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STRUCTURAL OPTIMIZATION DESIGN OF FARADAY CUP FOR BEAM COMMISSIONING OF CSNS*

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Abstract

Faraday cup is used to absorb and stop the beam during the two phases of beam commissioning, such as the front end (FE) system and the temporary line after the drift tube linac (DTL) at the Chinese Spallation Neutron Source (CSNS). According to the beam physical parameters, graphite is selected to stop the beam directly, and oxygen-free copper which is just behind the graphite as the thermal conductive material. By the analysis and comparison of the target type and cooling efficiency, the single slant target is adopted. The incident angle between the target surface and the beam is set as 10°, meanwhile a new waterfall type water-cooling structure with parallel tunnels is designed to improve the cooling efficiency. The finite element software ANSYS is used for thermal analysis of the model, by which the diameter and interval of water cooling tunnels are optimized. The faraday cup discussed in this paper is finally successfully installed in the beam commissioning line and went well.

INTRODUCTION

Faraday cup acts as a beam absober, which could stop the beam directly in the low energy section, and attenuate the beam energy to be absorbed by the outer protective body in the high section [1]. As the last device of the whole beam transportation line during the two beam commisioning phases of FE system and the temporary line after DTL at CSNS, the mechanical design of faraday cup needs to meet the principals as follows:

1. There is no limit to the length, but economic benefits should be considered.
2. Water-cooled sealing welds must be located outside the vacuum.
3. Structural design and process should be optimized to facilitate manufacturing.
4. The dose of activation needs to be reduced to the radiation protection requirements.

In this paper, a novel structure of faraday cup with single slant target is developed and optimized to the need of accelerator commission.

MATERIAL

Materials commonly used for beam stop are copper, aluminum, nickel and graphite. According to Doll [2], the relationship between the number of neutrons produced by a single proton impacting and the proton energy is analysed for four different beam absorbing materials. For graphite, in the entire energy range, the number of neutrons produced by a single proton are the lowest. Furthermore, according to Acharya *et al.* [3], comparing with the half-life of activated products and the associated γ-ray energy, graphite is also better than the other beam absorbing materials listed. For optimizing the design and subsequent treatment, and reducing the radiation activation of the device as well, high-purity dense graphite (density is more than 2.0 g/cm^3) is selected as beam absorbing material.

Copper is chosen as the cooling and vacuum sealing material. It has excellent performance of conductivity and ductility, and it is also easy to realize machining and vacuum brazing. But copper's threshold value of proton energy activation is low to only about 2.7 MeV. Therefore, the beam absorbed by graphite can reduce the activation of copper and the heat generated can be conducted away through the copper plate quickly.

TARGET

Common structure for faraday cup are conical target, ogive target, and plate target, etc [4]. Ogive target has a strict requirements on beam alignment, so it is not suitable when the transverse beam size σ is small. Moreover, this kind of target structure is irregular, which leads to machining difficulties. Then, the machining of conical target is much more difficult than plate target, and its cone tip can not be process to absolute zero.

A structure of single slant target with low manufacture cost is selected in this paper, only under the condition of length acceptable, as shown in Fig. 1. To ensure the mechanical strength and all 20 MeV proton beam energy deposited in the graphite layer, the thickness is chosen as 2 mm, and the incident angle is 10° as well.

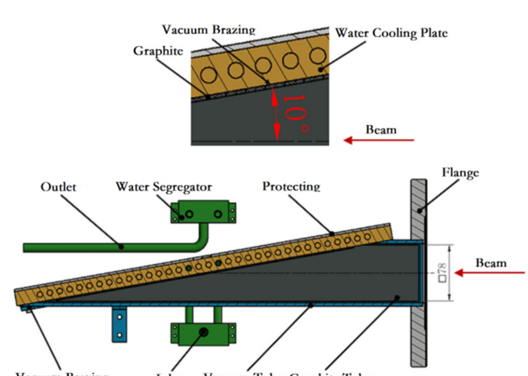

Figure 1: Longitudinal section view of Faraday cup.

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WATER-COOLING STRUCTURE

Thermal effect will be generated on faraday cup after beam absorption, so an effective water-cooling structure is necessary. In this paper, two kinds of water-cooling structures are considered. One is micro-fin water-cooling structure which refer to ADS-RFQ, as shown in Fig. 2a, with it's dimensions a = 0.5 mm, b = 2 mm, l = 6 mm, and d = 3 mm. The other is parallel-tunnel water-cooling structure, as shown in Fig. 2b, with it's dimensions as the thickness of plate is 20 mm, the diameter of tunnels is 10 mm, and the interval between tunnels is 20 mm.

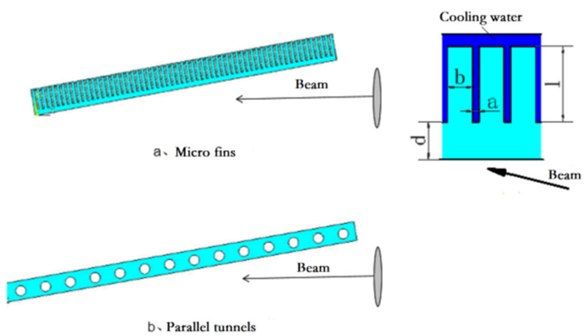

Figure 2: Schematic diagram of water-cooled structure.

The physical parameters in two phases of beam commissioning are listed in Table 1. Once the angle between beam and target surface set as 20°, thermal analysis is carried out on the two different water-cooling structures under the same beam boundary conditions, and the results are presented in Fig. 3. Under the beam energy of 3 MeV and 20 MeV, with the increasing of beam size σ, both of the peak temperatures decrease, and the speeds slow down gradually. The peak temperature of micro-fin structure is slightly lower than that of the parallel-tunnel structure, and the cooling efficiency is about 7% to 10% higher. However, with the increasing of beam size σ, the peak temperatures are getting closer, and the results are so close that indicates there is no significantly different cooling effect between this two structures.

Table 1: Physical Parameter in Two Phase of Commissioning

Parameter	Value	
	FE	DTL
Energy, MeV	3	20
Peak current, mA	15	15
Beam frequency, Hz	5	5
Pulse width, μs	500	500

Considering that the mechanical processing of micro-fin structure is much more complicated, parallel-tunnel structure with simpler technology is selected. At the same time, structure with upper and lower water tanks are used to replace the structure with bending tube to achieve less water resistance, greater water flow and better cooling effect.

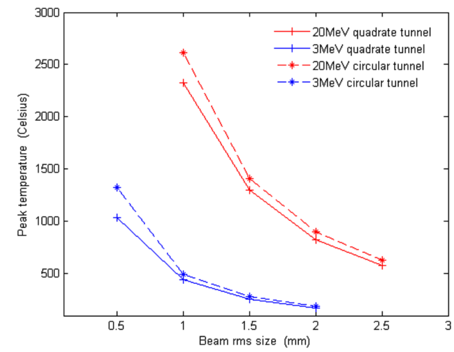

Figure 3: Efficiency comparison of water-cooled structure.

INCIDENT ANGLE

Based on the beam parameters in Table 1, safety coefficient (200%) is considered in the simulation, and the average beam power is set as 1.5 kW. When the beam size σ = 2 mm, the max power density of the beam J_o can be calculated by the following equation:

$$J_o = \frac{P_t}{2\pi\,\sigma^2} = 59.7\ (\mathrm{W/mm^2}), \tag{1}$$

in which, P_t is the total beam power.

The temperature of brazing plane between graphite and oxygen-free copper must below the brazing temperature (780 ℃ ~ 840 ℃), and the temperature of cooling water must below the boiling point (100 ℃). Therefore, the power density of vertical to the target surface is controlled as the max allowable power density J_{perm} = 25 W/mm^2. Then, the critical incident angle between beam and target surface β_0 could be obtained by the following equation:

$$\beta_0 = sin^{-1}(J_{perm}/J_o) = 24.76°. \tag{2}$$

At this point, the beam expands into ellipse shape (3σ, 3σarcsinβ_0) along the beam impacting plane. The relationship between the peak temperature and the incident angle is shown in Fig. 4. The peak temperaure simulated by ansys is 2134 K under the condition of β_0 = 20° and σ = 2 mm, which is lower than the melting point of graphite. Because there is no limit to the device length, the final incident angle is set as 10° under the consideration of enough safety coefficient. By the defined angle and given diameter of the entrance r_0 = 70 mm, the length of the single slant target is 403 mm, which is acceptable.

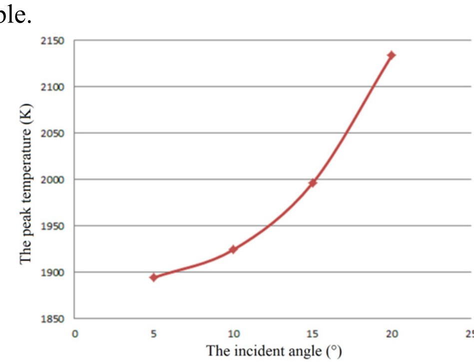

Figure 4: The peak temperature vs. the incident angle.

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OPTIMAL DESIGN

Based on the basic model with the water-cooling plate thickness of 20 mm and tunnel interval of 20 mm, the relationship between the peak temperature and the diameter of the tunnel under the impacting of 20 MeV beam is shown in Fig. 5. The results indicates that the peak temperature decreases gradually with the tunnel diameter increasing, and the peak temperature drops to 1924.3 K when the tunnel diameter reach to 12 mm. Obviously, there is little infuluence on the cooling effect by the change of the tunnel diameter. Finally, the diameter of the tunnel is set as 12 mm with considering the mechanical strength of the copper plate.

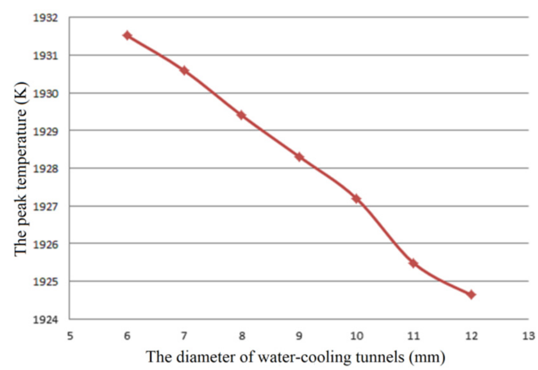

Figure 5: The peak temperature vs. the diameter of water-cooled tunnels.

Under the same basic model and beam energy described above, the relationship between the peak temperature and the interval of tunnels is shown in Fig. 6. It manifests that the peak temperature increases slowly with the interval of tunnels expanding, and the lowest peak temperature appears at the interval of 13 mm which is 1920.77 K. Similary, the cooling effect varies not obvious with the modification of the tunnel interval. Then the interval of the water-cooling tunnels is defined to 14 mm as the same reason described above.

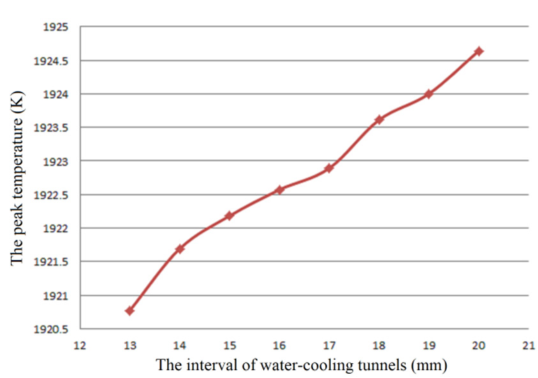

Figure 6: The peak temperature vs. The interval of water-cooling tunnels.

The temperature distribution of the beam impacting surface is shown in Fig. 7. The peak temperature appears in the center of the surface is 1921.69 K, which is consistent with the prediction. Then, the peak temperature of the brazing plane between graphite and copper plate is 395.26 K, which is lower than the brazing temperature. Meanwhile, the temperature around the tunnel surface is all lower than the water boiling point. In conclusion, all results described above are satisfied with the requirement of structural design.

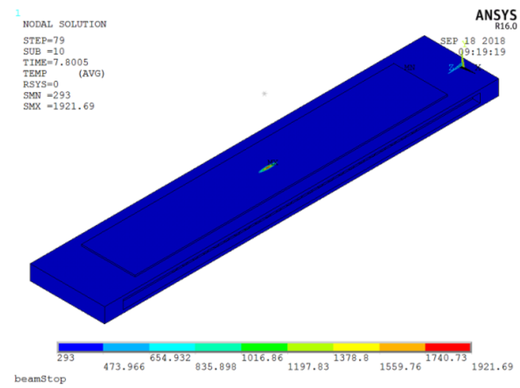

Figure 7: The temperature distribution on beam impacting surface.

CONCLUSION

A new type of faraday cup is designed and optimized， and successfully applied in the two phases of beam commissioning of CSNS FE system and DTL temporary line.

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