MULTI-PHYSICS ANALYSIS OF A CW FOUR-ROD RFQ *

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Abstract

The new injector SSC-LINAC is under design and construction to improve the efficiency and intensity of beams for the Separated-Sector Cyclotron (SSC). This will be accomplished with a normal conducting radio-frequency quadrupole (RFQ) accelerator. To match with the SSC, the RFQ must be operated on Continuous Wave (CW) mode with a frequency of 53.667 MHz. A four-rod structure was adopted for small dimensions of the cavity. While, it was a huge challenge on CW mode. A multi-physics theoretical analysis, including RF, thermal, structural and frequency shift coupling analysis, have been completed in response to the security and stable operation of the RFQ. The experimental measurement of frequency shift was also completed, which is consistent with the simulation. In this paper, the results of theoretical analysis and experiment are reported in detail.

INTRODUCTION

To achieve excellent performance in nuclear and atomic physics, the Heavy Ion Research Facility in Lanzhou (HIRFL) was upgraded successfully with a multifunctional Cooler Storage Ring (CSR) [1]. As the only injector of the HIRFL, the Sector Focusing Cyclotron (SFC) has to provide ion beams for both SSC and CSR. The SSC has to be shut down when the SFC provides the beams to the CSR, which causes the low utilization of the HIRFL. Furthermore, a higher beam intensity, which cannot be satisfied by the SFC, is required by several new experiments such as the super heavy element and precise mass measurement experiments. In order to solve the two problems, a linear accelerator called SSC-LINAC was proposed as a new injector of the SSC to replace the SFC [2]. The SSC-LINAC consists of a superconducting high-charge-state electron cyclotron resonance (ECR) ion source, a low energy beam transport (LEBT) line, a four-rod RFQ, a medium energy beam transport (MEBT) line, three DTLs and a high energy beam transport (HEBT) line [3], as shown in Fig. 1.
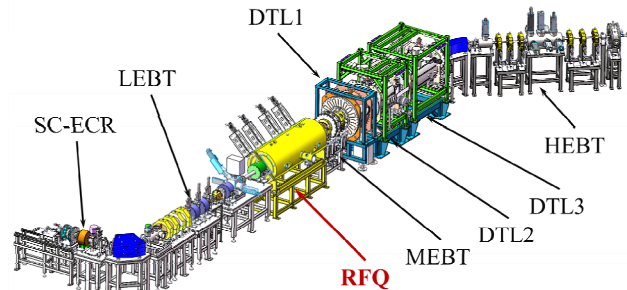

Figure 1: Layout of the SSC-LINAC.

The RFQ accelerator is a critical component of the SSC-LINAC. It accelerates intense beams and operate in CW mode, which was the greatest challenge for a four-rod structure. To control the emittance growth and beam losses caused by intense beams, a quasi-equipartitioning design strategy was applied in beam dynamics [4]. The main parameters of the RFQ are listed in Table 1. Furthermore, cooling channels design have been finished carefully. The bottom plate, stems and mini-vanes are all cooled by deionized water to ensure the CW mode operation [5].

Table 1: Main Parameters of the SSC-LINAC RFQ [4]

Parameters	Values
Frequency	53.667 MHz
Ratio of Mass to Charge	3~7
Design Beam Current	0.5 pmA
Input Energy	3.728 keV/u
Output Energy	143 keV/u
Inter-Vane Voltage	70 kV
Cavity Length	2.527
Transmission efficiency	94.1%

MULTI-PHYSICS THEORETICAL ANALYSIS

To demonstrate the security and stable operation of the RFQ, a multi-physics theoretical analysis was finished by using the Computer Simulation Technology (CST) [6] code. The analysis consists of RF, thermal, structural and frequency shift coupling analysis. The RF analysis determine the power losses of the RFQ cavity. In the thermal analysis, the power losses are used as heat loads to determine temperatures. Displacements and stresses are deter-

mined by the structural analysis with temperatures and pressure boundary conditions. A frequency shift is obtained in the second RF analysis with displacements. The effects of the coupler and the plungers were ignored in the multi-physics analysis to get more efficient.

RF Analysis

To match with the SSC and get a high accelerating gradient, the RFQ frequency was chosen as 53.677 MHz, which is four times of the SSC. A four-rod structure is very suit for this frequency, because of its small dimensions. It consists of a cylinder wall, 4 mini-vane rods, 12 stems and a bottom plate, as shown in Fig. 2.
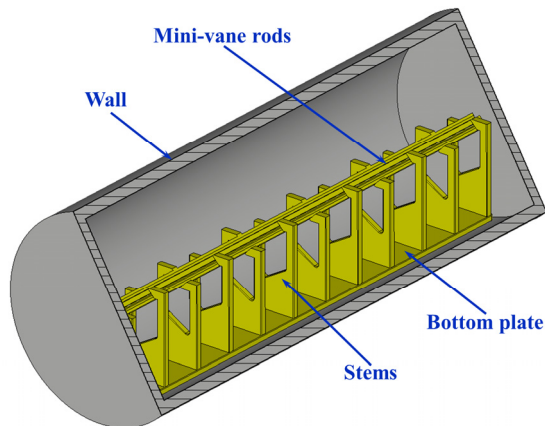

Figure 2: The CST model of the SSC-LINAC RFQ for the multi-physics analysis.

The RF analysis was completed to get the RF power loss fields on cavity surfaces, which is determined from the magnetic field distribution. Figure 3 shows RF simulation results of surface power loss. These fields are used as the heat loads on to the thermal model. A RF power of 30 kW is needed to accelerate ion beams with a mass-to-charge ratio of 7, such as $^{238}U^{34+}$ beams.
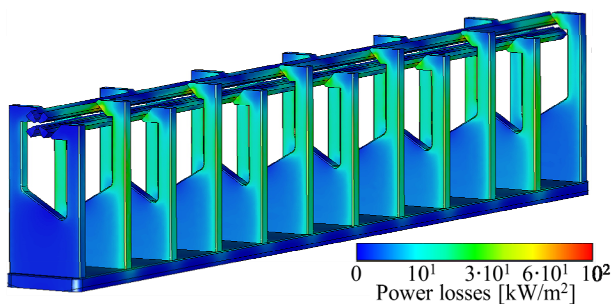

Figure 3: The power loss distribution of the cavity with a total power loss of 30 kW.

Thermal Analysis

In the thermal analysis, heat loads of the cavity, cooling channels and convection coefficients of cavity surfaces must be determined at the first step.

RF power loss fields were transferred to the thermal model and applied to the surfaces as heat loads. Power losses of cavity parts are shown in Fig. 4.
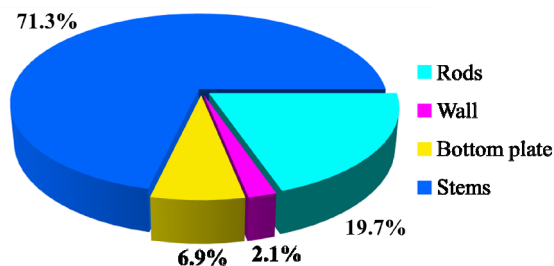

Figure 4: Power losses of cavity parts [7].

As shown in Fig. 5, cooling channels of the cavity consist of two parts: one part is the cooling channel of four rods, and the other is the cooling channel of the bottom plate and stems. The heat load of the cylinder wall account for only 2.1% of the total load. It can be cooled well by the heat transfer between the surface of the cylinder wall and the ambient air. Therefore, the wall has no more cooling requirement.
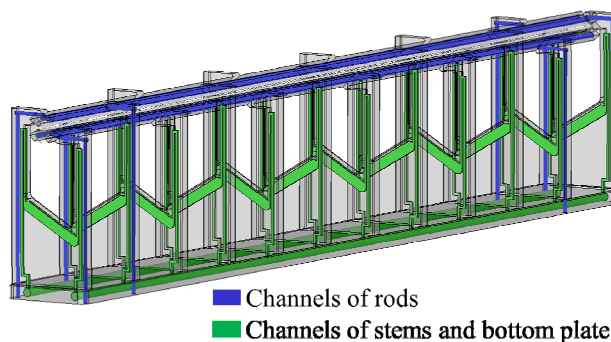

Figure 5: Cooling channels of the cavity.

The convection coefficient of the cooling channels was evaluated by the following formulae [7]:

$$h = \frac{\kappa \bullet Nu}{D} \qquad (1)$$

Where κ is the thermal conductivity of the water, D is the diameter of channels, Nu is the Nusselt number defined as:

$$Nu = \frac{(f/8)(Re-1000)Pr}{1+12.7(f/8)(Pr^{2/3}-1)} \qquad (2)$$

where f is the Darcy friction factor calculated by the following formula:

$$f = (0.79\ln(Re)-1.64)^{-2} \qquad (3)$$

Re is the Reynolds number given by

$$Re = \frac{vD\rho}{\mu} \qquad (4)$$

v is the flow velocity, ρ is water density and μ is the absolute viscosity. Pr is the Prandtl number given by

$$Pr = \frac{\mu C_p}{\kappa} \qquad (5)$$

C_p is the specific heat of water.

The temperature of the ambient air and the cooling water was set to 20℃. Temperatures of the cavity with

kinds of RF powers were simulated in the thermal analysis. Figure 6 shows surface temperature results with a RF power of 30 kW. The maximum temperature is 41.95℃. It exists at the top of stems, where there isn't any cooling channel.
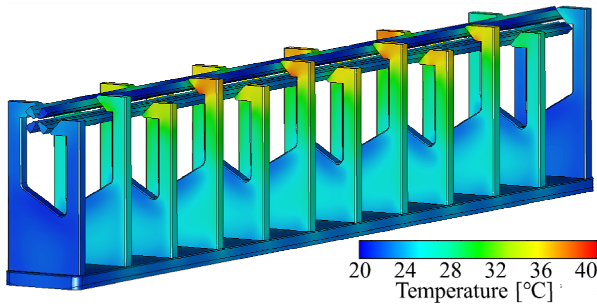

Figure 6: The temperatures of the cavity with a total power loss of 30 kW.

Structural Analysis

The temperatures of the cavity from the thermal analysis were transferred to the structural model. Displacement results are shown in Fig. 7. Displacements caused by the thermal expansion are below 0.105 mm. The stress level is below 14 MPa as shown in Fig. 8. It is safe for full power operation on CW mode.
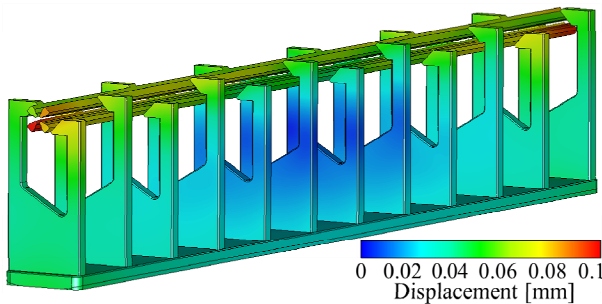

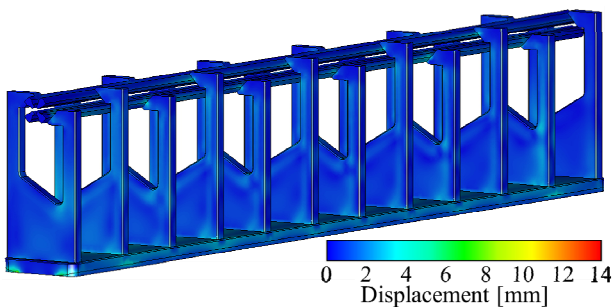Figure 7: Displacement results of the cavity with a total power loss of 30 kW.

Figure 8: Stress contours of the cavity.

Frequency Sensitivity Analysis

The frequency shift, which caused by the change of cooling water temperature and RF power, must be controlled at reasonable range for the stable operation of the RFQ with full power. So, it is necessary to make a frequency sensitivity analysis.

Figure 9 shows the result of frequency shift caused by RF power. A frequency shift rate of -2.48 kHz/kW was obtained by a linear fit. Frequency shifts caused by temperature change of the cooling water were given by Fig. 10. The frequency shift rate is -1.06 kHz/℃.

A RF power of 35 kW with an appropriate margin and a water temperature variation range of ±5 ℃ were used to evaluate the total frequency shift, which was -97.4 kHz. The shift can be tuned by automatic RF controlling system with a maximum tuning capacity of 191.5 kHz, so that the RFQ can operate with a stable resonance frequency.
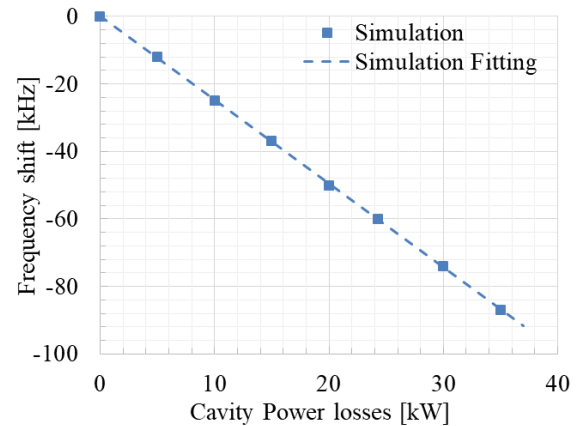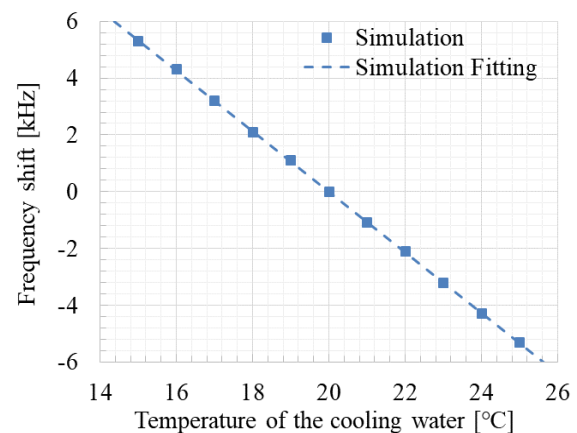

Figure 9: Frequency shift caused by RF power.

Figure 10: Frequency shift caused by temperature change of the cooling water.

FREQUENCY SHIFT EXPERIMENT

The frequency shift experiment has been finished during the RF power conditioning. Figures 11 and 12 show results of frequency shift measurements. Frequency shift rates caused by the RF power and the temperature change of the cooling water were -2.58 kHz/kW and -0.987 kHz/℃, respectively. Comparing with simulation and experiment results, the deviation value of Frequency shift rates caused by the RF power is less than 5%. Frequency shift rates caused by the temperature change of the cooling water agreed well with the simulation ones within less

than 7% relative error. this proves that multi-physics simulation results with the CST code is credibFle.
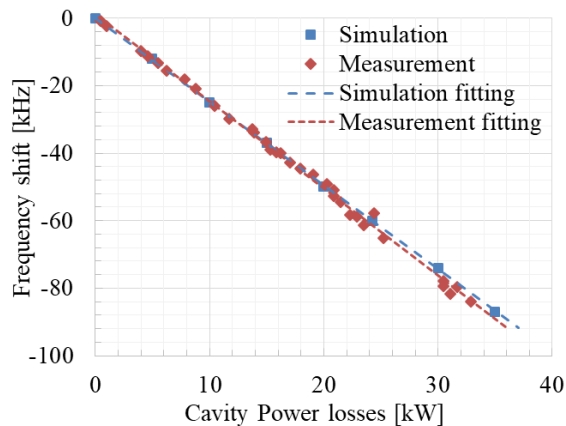

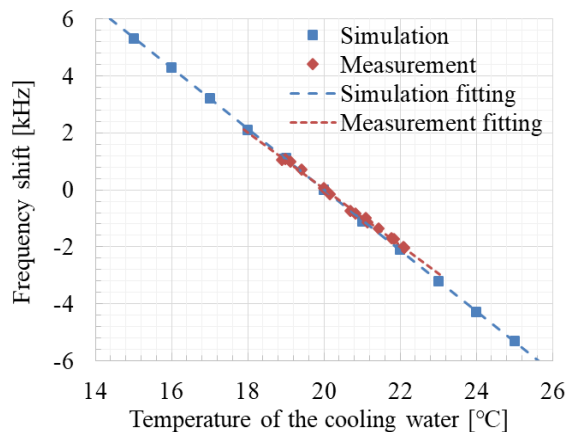Figure 11: Comparison of frequency shift caused by RF power in simulation and measurement.

Figure 12: Comparison of frequency shift caused by temperature change of the cooling water in simulation and measurement.

CONCLUSION

A multi-physics theoretical analysis, including RF, thermal, structural and frequency shift coupling analysis, was finish for the CW four-rod RFQ of the SSC-LINAC by using the CST code. Displacements caused by the thermal expansion are below 0.105 mm. The stress level is below 14 MPa, which is safe for full power operation on CW mode. A total frequency shift caused by the change of cooling water temperature and RF power is below 100 kHz, which can be tuned by automatic RF controlling system in stable operation. The experimental measurement of frequency shift was also completed, which agreed with the simulation within less than 7% relative error. This can verify the reliability of the CST code.

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