# ON THE MECHANICAL DESIGN OF A 1.5 GHz LANDAU CAVITY

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*Abstract*

A third harmonic Landau cavity with the fundamental mode of about 1.5 $GHz$ is under development at SRRC. The cavity consists of inner copper layer and outer stainless steel layer. The vacuum-brazing process is adopted for cavity construction. The maximal power flow density on the cavity surface will be about 52.19 $W/cm^2$, as the total thermal loading of 32 $kW$. To verify the cooling capacity, the finite element method is adopted to perform the thermal and stress analyses. Under 15 $m^3/hr$ water flow rate, the temperature rise on the cavity body will be less than 14 $^\circ C$. And the maximal equivalent stress on the copper layer of 29.75 $N/mm^2(MPa)$ is achieved, which is much less than the yielding stress of copper.

## 1 INTRODUCTION

A third harmonic Landau cavity with the fundamental mode of about 1.5 $GHz$ is under development at SRRC[1, 2]. The inner profile of the cavity is of bell-shape without nose cone. The cavity body is consisted of inner copper layer and outer stainless steel layer. During normal operation, the total thermal loading on the inner surface of the cavity will not exceed 32 $kW$, and the corresponding maximal surface power flow density is 52.19 $W/cm^2$[1]. Obviously, a suitable cooling system is necessary for such a high power loading. The cooling design is to make the the temperature rise so low that the thermal stress is lower than the materials' yielding stress.

The 3D finite element models have been established to estimate the temperature rise and the stress distribution on the Landau cavity, and then the improvements on the cavity stucture and cooling system were progressed[3]. The commercially available finite element codes ANSYS[4] and P3/PATRAN[5] were used in our calculations. A prototype cavity has been constructed based on these optimal results. The mechanical design and machining process of the 1.5 $GHz$ Landau cavity, and some analytical results are described in this article.

## 2 MECHANICAL DESIGN

The prototype Landau cavity at SRRC consists of two metallic layers. The inner layer will be fabricated from oxygen-free electrical (OFE) copper C10100, while the outer one is made of stainless steel. The mechanical drawing of the cavity body is shown in Fig. 1. The strength and stiffness of stainless steel are much better than those of OFE copper. Moreover, the coefficient of thermal expansion of stainless steel, $17 \times 10^{-6}/^\circ C$, is close to the one of copper, $16.6 \times 10^{-6}/^\circ C$. Therefore, the stainless steel is chosen as the material of the outer layer of the Landau cavity to protect the cavity and to increase its rigidity.

As shown in Fig. 1, most of the cooling channels are located at the inner copper layer for better cooling efficiency. For the same reason, some cooling channels are directly cut on the cavity body instead of buring the cooling pipes. On each curved part of the cavity, the cooling channels are distributed as seven rings. These ring-typed channels are connected in serial by additional shortcut channels to produce single-directional water flow. The water inlets and the corresponding outlets are expressed by arrows in Fig. 1. On the central cylindrical part of the cavity, the cooling channels, locating on the copper layer, are straight and parallel to the beam-flying direction (Z-axis). Total thirty-two straight cooling channels are equally distributed around the circumference. Moreover, there are some connecting shortcut channels on the stainless steel layer to make the cooling water flow serially along the straight cooling channels. These straight parallel cooling channels are divided into two groups, sixteen channels for each group with individual inlet and outlet, so that each group cools half of the central cavity body.

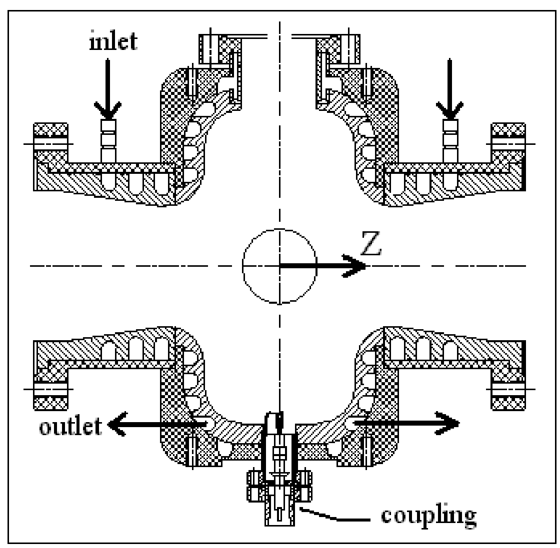


Figure 1: Cross section of the 1.5 $GHz$ Landau cavity in SRRC

For easy machining, both the OFE copper and stainless steel layers will be fabricated in four sections: two end sections and two symmetric sections for the main body. These sections are lathed first to get the desired shape. The ring-typed cooling channels and welding slots are also machined by a lathe. The inner copper layer of the prototype of the Landau cavity after this manufacture process is shown in Fig. 2.

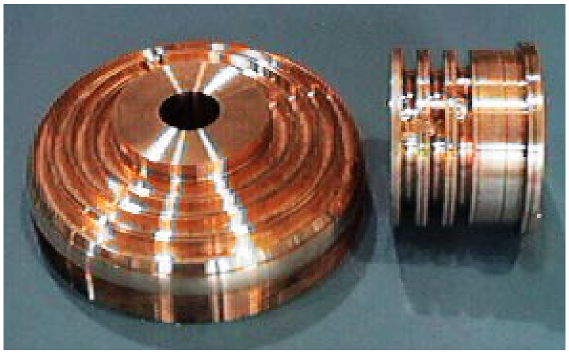

Figure 2: The OFE copper layer of the Landau cavity with the ring-typed cooling channels finished

Notice that the straight parallel cooling channels have not been made yet.

Secondly, every corresponding copper section and steel section are put into a vacuum-brazing machine to be precisely brazed together with the help of the Au-Cu solder under the temperature of about 1010 $^{\circ}C$. As the central copper and steel sections are brazed together, the straight parallel cooling channels will be made by a boring machine. Then, the vacuum-brazing operations are proceeded again and again to construct the whole cavity. Obviously, the vacuum-brazing process is quite a complex and time-consuming work.

To compensate the resonant frequency shift due to the mechanical tolerance, the modeling uncertainty, the operation requirement, the structure deformation from thermal expansion, etc., two mechanical plunger turners will be installed on the cavity. In addition, the RF-power will be inputted through a hole coupler as the cavity to be operated in the active mode in the future. The turners and the coupling network are all located at the middle plane of the cavity, as shown in Fig. 1. A boring machine is used to dig three holes on the brazed cavity body for the connecting rings of the turners and the coupling network. The outer stainless steel layer is now very useful to prevent the cavity from the damaged defromation during the digging process. However, the diameters of these three holes are larger than the distatnce between two straight parallel cooling channels, the cooling channels are discontinuous now. So the corresponding cooling channels are cut on the connecting rings for the turners and the coupling network to maintain the cooling water flow.

## 3 THERMAL LOADING AND COOLING

Under the estimation of 300 $kV$ gap voltage, the calculation on the power flow density distribution[1] shows that the total RF power dissipation on the inner surface of the Landau cavity is about 32 $kW$ with a maximal local power flow density of 52.19 $W/cm^2$. The power density distribution is applied to the finite element models as the applied surface heat flux. Because the applied thermal loading on a single element surface must be the same for the ANSYS thermal element "SOLID 90", the power flow density distribution is transferred to an equivalent heat flux.

The heat transfer between a moving fluid and a solid face can be simply expressed as:

$$q'' = h(T_s - T_m) \tag{1}$$

in which $q''$ is the heat flow per unit area, $h$ the surface heat transfer coefficient, and $T_s$ and $T_m$ the solid surface temperature and bulk fluid temperature, respectively. The formulas used in this work for heat transfer can be found elsewhere[6].

In the finite element anslysis, the surface heat transfer coefficient $h$ has to be assigned on the surfaces of the channels as boundary conditions. However, this coefficient depends on the cross-section of cooling channels which affects the mean fluid velocity $u_m$. For our cooling channel design, the cross-sections of the cooling channels are not identical, so a complete spreadsheet calculation for $h$ on every cooling channel is necessary. It is clear from Eq. (1) that, under the same heat flow density $q$ and bulk fluid temperature $T_m$, the larger the surface heat transfer coefficient $h$, the lower the solid surface temperature $T_s$ will be. Therefore, the larger $h$ means a better cooling efficiency.

As the mean fluid velocity $u_m$ increases, so does $h$. But it will also increase the pressure difference between the corresponding inlet and outlet of the cooling water. Restricted to the pumping capacity, the overall pressure difference is expected to be less than 5 $kgw/cm^2$ for every serial cooling channel group. The spreadsheet calculations show that the optimum water flow rates for the ring-typed cooling channels and the straight parallel ones are 3.5 $m^3/hr$ and 4.0 $m^3/hr$, respectively. The surface heat transfer coefficient $h$ will then distribute between 3.471 and 5.745 $W/cm^{2\circ}C$. The pressure differences for the ring-typed cooling channels and the straight parallel ones are 4.8 and 4.6 $kgw/cm^2$, respectively. Under the 32 $kW$ thermal loading and the 15 $m^3/hr$ cooling water flow rate, the water temperature rise of less than 1.9 $^{\circ}C$ is deduced for steady state.

## 4 FINITE ELEMENT ANALYSIS

In our numerical study, the thermal analysis is first performed to obtain the nodal temperature solution. Then the nodal temperatures are applied as body loads to a compatible structure model in the subsequent stress analysis. The compatible 20-node solid elements "SOLID90" and "SOLID95", provided by ANSYS, were adopted in the thermal and stress analyses, respectively. Both the elements have 3 nodes for single edge and are well suited to model curved boundaries.

Beause there are three holes on the middle circumference of the cavity for the turners and the coupling network, the cavity is asymmetric. The special conditions around these three holes were neglected, so the cavity was treated as a symmetric structure and only one sixteenth of the cavity body was modeled for the simplicity of the numerical modeling. There are 7344 elements and 37552 nodes for this model. The material constants adopted in analyses are listed in Table 1.

The analytical results show that the maximal temperature rise is 13.99 $^\circ C$, which is located at the central cylindrical part of the cavity. In the subsequent stress analysis the nodal temperatures were applied as body loads, while the reference temperature was set to zero. The surface pressure of 1 $kgw/cm^2$ was applied on the outer surface of the cavity to simulate the vacuum effect, while a pressure of 5 $kgw/cm^2$ was applied on the surface of cooling channels to simulate the water pressure. The equivalent stress, $\sigma_e$, i.e., Von-Mises stress, was adopted to check the thermal stress. This equivalent stress is defined as:

$$\sigma_e = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \quad (2)$$

Here $\sigma_1$, $\sigma_2$, and $\sigma_3$ are three principal stresses. The calculated equivalent stress is shown in Fig. 3. It can be seen that the maximal equivalent stress is 29.75 $MPa$, and the high stress region locates at the central cylindrical part of the cooper layer. Notice that the yielding stress for anneal copper is 55 $MPa$, i.e., the safety factor for stress is 1.85.

The temperature rise will also bulk up the cavity. This will change the resonant frequency of the cavity.

Table 1: Summary of the material constants used in the finite element analysis of the Landau cavitay.

| | Copper | Steel |
|---|---|---|
| Young's modulus ($kN/mm^2$) | 110 | 200 |
| Poisson's ratio | 0.33 | 0.3 |
| coefficient of thermal conductivity ($W/m^\circ C$) | 401 | 14.9 |
| coefficient of thermal expansion ($\times 10^{-6}/^\circ C$) | 16.6 | 17 |

According to the FEM results, the maximal expansion will happen at the central part due to the thermal effect. The maximal radial deflection is 5.7 $\mu m$. The elongation on the longitudinal direction is also in the same order as the radial deflection. The bellows in connection between the cavity and the vacuum chambers can take this longitudinal elongation. However, such effect is so small that the bulk can be easily compensated by movement of the turners installed on the cavity body.

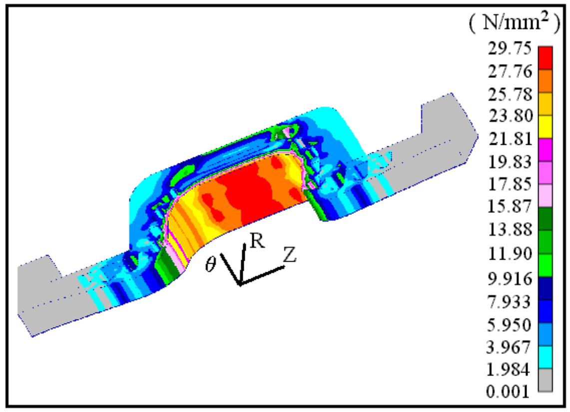


Figure 3: The equivalent stress of the cavity body under 32 $kW$ thermal loading.

## 5 CONCLUSION

The 3D finite element thermal and stress analysis is useful not only to improve the mechanical structure of the 1.5 $GHz$ Landau cavity, but also to verify the capability of the cooling channels. Both the water flow rate and the cooling channels were optimized to reduce the thermal effects. The manufacture of the cavity is very complicated, in particular in the complex vacuum-brazing process.

## 6 REFERENCES

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[3] M.C. Lin, Ch. Wang, T.T. Yang and L.H. Chang, "On the Thermal and Stress Analysis of a 1.5 $GHz$ Landau Cavity," in progress.

[4] Program ANSYS, a product of Swanson Analysis System, Inc., is a commercially available 3D code by using finite element method.

[5] Program P3/PATRAN, a product of MacNeal-Schwendler Corporation (MSC), is a commercially available 3D code that can be used as pre-processor and post-processor for some other finite element codes.

[6] F. P. Incropera and D. P. DeWitt, "Fundamentals of Heat and Mass Transfer," 2nd Edition, John Wiley & Sons, Inc., 1985, Ch. 8, pp. 367-416.