave (CW) proton accelerator will be developed by the Institute of Modern Physics (IMP) and the Institute of High Energy Physics. The driver linac is composed of two parallel 10 MeV injectors and a main linac accelerating to the final energy. The injector is composed of an ion source, low energy beam transport line (LEBT), radio frequency quadrupole accelerator (RFQ), medium energy beam transport line (MEBT) and a superconducting accelerator section, and both the CW RFQ and the low energy superconducting structures are believed to be very challenging, so there are two proposals suggested and studied by two teams independently. Injector Scheme Ⅱ is the one that was proposed and administrated by IMP. It is characterized with a relatively low RF frequency 162.5 MHz and is composed of an ECR proton source, LEBT, 2.1 MeV RFQ, MEBT1 and the superconducting section. The layout of Injector Scheme Ⅱ is shown in Fig. 1. RFQ will be the key element in Injector Ⅱ to guarantee the CW operation. The multi-physics analysis will be the very necessary simulation process in the RFQ design.

The RFQ of Injector Scheme Ⅱ is designed by IMP in cooperation with the Lawrence Berkeley National Laboratory (LBNL) [1]. It will accelerate proton beams from 35 KeV to 2.1 MeV. The 162.5 MHz frequency is chosen in order to decrease the power density on the surface of the cavity. The reason to apply a relatively low 65 kV inter-vane voltage is also to decrease the RF dissipation power. The specifications of the RFQ are listed in Table 1.

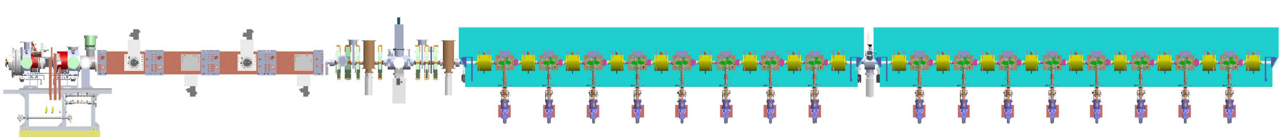

Fig. 1. (color online) The layout of Injector Ⅱ Linac for C-ADS.

Received 29 November 2013
* Supported by National Natural Science Foundation of China (91026001)
1) E-mail: wangj1984@impcas.ac.cn

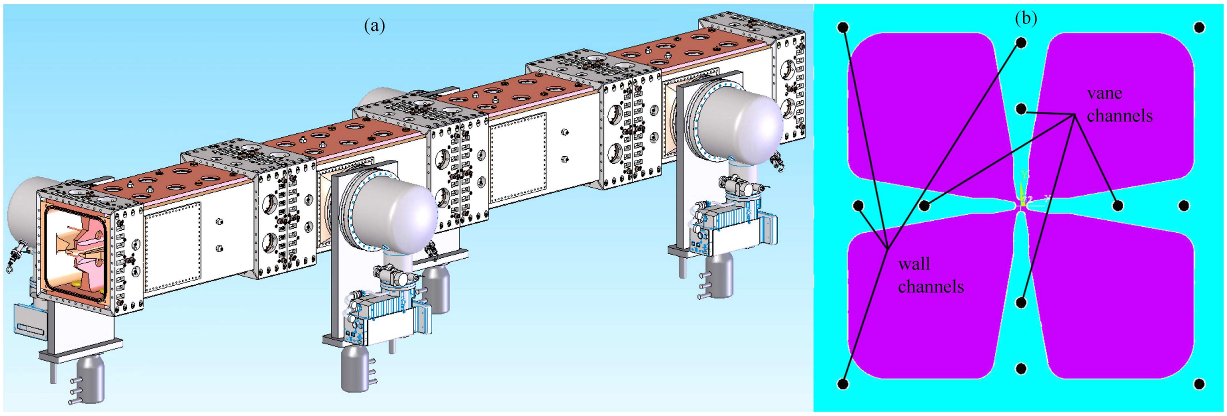

Fig. 2. (color online) 3-D model of the RFQ caity (a) and cooling water channels in cross section (b). There are 12 cooling water channels, 8 in the wall and 4 in the vanes.

Table 1. The main parameters of the RFQ.

parameters	value
ion species	proton
RF frequency/MHz	162.5
inter-vane voltage V/kV	65
total structure length/m	4.2079
power/kW	83.5
duty factor(%)	100

The structure of the RFQ is a four-vane type. The cavity will be divided into four segments with each being about 1.0 m long. The oxygen-free high-conductivity copper (OFHC) is adopted for its good performance in the heat conduction.

The RFQ cavity will produce Joule heat by RF dissipation power during operation, and the heat will induce the increase of the cavity temperature, if there is no efficient cooling it will lead to thermal deformation of the cavity geometry [2]. If the thermal deformation is too large, it will lead to the detuning of the cavity. So an efficient water cooling system is necessary for the CW RFQ stable operation. For our four vane type cavity, the cooling system consists of 12 longitudinal coolant passages in four-vanes, side walls and end walls. The distribution of the coolants is shown in Fig. 2. The multi-physics simulations are based on this model, and the cavity is analyzed to ensure the temperature rise and frequency shift are both at an acceptable level.

The true operation condition is variable, parameterization analyses is more believable on simulation of the various conditions. Parameterization analyses is useful as it can help to determine the RFQ's sensitivity to these actual conditions and can give us a reference on how to adjust the cooling water temperature when the RFQ cavity is under RF power training and beam commissioning.

2 Multi-physics analysis procedure

The multi-physics analysis is an iterative procedure including RF electromagnetic, thermal and mechanical analyses [3]. In our case, the 1/4 part of the section is simulated considering the symmetry of the structure as shown in Fig. 3. The model in the simulation is a 3-D slice of one quarter of the RFQ cross section, and the thickness is 1 mm in the z direction. The finite element code ANSYS [4] is used to solve such a problem. The simulation procedure is described below.

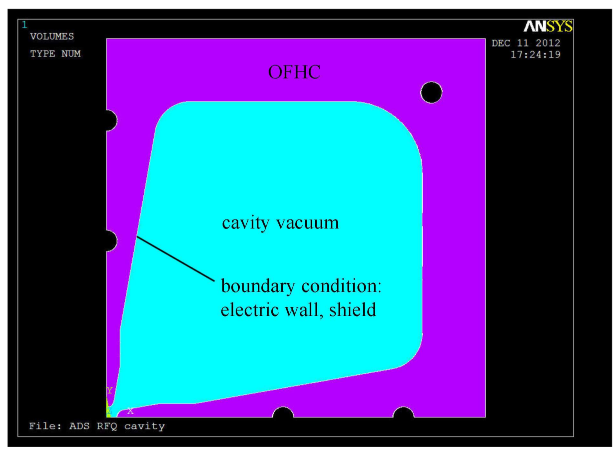

Fig. 3. (color online) The RFQ model and boundary conditions of RF simulation in ANSYS.

2.1 The radio frequency analysis

The geometry of the RF cavity is determined by the MWS [5] code. In the RF simulation, the RF frequency is 162.397 MHz of the complete 3-D model, including a Pi-mode stabilization loop, tuner periods, cut-backs tuning [6]. Firstly, the RF simulation is done by the ANSYS code. The boundary condition is the electric wall and shield as shown in Fig. 3.

The results of ANSYS and MWS codes are listed in Table 2 and they agree with each other very well.

So the heat distribution can be applied to the cavity walls for the subsequent thermal simulation.

Table 2. The results comparison between ANSYS and MWS.

code	frequency/MHz	Q-factor
MWS	162.569	16861
ANSYS	162.571	16848

2.2 Thermal analysis

The boundary condition is the heat convection between the water and the cavity. The convection coefficient for the water cooling is evaluated prior to the simulation by the following formula [7]:

$$h=\frac{k}{D}Nu_{\mathrm{d}}, \tag{1}$$

where k is the thermal conductivity of the fluid, D is the channel diameter, and Nu_{d} is the Nusselt number, which is calculated using Eq. (2).

$$Nu_{\mathrm{d}}=0.023Re_{\mathrm{d}}^{0.8}Pr^{0.4}, \tag{2}$$

Re_{d} is the Reynolds number, which is the measure of relative strength of the inertial and viscous forces in a fluid flow and can be evaluated according to Eq. (3).

$$Re_{\mathrm{d}}=\frac{\rho vD}{\mu}, \tag{3}$$

ρ is the fluid density, v is the fluid velocity, and μ is the dynamic fluid viscosity. And Pr is the Prandlt number, which is related to the material property.

In the simulation, the input RF power is the nominal value 83.5 kW. The environment temperature and the cooling water temperature are both set to be 20 ℃ and the cooling water velocity is 2.29 m/s. Fig. 4 shows the temperature profile of the calculated temperature distribution under the above-mentioned conditions, and we can see the maximum temperature is 24.9 ℃ and is located at the vane tips.

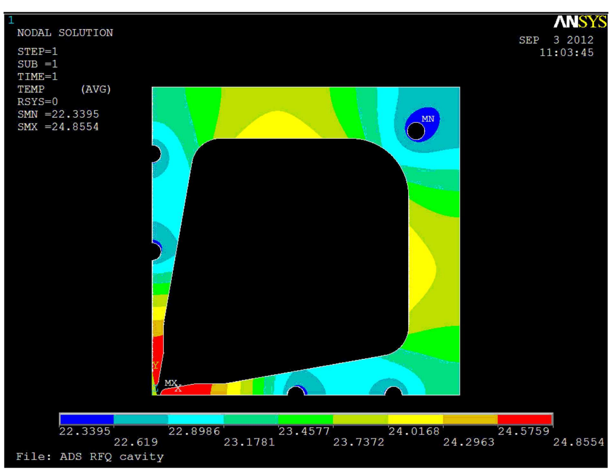

Fig. 4. (color online) Temperature profile of the RFQ simulated with ANSYS. The results are obtained with the 83.5 kW RF power.

2.3 Mechanical analysis

The temperature profile simulated in step 2 is used as boundary conditions for mechanical analysis. In the ANSYS code the thermal result can be coupled to mechanical analysis. Nodal temperatures are applied to the calculation of expansion. The mesh elements should be changed from the thermal element SOLID87 to the structure element SOLID187. The symmetry boundary conditions and the co-planar condition are applied to the appropriate surfaces. These conditions allow for axial growth of the RFQ cavity and accurate prediction of axial stresses. Also, the water pressure is applied to the surface nodes in the cooling channels and the vacuum pressure is applied to the surfaces of the inner cavity walls.

Determining the displacements due to the temperature load is essential for estimating the frequency shift of the cavity when it is in operation mode. Fig. 5 shows the displacement vector sum due to the thermal, vacuum

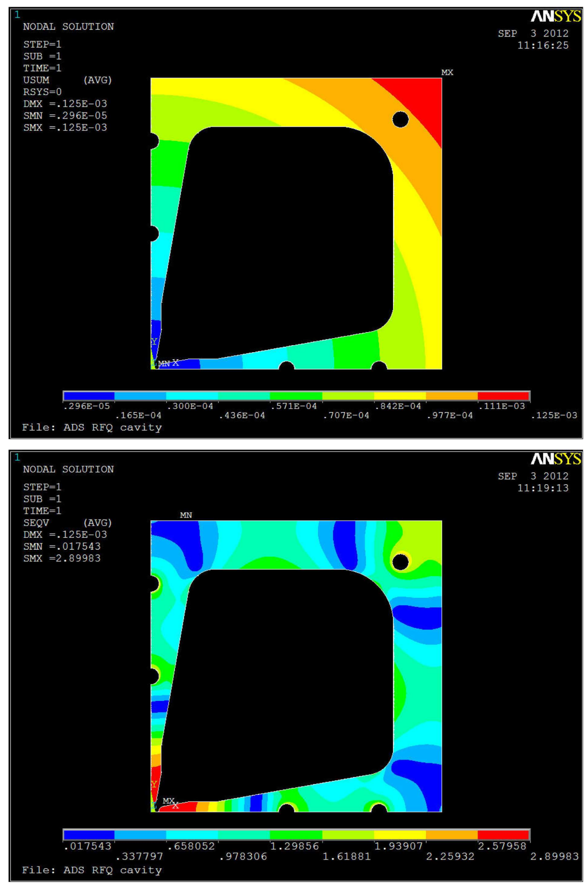

Fig. 5. (color online) The RFQ displacement vector sum and RFQ von-Mises stress (MPa). The above picture shows the displacement distribution, and the lower one shows the stress distribution. The simulation results correspond to the 83.5 kW input RF power.

and water pressure loadings. Overall displacement in the cavity is small, with a maximum of 125 μm at the farthest corner, opposite the vane tips. At vane tips, the displacement range is 3 to 16 μm, which is quite small as well. The maximum stress in the model is calculated as 2.9 MPa, which is far below the yield strength of OFHC.

2.4 Final RF analysis

Calculating the maximum frequency shift of the RFQ depends on the deformed cavity vacuum. The final RF analysis couples the structural result back to the HF electromagnetic analysis to determine the frequency shift of the RFQ after it reaches a steady operating condition. The deformed RF cavity geometry is used for this simulation by employing the mesh morphing method, which moves the cavity nodes such that they correspond to the structural displacements, which are evaluated in the structural simulation. Compared with the calculated frequency in the first step, the frequency shift of the cavity is 108 kHz.

3 Parameterization analyses

In the real situation, the cool water system will not work just as the designed value, the cooling water condition and cavity status parameterization analyses are necessary. In this section, the input power of cavity, cooling water temperatures and water velocities are varied to examine how they affect heat dissipation and result in a frequency shift of the cavity. The results under different conditions are illustrated in the following. The base boundary conditions: environment temperature and cooling water temperature are set to be 20 ℃, and cooling water velocity is 2.29 m/s. There is one note that the frequency shift is set to be zero when the cavity is under the base boundary condition.

3.1 Water velocity effect

In our water cooling system, the water channel in the vane and walls are controlled separately. The effect of wall and vane cooling water on the frequency shift are plotted in Fig. 6. From the figure, we can see that when the water velocity changes from 2 m/s to 2.7 m/s, the frequency shift is smaller than 6.0 kHz, which is below the band width of the RFQ cavity.

3.2 Input RF power effect

In the analysis, the cavity temperature increase, maximum displacement, maximum stress and frequency shift caused by input RF power are studied. In Fig. 7, the cavity temperature increase, maximum displacement, and maximum stress all vary linearly with the input RF power, while the frequency shift is inverse. This is because the cavity dimension will enlarge slightly which will induce the cavity frequency decrease. The frequency shift is less than 10 kHz between cold and full power cavities. The simulation can also give us a reference to reduce the reflecting power by changing the frequency of the power amplifier.

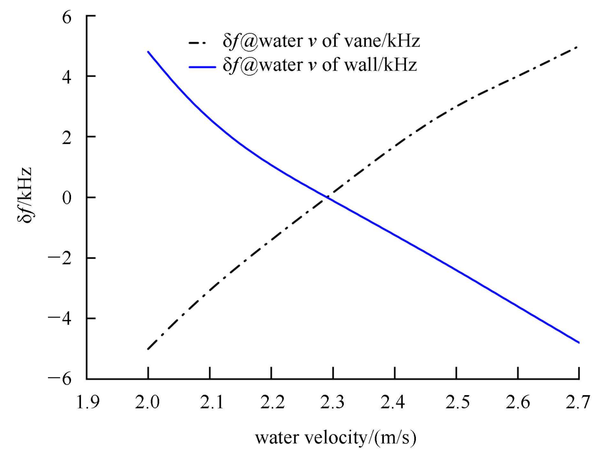

Fig. 6. Relations between cavity frequency and water velocity at the nominal input RF power 83.5 kW.

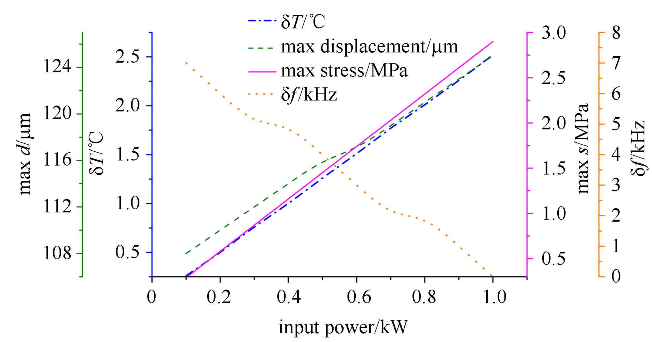

Fig. 7. (color online) Relationships between input power and temperature increase, maximum displacement and stress, and frequency shift under the boundary conditions that the environment temperature and cooling water temperature are set to be 20 ℃, and the cooling water velocity is 2.29 m/s.

3.3 Cooling water temperature effect

The effects of cooling water temperature from vane, wall and total are separately shown in Fig. 8. From the figure, it can be seen that the frequency decreases at a ratio of -16.125 kHz/℃ with increasing the temperature of cooling water in the vane, while the effect from cooling water in the wall is inverse at a ratio of 12.875 kHz/℃. The frequency drift from the total cooling water change goes down at -3 kHz/℃. From the simulation, the frequency drift is more sensitive to the cooling water in the vane. This gives us a guide that the wall water temperature will be fixed to adjust the vane water to tune the cavity frequency.

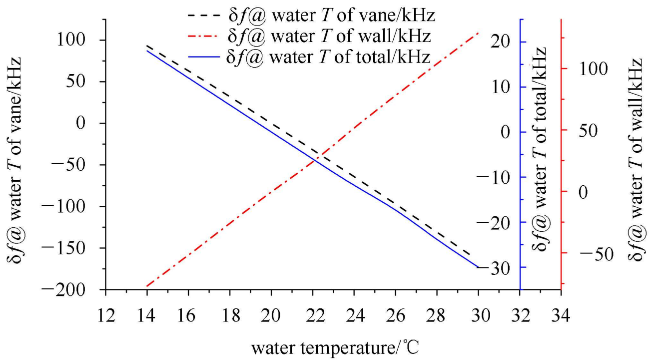

Fig. 8. Frequency shift responding to water temperature with the 2.29 m/s cooling water velocity and 83.5 kW input RF power.

4 Conclusion and outlook

The processes of multi-physics analysis are presented in this paper. The analysis processes can also be used in the other room temperature RF structures. The parameterization analyses of input power, cooling water temperature and velocity are studied. The results show that the cooling water system can meet the requirements of RFQ cavity operating at full power. Also from the parameterization analysis, we can get reference of tuning the cavity at RF power training and beam commissioning.

The 2-D simulation has been done, more accurate 3-D model simulation will be simulated and studied in the further work.

One of the authors Wang Jing would express her sincere thanks to Andrew Lambert(LBNL) for his useful talk and suggestion on the use of ANSYS code.

References

1 ZHANG Zhou-Li, HE Yuan, SHI Ai-Min et al. Design of a Four Vane RFQ for China ADS Project. Proceedings of LINAC2012. Tel-Aviv, Israel, 2012. 942–944
2 PENG Zhao-Hua, GUAN Xia-Ling. Atomic Energy Science and Technology, 2005, **39**(2): 160–163 (in Chinese)
3 WU Xi, YUAN Ping, HE Yuan. Chinese Physics C, 2011, **35**(10): 952–954
4 ANSYS. Inc. Canonsburg, Pennsylvania, USA. www.ansys.com
5 http://www.cst.com/
6 ZHANG Zhou-Li, HE Yuan, ZHANG Bin et al. Study of Influence of Radial Matcher Section End Shape on RFQ Cavity Frequency. Chinese Physics C, 2014, **38**(7): 077007
7 YANG Shi-Ming, TAO Wen-Quan. Heat Transfer. The Fourth Edition. Higher Education Press, 2006. 197–218