THERMAL CHARACTERISTICS OF A NEW RFQ FOR J-PARC

Y. Kondo*, K. Hasegawa, T. Morishita, JAEA, Tokai, Naka, Ibaraki, 319-1195, Japan
H. Matsumoto, F. Naito, KEK, Oho, Tsukuba, Ibaraki, 305-0801, Japan

Abstract

A new RFQ for the J-PARC linac is under construction. The resonant frequency tuning of this RFQ during operation will be performed by adjusting the temperatures of the cooling water channels. Steady state and transient thermal analyses with FEM codes have been carried out to investigate the tunability of this RFQ.

INTRODUCTION

A new RFQ for J-PARC is now under construction[1]. This RFQ is being built as a spare of the operating RFQ[2], therefore the specification is almost same as the existing one, as shown in Table 1. In this paper, we refer the new RFQ as RFQ II, whereas the operating RFQ as RFQ I.

Table 1: Main parameters of RFQ II.

Beam	H^-
Resonant frequency	324 MHz
Injection energy	50 keV
Extraction energy	3 MeV
Peak beam current	30 mA
Repetition	25 Hz
RF pulse length	600 μs
Duty	1.5 %

RFQ II consists of longitudinally segmented 3 units, and the vane lengths are 1057.2 mm, 1053.6 mm and 1052.3 mm, respectively. The fine tuning of the resonant frequency is performed by adjusting the temperature of the cooling water, like other RFQ's such as LEDA[3] and SNS[4]. RFQ II has two types of cooling-water channels, one is for vanes and the other is for cavity wall. For the simplicity, we are assuming to change the water temperature of one type. To investigate the frequency response to the water-temperature change, the Finite Element Method (FEM) analyses have been performed. The nominal repetition rate of RFQ II is 25 Hz, but the final requirement of the J-PARC linac is 50 Hz [1]. Therefore, we considered the 3 % duty case, in addition to the 1.5 % duty case.

ANALYSIS PROCEDURE

The temperature distribution and deformation due to the heat loading of the RFQ were analyzed with ABAQUS[5]. Figure 1 shows the temperature distribution with 3 % RF duty factor obtained with ABAQUS.

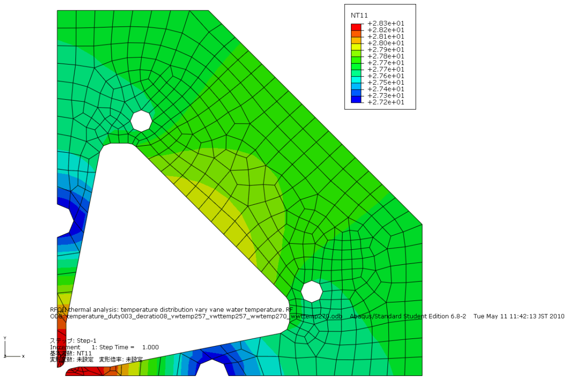

Figure 1: Temperature distribution obtained with ABAQUS. The duty factor of the induced RF power is 3 %. The water temperature of the vane channel is 25.7 °C and that of the cavity-wall channel is 27.0 °C.

The heat load on the cavity surface was obtained from the calculated power dissipation with SUPERFISH[6]. The power dissipation of each segment was divided by an empirical degradation factor 0.8 and multiplied by the duty factor to be the heat load. Total power dissipation from the SUPERFISH calculation is 912 W/cm.

RFQ II is equipped with 4 vane cooling-water channels and 8 cavity-wall cooling-water channels, as shown in Figure 1. In Table 2, the properties of the cooling-water channels are summarized.

Table 2: Summary of the cooling-water channels.

	vane	**cavity wall**
Diameter (mm)	15	10
Flow speed(m/sec)	2	2
Flow rate (l/min/channel)	21.2	9.4
Number of channels (/unit)	4	8
Flow rate (/unit)	84.8	75.4
Heat convection (W/m^2·K)	7600	8200

Heat-convection coefficients of the cooling-water channels were calculated as followings; heat-convection coefficient h is written as[7]

$$h = \frac{k}{d} Nu_d, \tag{1}$$

where, k is the thermal conductivity of water, d is the diameter of the water channel and Nu_d is the Nusselt number,

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[*] yasuhiro.kondo@j-parc.jp

[1] The 50 Hz operation is required when both the Rapid Cycling Synchrotron (RCS) and the Accelerator Driven System (ADS) for transmutation will be operated

$$Nu_d = 0.023 Re_d^{0.8} Pr^{0.4}. \tag{2}$$

The Re_d is the Reynolds number,

$$Re_d = \frac{\rho u_m d}{\mu}, \tag{3}$$

where ρ is the density, u_m is the averaged flow speed and μ is the viscosity of water.

And Pr is the Prandtl number,

$$Pr = \frac{c_p \mu}{k}, \tag{4}$$

where c_p is the heat capacity at constant pressure.

Subsequently, the displacement of each segments from the initial state, which is 27 °C uniform, was calculated. Then the frequency shift was calculated from the dF/dx and dF/dy obtained with SUPERFISH.

FREQUENCY TUNING RANGE

Figure 2 shows the frequency shifts as functions of the vane-cooling-water temperature and the wall-cooling-water temperature obtained with steady state analyses. In both cases, the frequency ranges are about ± 150 kHz with a temperature range of ± 5°C.

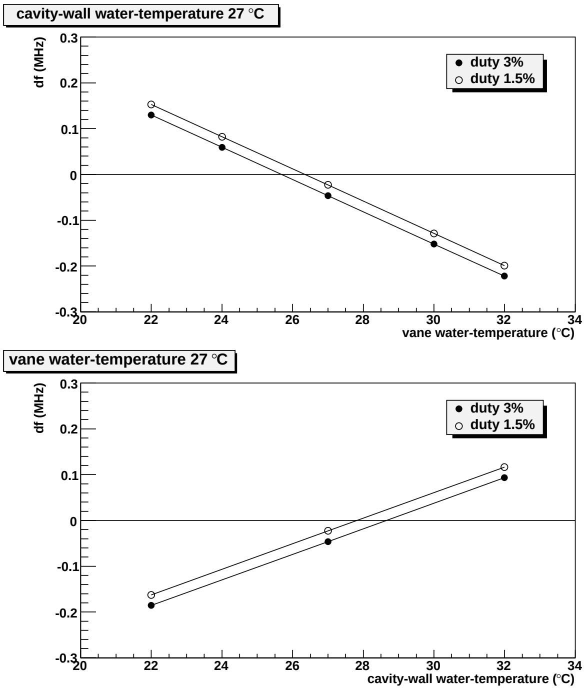

Figure 2: Calculated frequency shifts. The upper figure represents the case of changing the vane-cooling-water temperature and fixing the wall-cooling-water temperature 27 °C. The lower is the case that the wall-cooling-water temperature is changed.

Table 3 is a summary of the frequency shifts, heat loads and temperature rises of the duty 3 % case. For the field stability along the longitudinal direction, it is better to keep the temperature rise along the cooling-water passage low. The three units of RFQ II are individually cooled, therefore, the temperature rises are less than 1 °C in any cases.

TRANSIENT ANALYSIS

If significant changes of heat load occur during the operation, RFQ's are detuned due to the temperature change and some tuning procedure may be necessary. Most typical case is an RF break down, therefore, power-off transient analyses have been carried out.

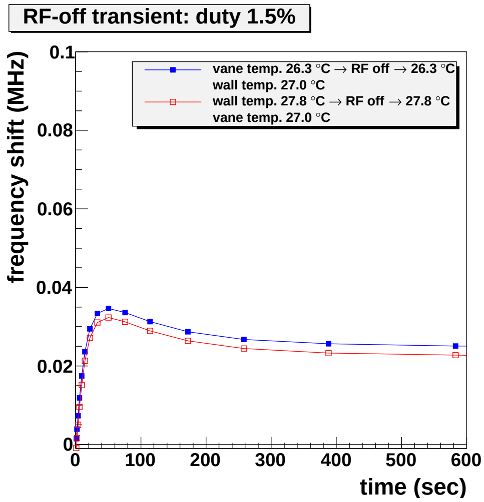

Figure 3: RF-off transient of the 1.5 % duty operation.

Figure 3 represents the power-off transient of duty 1.5 % operation. At time zero, the induced power has been off and even after that, the water temperatures keep the steady-state operation's values. The maximum frequency shift is 35 kHz. The reflection factor Γ can be derived from the frequency shift as following; Γ is written as

$$\Gamma = \frac{Z_L' - Z_0}{Z_L' + Z_0}, \tag{5}$$

where Z_L' is the impedance of the cavity coupled with the transmission line and Z_0 is the characteristic impedance of the line. The Z_L' is

$$Z_L' = \frac{Z_0}{\beta}\left\{1 + iQ_0\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)\right\}. \tag{6}$$

Here β is the coupling factor, Q_0 is the Q-value of the cavity, ω_0 is the resonant frequency and ω is the frequency. The $\omega_0/2\pi = 324$ MHz, β assumed to be 1.5 for RFQ II and Q_0 is typically 8000, thus $|\Gamma|^2 = 0.35$ for $\Delta\omega = 35$ kHz. This is within the limit of the reflecting-power, therefore, in the duty 1.5 % operation, no tuning procedure is necessary in case of the RF break down and the start-up.

On the other hand, in Figure 4, the transient behaviour of the duty 3 % operation is shown. The open and closed squares represent the transient without tuning. This shows

Table 3: Summary of the steady state analysis of the duty 3 % case.

	Vane			**Cavity wall**		
Temperature (°C)	22.0	25.7	32.0	22.0	28.7	32.0
Frequency shift (MHz)	0.130	0.000	-0.222	-0.186	0.001	0.093
Sensitivity (kHz/°C)		-35			28	
Temperature rise (°C/unit)	0.7	0.4	-0.1	0.8	0.2	-0.1

that more than half of the forward power will be reflected and it is better to apply some tuning procedure.

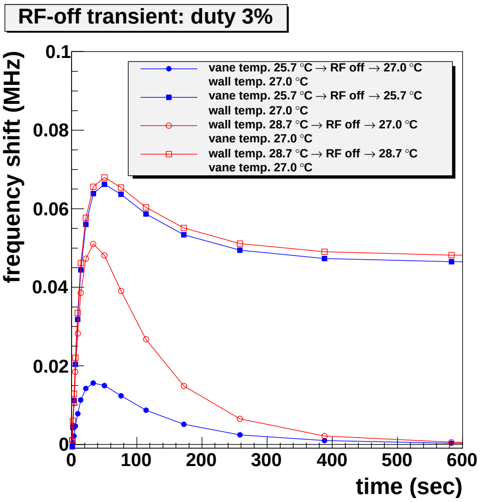

Figure 4: RF-off transient of the 3 % duty operation.

Open and closed circles are represent the transient behaviour with tuning. The RF power is off at time zero, and at the same time, the cooling-water temperatures are changed to 27.0 °C without delay. Open circles are the transient with changing the wall-water temperature. The vanes immediately shrink when the RF is off, on the contrary, the hole RFQ body shrinks slower than the vanes due to the large heat capacity. This causes the large frequency shift around time = 40 s. The LEDA and many other CW RFQ's adopted or are adopting the method changing the wall-water temperature[3]. With this method, if the RF power is reduced, the water temperature should be lowered. This is natural way and matching to the closed-loop cooling-water system. However, for pulse RFQ's, the power dissipation and required cooling power is much smaller than those of the CW RFQ's, thus the time constant of the tuning is longer.

Closed circles in Figure 4 shows the transient of the vane-water temperature changing case. The heat capacitance of the vanes are small, so good tuning response can be obtained. To change the vane-water temperature, the closed-loop cooling-water system cannot be used. One possible way to change the temperature quickly is directory mix the supplied hot and cold water.

COOLING WATER SYSTEM FOR RFQ II

The cooling-water system for RFQ II is now under construction. In Table 4, the specifications of this system are summarized. As described in above section, the dynamic tuning is not needed for duty 1.5 % operation. The set value of the water temperature is variable, but fixed during the operation. This system supplies cooling water to the vane channel or the wall channel. The common cooling-water system to another cavities of the linac is used for the other channel.

Table 4: Specifications of the RFQ II cooling-water system.

Temperature range	22°C ∼ 32°C
Max. cooling power	16 kW
Max. flow rate	300 l/min
Temperature stability	±0.1°C

CONCLUSIONS

Thermal analyses of a new RFQ (RFQ II) for J-PARC have been performed. The tuning range of the resonant frequency by changing the temperature of the cooling water ±5 °C is ±150 kHz. For the nominal duty factor (1.5 %) operation, no dynamic tuning is needed. From these studies, the specifications of the cooling-water system have been decided and it is constructing now.

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