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THERMAL AND STRUCTURAL DESIGN OF AN RF CAVITY FOR A CW MICROTRON

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Abstract

Thermal and structural analysis of an rf cavity for a CW microtron has been carried out. The cavity employs slot coupled 2-cell structure. The resonant frequency and the wall loss of the cavity are 500 MHz and 20 kW per cell, respectively. The frequency shift caused by the thermal deformation is expected to be –129 kHz through the analysis, which can be corrected by movable tuners. The frequency shift caused by room and cooling water temperature changes are also determined. The maximum Von Mises stress is expected to be 31 MPa, which is low enough compared with the yielding stress of copper.

1 INTRODUCTION

High power electron beams are necessary for industrial application: X-rays irradiation and electron irradiation for the processes such as sterilization for medical equipments, SOx and NOx treatments systems of flue gas and food pasteurisation and defect analysis in semiconductors with a slow positron beam. Required energies for the applications are about 5 MeV, 10MeV and higher than 15 MeV, respectively. The required beam power is several tens of kW. Development of accelerators operated in a continuous wave (CW) mode is a key issue for the applications because the accelerators require compactness, low cost and stable operation.

A CW microtron, with a racetrack beam trajectory and a high beam current, is proposed for these fields [1]. New shaped bending magnets are proposed to adjust the beam orbit of each turn and acceleration phases. A 500 MHz normal conducting rf cavity is installed in the straight section.

The rf system of the CW microtron is a core part from the point of view of the power efficiency. The cavity has to be controlled precisely to compensate the change of parameters during the operation. Therefore, the resonant frequency and the frequency shift of the cavity has to be estimated precisely, consequently the thermal deformation of the cavity needs a precise estimate, as well. High power operation may damage the cavity, such as the plastic deformation, crack and so on, due to fatigue of copper. Thus, it is essential to perform an optimum design of the cavity, with suitable values of all parameters based on the detailed analysis using a numerical analysis and so on.

The thermal structural analysis based on a 2D finite element model has been done to estimate the temperature rise of the cavity, rf frequency shift due to thermal deformation and the stress distribution. The optimisation of the cooling system has been performed as well. For all analyses, SUPERFISH and the commercially available finite element method code ANSYS were used in this analysis. This paper describes the results of analyses and the design of the cavity. The designs were mainly done with the parameters of the accelerated energy of 5 MeV.

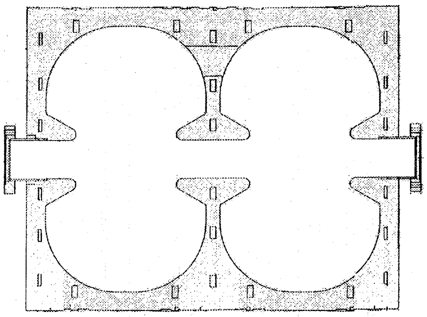

Figure.1 Cross sectional view of the rf cavity

2 DESCRIPTION OF THE CAVITY

Figure 1 shows the cross sectional view of the rf cavity. For simplicity, other parameters such as a vacuum port, a coupler port, and other ports are not shown. The cavity consists of slot-coupled cavities with two cells. The selected resonance frequency of 500 MHz is mainly based on the consideration of input rf power and the total size of the accelerator.

The cavity is designed to operate in the π-mode. Nose cones and rounded shape of the cavity design is applied to make the shunt impedance higher. The material of the cavity is class-1 oxygen free copper so that high electrical and thermal conductivity and low out-gassing rate can be obtained. The design parameters of the cavity are shown in Table 1.

Table 1: General parameters of the cavity

Beam power	30 kW	Cell length	295 mm
Wall loss	40 kW	Outer dia.	500 mm
Radio freq.	500 MHz	Bore dia.	65 mm
Number of cells	2	Gap volt. /cell	0.5 MV

3 THERMAL AND STRUCTURAL ANALYSIS

3.1 RF analysis

A power density distribution of the inner surface of the cavity was calculated by using SUPERFISH with a 2D cylindrical model. Three-dimensional structures such as coupling slots, a vacuum port, a coupler port and other ports were not taken into account in the calculation. Under the calculation, the input power was normalized to satisfy the required gap voltage of 0.5 MV, so that all results of the calculation give an actual value for the cavity design. According to the results, the total rf power dissipation of inner surface of the cavity was about 20 kW, where correction factor due to the fabrication was added, per cell. Figure 2 shows the distribution of the power density obtained from the calculation in which was viewed with ANSYS mesh generation module. The lengths of arrays describe the distribution. The highest loss was about 8 W/cm^2 where is around the nose cone. This power density distribution was applied to the thermal and structural analysis. The shunt impedance Rsh and Q-value of the cavity were also calculated. The results were Rsh=17 MOhm/cell and Q=41000, respectively.

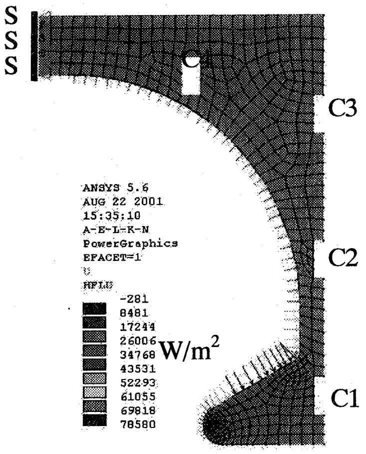

Figure 2 Heat flux distribution of inner surface of the cavity (viewed by ANSYS mesh generator)

3.2 Design of cooling channels

Heat transfer calculations using spreadsheet have been done to determine the optimum cooling channel. Attention was paid to indexes such as the fluid velocity and the maximum pressure drop of the cooling system. Several cases of calculations have been done with varying parameters in cooling channels such as heat exchange area, fluid velocity, and temperature rise of the water through the cavity. The total flow rate of water per cell was selected to be 50 l/min. Consequently, the mean fluid velocity is 2.0 m/s. The maximum water pressure drop was expected to be 2.6 kg/m^2. The surface heat transfer coefficient was calculated 8323 W/cm^{2}K. Under the power dissipation of 20 kW per cell of cavity, the water temperature rise through the cavity was expected to be about 6 °C.

3.3 Finite element analysis

The thermal and structural analysis has been performed to estimate cavity thermal deformation by using ANSYS code. The cavity frequency shift caused by this deformation was also estimated with the frequency sensitivity calculated by SUPERFISH. The equivalent stress, Von-Mises stress, distribution was also calculated.

The heat transfer coefficient of each cooling channel obtained from the spreadsheet calculation described above was used. The power density distribution obtained from the rf analysis by SUPERFISH was used. Water temperature in each channel was given by averaging the temperature rise derived from the total temperature rise of water.

To find the optimum values for the cavity design, attention was paid to indexes such as the maximum temperature and the equivalent stress loaded on copper. In this design, we adopted temperature of 70 °C and equivalent stress of 34 MPa where is the 50 % value of the yielding stress of copper, as the maximum acceptable values.

Several models with different channel location were generated and calculated. The model was based on a half-cell model to save the memory consuming, calculation times and so on. A symmetric boundary condition was applied along the line marked with "s" in Figure 2. Two groups of water channels, C4 and C1-C2-C3, were taken into account since we designed that water of each channel flows in parallel. C1 is the inlet and C3 is the outlet. The average temperature in each channel was added as an initial condition. The result of optimisation showed that the cooling channel nearest to the nose cones was the most sensitive. Results of the various models having different C1 locations were compared and the optimum channel location was chosen. The summary of the optimisation is described in the end of this chapter.

Figure 3 shows the temperature distribution of the model with optimum channel location.

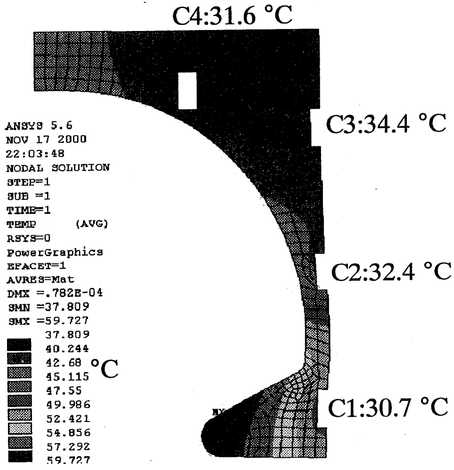

Figure 3 Cavity temperature distributions

The water temperature at the water inlets was set to 30 °C. A heat flux to the atmosphere from the cavity was also taken into account. According to the table, the heat flux of 281 W/m^2 [2] was estimated in this case.

Under these conditions, the maximum copper temperature was calculated to be 60 °C at nose cones. The average temperature at the outer surface of the cavity was about 41 °C. The maximum thermal deformation of r-axis and z-axis per cell was 70 μm and 140 μm, respectively. The cavity deformation in each coordinate due to the vacuum condition were 0.5 μm for r-axis and 5 μm for z-axis, where the surface pressure of 1 kg/cm^2 was loaded. Figure 4 shows the thermal deformation distribution and the order of the cavity segmentation.

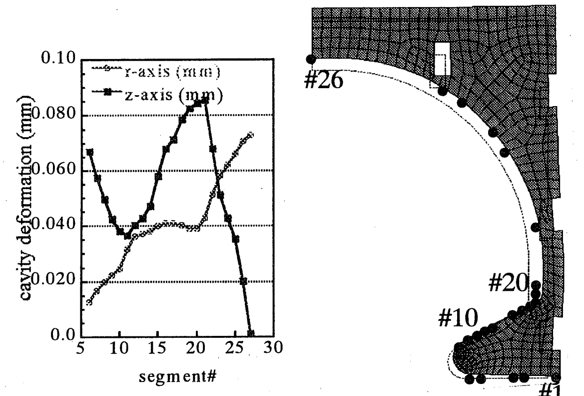

Figure 4 Distribution of cavity thermal deformation

Thus, with the results above and frequency sensitivity calculated by SUPERFISH, the cavity frequency shifted is estimated to be –129kHz. This value can be corrected by movable tuners.

To determine the frequency shift due to temperature change of atmosphere, the sensitivity analysis was carried out by varying the room temperature in the range of 5 to 30 °C and the water temperature at inlets of cooling channels in the range of 20 to 42 °C. Figure 5 shows the sensitivity curve obtained by the analysis. It was determined that the sensitivities of cavity frequency shift in terms of the room temperature change and the water temperature change are 0.8 kHz/°C and 7 kHz/°C, respectively.

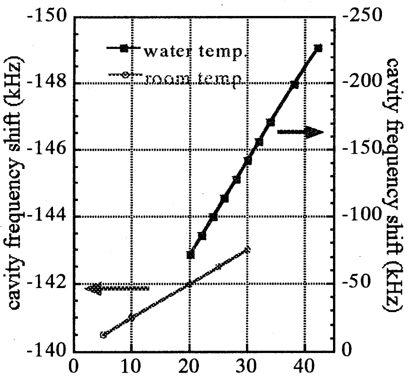

Figure 5 Sensitivity of cavity frequency shift in terms of the room and the water temperature change

To determine the thermal stress, the equivalent stress (Von-Mises stress) was adopted. The maximum equivalent stress was 31 MPa. This is low enough compared with the yielding stress of annealed copper, 69 MPa [3].

3.4 Summary

As described above, the thermal and structural design was carried out. The design parameters of the cavity are summarized in Table 2.

Table 2 Summary of the cavity parameters

Max. thermal deformation per cell	r:70μm, z: 140 μm
Cavity Frequency shift	–129 kHz
Sensitivity rf freq. of the room temp.	0.8 kHz/°C
Sensitivity rf freq. of the water temp.	7 kHz/°C
Max. equivalent stress	31 MPa
Max. copper temp.	60 °C
Average copper temp. at the outer surface	41 °C
Pressure drop of water through the cav.	2.6 kg/m^2

At the cavity optimisation, the maximum yielding stress, frequency shift and maximum copper temperature of the cavity of each model were compared. Table 3 summarizes the results of the calculation. It was pointed out that as decreasing the yielding stress, the cavity frequency shift increases. It is more important to decrease the yielding stress low enough than to keep the frequency shift lower, because the frequency shifts are all small enough compared with the frequency range which movable tuners can cover. Therefore, the model having the lowest maximum stress was chosen to be the optimum design.

Table 3 Typical results of cooling channel optimisation

Model #	$r_{innermost}$ cooling chan. (mm)	Max. stress (MPa)	Freq. shift (kHz)	Max. Cu temp. (°C)
#1	45	38	-121	62
#2	50	35	-124	60
#3	55	31	-129	59.7

4 CONCLUSIONS

The thermal and structural design of the rf cavity of the CW microtron was performed. The optimum design of the cavity was obtained. All calculated results were reasonable for the fabrication of the cavity and the continuous operation of the cavity.

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5 REFERENCES

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