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ARTICLE

Cooling simulation of RFQ linac with three-layer structure for high duty cycle operation

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To realise a high duty cycle radio frequency quadrupole linear accelerator (RFQ linac), it is important to design an appropriate cooling path. Especially in a four-vane type RFQ linac, heat is concentrated at both ends of the vane electrodes. This local temperature rise causes a shift in resonance frequency and distortion of the electric-field distribution. We believe that a three-layered RFQ cavity is advantageous for such high power loading, because cooling channels can be formed close to both ends of the vane electrodes. A thermal analysis of an RFQ cavity with this structure was performed by multiphysics simulation. A 200 kW of heat generation, which is equivalent to 100% duty cycle operation, was assumed. The maximum temperature at the end of the vane was 165 °C and the maximum elongation along the beam axis was 0.197 mm. The observed resonant frequency shift was 0.127 MHz, well within the tunable range. These results indicate the feasibility of CW operation in a three-layer, four-vane RFQ cavity.

Keywords: RFQ linac; three-layer structure, cooling simulation, multiphysics simulation

1. Introduction

Nowadays, high-duty factor linear accelerators have been widely used for medical applications, including medical isotopes, eg Astatine-211 for α-ray therapy [1, 2] and for boron neutron capture therapy (BNCT) [3]. For example, the RFQ for BNCT, assuming a lithium target, requires proton acceleration to about 2.5 MeV. In this case, the total length of the cavity would be about 3 meters, and heat loss of approximately 200 kW is assumed. If the acceleration current is 20 mA, the combined beam power would require a continuous RF output power of 250 kW or more. To obtain a high beam power, a high duty factor operation of the accelerator system is necessary since available peak beam current is restricted by a space charge limit. Sometimes, continuous wave (CW) operation is demanded. To cope with this situation, Tokyo Institute of Technology (TITech) and Time Inc. have developed a three-layer structure cavity of four-vane type RFQ that can be operated at a high duty factor [4, 5, 6].

Figure 1 shows a conceptual diagram of the RFQ. The three-layers of an RFQ comprise Upper Minor Vane, Major Vane, and Lower Minor vane. The Major Vane has two vanes and the Minor Vane has one vane. The Major Vane is sandwiched between two Minor Vanes and assembled with bolts. The structure enables us to easily assemble and disassemble the cavity. Because, this structure does not require brazing, welding, or other thermal processing, the cost and fabrication period can be suppressed. Each vane tip position can be precisely controlled by the machining process and it is possible to have fine adjustment of resonance frequency and electric field distribution by applying additional machining after the fabrication. Another important feature of this structure is that the cooling channels can be machined directly from the outside of the cavity. This approach dramatically increases the degree of freedom in designing the channels.

One of four-vane type RFQ cavities with three-layer structure is currently in operation in the RANS-II system at RIKEN[4], which started operation in July 2019, with a resonance frequency of 200 MHz and a length of 2.5 m. Recently, another 200 MHz 3 m long RFQ with a duty of 5% at 200 kW of wall loss was constructed and successfully commissioned at Mirrotron in Hungary [5]. It has been proven that several percent of duty factor works fine. However, it is necessary to investigate how much duty this structure can withstand and whether CW operation is possible. To verify the heat load of the three-layer structure, thermal analysis was carried out by using CST STUDIO SUITE (CST)[7].

2. Design of the four-vane RFQ with three-layer structure

2.1. RFQ models for thermal calculations

To perform the calculations, a three-dimensional model with simplified geometry based on the manufactured RFQ provided to Hungary was created. The four-vane type RFQ consists of four electrodes, called vanes, arranged symmetrically in the vertical and

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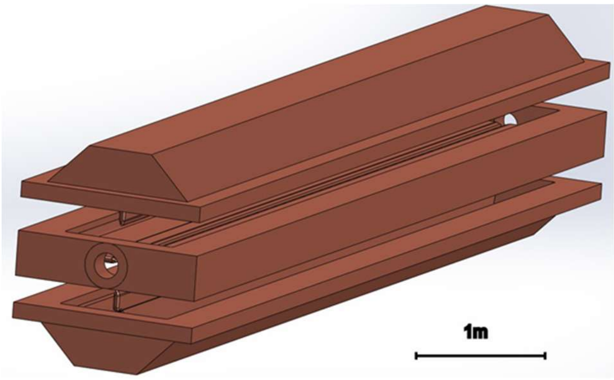

Figure 1. Overview of the four-vane RFQ cavity with three-layer structure.
The RFQ was designed on a joint patent [6] by the Tokyo Institute of Technology and TIME co., Ltd.

Figure 2. The internal structure of the RFQ.

horizontal directions relative to the beam axis. The passage of inductive flux is adjusted by optimising the dimensions of the area between the ends of those vanes and the end plates, called end cut, and the voltage between the vanes is typically kept constant along the beam axis. **Figure 2** shows the cross sectional structure of the RFQ.

The electric field distribution was designed to have a variation of ±3% along the beam direction. The resonant frequency of the RFQ was adjusted to 200 MHz. The average aperture diameter was modeled to be 5.57 mm and the inter vane voltage was simulated at 105 kV (corresponding to a Kilpatrick value = 1.71). A 200-kW wall loss obtained from the electromagnetic field analysis corresponds to the heat generated during CW operation. The vane length occupies 2884 mm of 3.0 m total cavity length. Unlike the actual RFQ, this model has a simplified structure. Both ends of the vanes are identical structure on the incoming and outgoing sides, and there is no modulation at the vane tips. The interior corners of the RFQ are not rounded to allow for a shorter computation time.

2.2. Multiphysics analysis approach

To achieve stable operation, it is necessary to avoid the effects of deformation of the vane caused by localized heat generation, which can lead to a shift of resonant frequency and distort of the electromagnetic field distribution. Therefore, the main challenge was the cooling of the vanes; the largest heat generation point in the RFQ was at the end of the vane in the model. To investigate the effect of flow rate and velocity in the cooling channel on vane deformation, electromagnetic analysis was followed by thermal and structural analysis.

The calculation procedure involves calculating the heat generated by wall losses from the electromagnetic field distribution on the copper surface at the inner surface of the RFQ and loading it into a thermal analysis model. This model includes a temperature distribution that is used to calculate stresses and deformations. Since heat generation is a factor in deformation, CST's Conjugate Heat Transfer Solver (CHT) was used to simultaneously analyze heat conduction and convection using Computational Fluid Dynamics (CFD) techniques.

3. Design of cooling channels

The cooling channels should be optimized to minimize local deformation and stress on the vanes and RFQ cavities. In previous study examples, the RFQ's, outer wall and inside the vane are equipped with a linearly shaped channel [8, 9,10,11]. On the other hand, this model aims at efficient cooling by increasing the contact area of the cooling water in the limited interior of the vane.

The thickness between the cooling channel and inner surface of the cavity was designed to be no less than 7 mm, similar to the 5% duty RFQ channel [5]. Due to the thin thickness of the vane near tip, the channel cannot be made in the tip region. However, the heat exchange point is close enough to the heat-dispersed area, the tip of the vane can be cooled efficiently. Two separate cooling channels were assumed per vane, for a total of eight channels. The

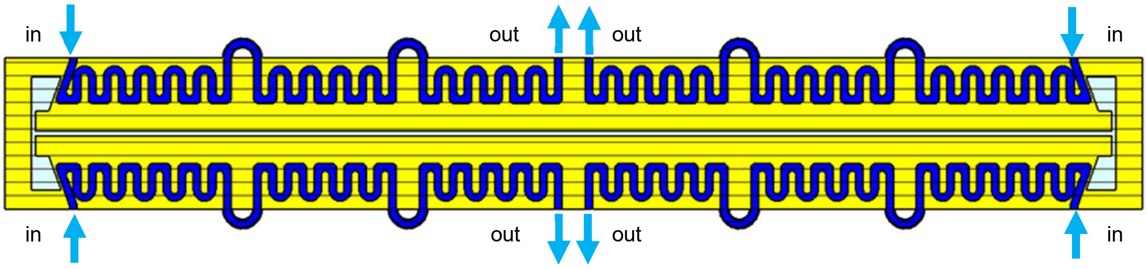

Figure 3. Water cooling channels and flow directions.

cooling water enters from the edges of the vane and flows toward the center of the RFQ. **Figure 3** shows the cooling channels. The diameter the channels was determined as 20 mm, to avoid the flow in the channel become turbulent (Reynolds number Re $\geqslant$ 2300). As the maximum flow velocity, the equivalent range of 4.6 m/s is assumed, which was reported by the Argonne National Laboratory for the CW RFQ (ATRAS [11]).

4. Cooling simulations for CW operation

Thermal analysis was performed with the CST CHT solver and stress analysis was performed with the CST mechanical solver. The temperature distribution, the flow velocity, and the vane tip stretch were simulated for cooling water flow rates of 30 l/min, 50 l/min, and 70 l/min at 20°C in a system with a wall loss of 200 kW and an initial RFQ temperature of 20°C. The RFQ material was assumed to be copper, the cooling fluid was water, and there was a vacuum inside the RFQ. This analysis also included the effect of gravity.

Table 1. Thermal and structural analysis result CST (200 kW)

Flow rate, l/min	30	50	70
Max temperature, °C	179	165	156
Max velocity, m/s	3.2	5.3	7.4
Velocity (outlet), m/s	1.6	2.3	3.4
Max absolute deformation, mm	0.291	0.213	0.207
Water temperature (outlet), °C	54.2	29.4	27.5
Frequency shift, MHz	-0.154	-0.127	-0.113

The results are shown in **Table 1**. The cooling water flow rate of 30 l/min is within a safe range of the flow velocity, however the cooling water temperature rise is 34.2°C which seems a high value, indicating insufficient cooling. In the case of cooling water flow rates of 70 l/min, the flow velocity is too high and there is concern about erosion. At a cooling water flow rate of 50 l/min, the maximum flow velocity was as high as 5.3 m/s in some areas, but overall the flow velocity was 2.3 m/s, which seems to be acceptable for cooling.

Figures 4 and **5** show the temperature distribution and the flow velocity distribution with a cooling water flow rate of 50 l/min. The temperature at the end of the tip of the vane, in the centre of the vane, and at the outer wall of the RFQ was 165°C, 60°C, and 30°C, respectively. The temperature rise is below 9°C. The deformation distribution is shown in **Figure 6**. The maximum translated point was at the edge of the vane. Each component of the vane displacement was 0.055 mm for the y axis and 0.197 mm for the z axis. There is no significant local displacement in the outer wall of the cavity. The shift in resonance frequency was predicted at only -0.127 MHz.

In the actual operating RFQ, interior does not have sharp edges, and each plane is connected by a smoothly curved surface. This is to prevent discharges and local heat stresses. However, the RFQ model for the simulation consists of a polyhedron and no curved connections were applied. This may lead to slightly severer results.can meet the requirements for leakage test of iodine adsorbers. The new method is efficient to evaluate leakage rate of iodine adsorber. It also has advantages of simple operation, low toxicity and damage to people and environment, and good repeatability, and can be used in adsorber routine test and on-site test.

5. Summary

To explore the possibility of CW operation of a three-layer four-vane RFQ cavity, electromagnetic, thermal, and structural analyses using CST were performed from the point of view of heat load. This structure can form flexible and efficient cooling channels near the vane ends. The RFQ model for the calculations assumed two cooling channels per vane, for a total of eight channels. Assuming a heat generation of 200 kW, which corresponds to operation at 100% duty cycle, a cooling water flow rate of 50 l/min was shown to be appropriate. The maximum flow velocity of 5.3 m/s was observed at the corner of the channel, but the total velocity was 2.3 m/s, which is considered a value that does not cause erosion. The largest temperature increase was observed at both ends of the tip of the vane, reaching 165°C. The temperature distribution in the center of the vane was about 60°C, and that on the exposed outer wall was about 30°C. The temperature rise except at both ends of the vane is in the safe range. The maximum displacement was 0.197 mm at the edge of the vane, as well as the temperature rise, in the beam direction. The resonant frequency shift caused by the deformation was -0.127 MHz, which is within the tunable range for normal operation. Furthermore, it is possible to modify the predicted displacement in advance during cavity machining process to achieve the design dimensions during CW operation.

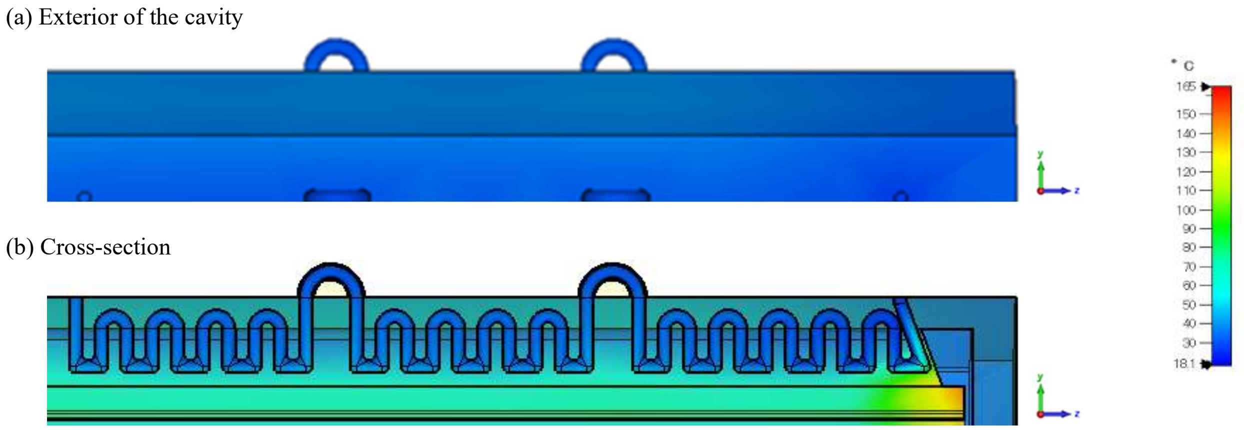

Figure 4. Temperature distribution (flow rate: 50 l/min).

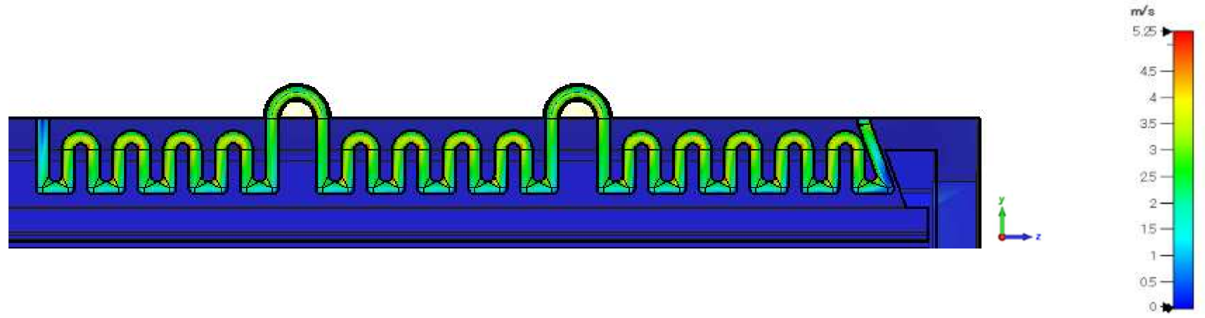

Figure 5. Distribution of flow velocity (flow rate: 50 l/min).

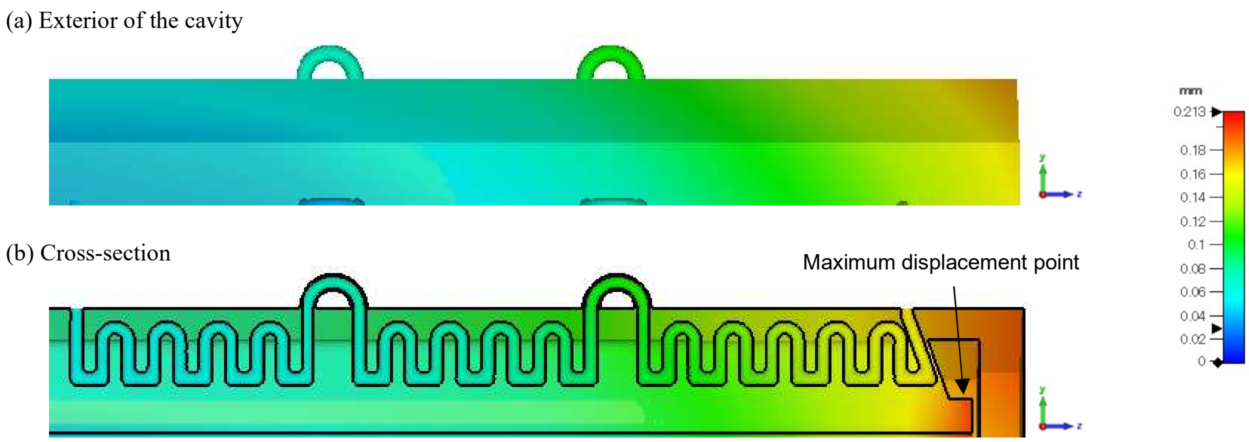

Figure 6. Distribution of displacements (flow rate: 50 l/min).

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