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BEAM DUMP DEVELOPMENT FOR HIGH POWER PROTON AND ELECTRON BEAM

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Abstract

The high-intensity 100 MeV proton cyclotron CYCIAE-100 had provided 52 kW beam to the beam dump in 2018, is planning to be upgraded at China Institute of Atomic Energy (CIAE). It is designed to provide a 75-100 MeV, 1 mA proton beam. A new beam dump for higher beam power have been developed since 2020. At the same time, a 1:4 scale, RF cavity with Q value up to 42000, is constructed for the engineering feasibility verification of a 2 GeV/6 MW CW FFAG, which is also being considered as a main accelerating cavity of a 100 kW electron accelerator. The electron beam will be rotated and accelerated 7 times by the gradient dipoles and the high Q cavity. The beam dump is designed to also use for the 100 kW electron beam. With the same-level beam power of the two accelerators above the content, a beam dump for absorbing two kinds of particle beams according to the characteristics of the modification was designed. The energy deposition of 100 MeV proton beam and 5 MeV electron beam in the beam dump was investigated by the Monte-Carlo simulation program FLUKA. The beam dump cooling structure was optimizing by ICEM-CFD and fluent, so that the water temperature was controlled less than 100 ℃, and the maximum temperature on the beam dump is less than 450 ℃. The beam dump is designed as a cube (450 mm * 200 mm * 200 mm) with two 2.5° V-type copper pentagon and two flat parts. All the details about the simulation of energy deposition, thermal distribution and structure design will be presented in the paper.

INTRODUCTION

The high-intensity 100 MeV proton cyclotron CYCIAE-100 had provided 52 kW beam in 2018, is planning to be upgraded to provide the beam power reached 75-100 kW proton beam [1, 2]. A 1:4 scale, RF cavity is constructed for the engineering feasibility verification of a 2 GeV/6 MW CW FFAG, which is also being considered as a main accelerating cavity of a 100 kW electron accelerator [3]. The beam dump is the major part for absorbing high-energy particle beam at the end of accelerator. With high power density and small cross-section, if the heat flux is not reduced and the heat is not taken away in time, the vacuum will be destroyed, and even affect the normal operation of accelerator.

STRUCTURAL DESIGN

The beam dump, shown in Fig. 1, is located in a vacuum box at the end of the beam line designed, as a cube (450 mm * 200 mm * 200 mm). the beam dump consists of two 2.5° V-type pentagon and two flat parts fabricated from copper. Two fluid regions are distributed symmetrically as S-channels. The fluid regions are almost parallel to the 2.5° V-surface, and the distance from the V-surface is about 20~25 mm. The gap of channel is optimized to 3 mm and with 3 fins, the thickness is 1.5 mm, to enhance convective heat transfer. The purpose of the two side plates is to block the few edge beam particles that might be present.

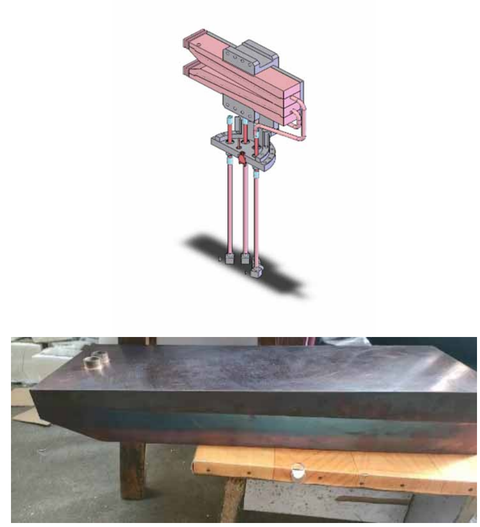

Figure 1: Three-dimensional drawing of the beam dump and the 2.5° V-type copper pentagon target in processing.

CALCULATION ABOUT THE BEAM ENERGY DISTRIBUTION

In order to obtain more accurate temperature distribution, the input condition of the V-type pentagon in the depth of direction is result of heat source probability density calculated by FLUKA, and the energy of the beam and copper has a Gaussian distribution. Figure 2 shows the energy probability of the proton/electron-copper interaction in the depth direction. The energy deposit increases with incidence depth, and the relation is not linear. For easy to calculation, the relationship between the energy deposit and incidence depth is assumed to be energy probability density.

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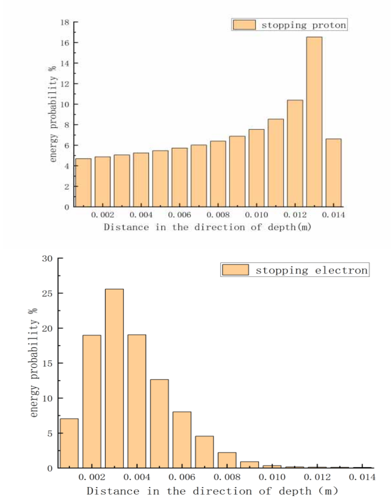

Figure 2: Energy probability in the beam dump of (a) 100 MeV proton, (b) 5 MeV electron.

MESH AND THERMAL ANALYSIS

Figure 3 shows the 2.5° V-type pentagon target divided into five areas to optimize calculate the temperature distribution with ICEM. To adapt probability density of proton and electron particles, two energy distribution regions are separated as 2.5° inclined plane and 30° inclined plane according to proton range. When the beam dump intercepts electrons, the energy probability density at the distribution regions beyond the depth of 10 mm is assumed to be 0. Two fluid regions are separated as Tube A and Tube B to improve the speed of calculation. Hexa-mesh is used in the above four regions. The last area called heat transfer region is meshing with Tetra-mesh. Those five grids are merged into one grid [4]. Table 1 shows the mesh information of different regions.

The beam dump should be designed to prevent the temperature from exceeding the boiling point, otherwise bubbles forming in the overheated area will isolate the water and copper, causing the temperature to get out of control and damaging the beam dump from the inside face. In addition, the maximum temperature of the beam dump should not exceed the melting point of the material to prevent damage the dump from the outside face. Cooling water is entered into beam dump from the trumpet, taking away 50 kW from one V-type target.

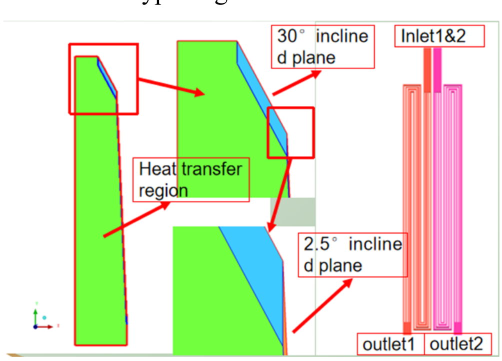

Figure 3: Divided Regions of the V-Type Pentagon.

Table 1: Mesh Information

Region	Element Types	Total Elements
2.5° inclined plane	Hexa-mesh	70 thousand
30° inclined plane	Hexa-mesh	16 thousand
Tube A	Hexa-mesh	27 thousand
Tube B	Hexa-mesh	27 thousand
Heat transfer region	Tetra-mesh	600 thousand

The fluid mechanics software fluent was used to simulate the temperature distribution. The viscous model was adopted k-ε model. The flow rate of cooling water was 1 kg/s and the corresponding inlet pressure was about 0.07 MPa. After entering the fin area, the cross section of fluid decreases and the flow velocity increases. The flow velocity distribution and heat transfer coefficient of cooling water is shown in the Fig. 4. The average velocity in the fin gap area is about 1.9 times of where without fins at the inlet and outlet, the highest velocity occurs at the end of the U-tube with the smallest turning radius in the fin gap. The distribution of convective heat transfer coefficient is same as that of velocity.

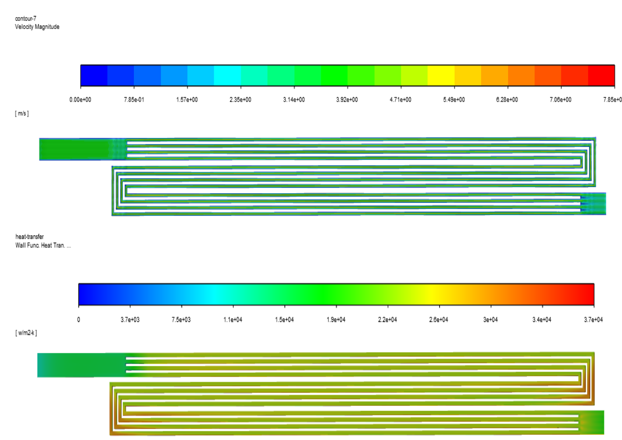

Figure 4: Distribution of Velocity and Convective Heat Transfer Coefficient.

Assuming the beam size is 9 mm, assembled symmetrically along the central plane of the beam, each V-type target absorbs half of the beam, which is 50 kW. Flow rate is 1 kg/s and the temperature of inlet water is about 27 ℃. Figure 5 shows the curves of the peak temperature on the target and the surface of the cooling channel at different y director. As y director increasing, the temperature on the target and on the surface of channel rises to the maximum temperature at 0.05 m, the position where the Angle of the target is 2.6°, then the temperature gradually decreases from 0.05 m to 0.3 mm. and rises again to the peak temperature at 0.33 m, the Angle of the target becomes 30°, then the temperature drops rapidly.

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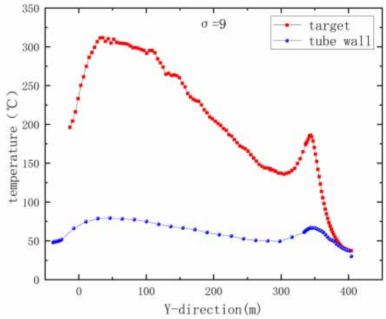

Figure 5: Curves of Peak Temperature.

Figures 6 and 7 show the temperature distribution, under four conditions, which are formed by the combination of two kinds of particles (100 MeV proton and 5 MeV electron) and two kinds of depth direction energy distributions (average density and probability density). For the condition of V-type target stopping 100MeV proton with energy distribution as probability density. The highest temperature is about 357 ℃ (Th) at the 2.5° inclined plane, the peak temperatures is about 190 ℃ (Tp1) at the 30° inclined plane, and about 80 ℃ (Tp2) at the surface of the cooling channel. The results of other conditions are shown in Table 2, it shows that the temperature on the target is much lower than the melting point of copper and the fluid wall temperature does not exceed the boiling point of water. A phenomenon is that the temperature on the target calculated using the energy distribution of probability density is lower than the average density, and the energy distribution has little effect on the temperature of surface channel.

Table 2: Maximum Temperature in the Crucial Area

Particle	**Energy Distribution**	T_h	T_{p1}	T_{p2}
proton	probability density	357	190	80
proton	average density	374	264	82
electron	probability density	373	334	84
electron	average density	396	316	85

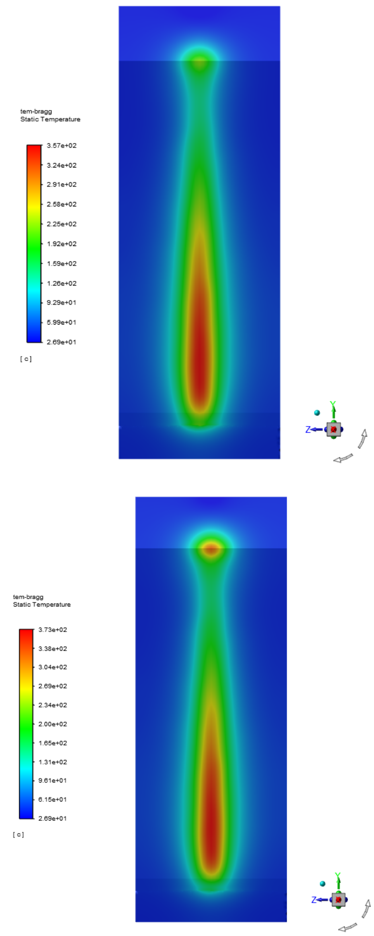

Figure 6: Temperature distribution of calculation energy probability density in depth direction by FLUKA, (a) target stopping 100 MeV proton, (b) target stopping 5 MeV electron.

Figure 8-a shows the curves of the maximum temperature by different flow rate at beam size 9 mm, when the beam flow rate is reduced to 30 L/min (0.5 kg/s), the wall temperature exceeds 100 ℃. Figure 8-b shows the curves of the maximum temperature by different beam size at flow rate 1 kg/s, when the beam size is less than 6 mm and the wall temperature exceeds 100 ℃. The beam dump should be avoided from operating under these critical conditions.

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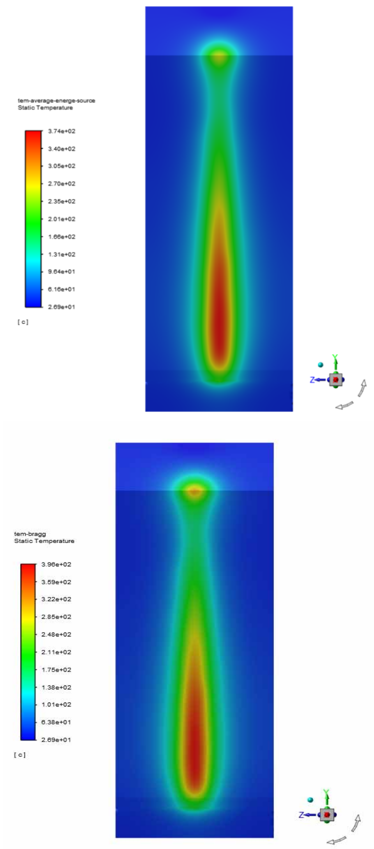

Figure 7: Temperature distribution of average density in depth direction, (a) target stopping 100 MeV proton, (b) target stopping 5 MeV electron.

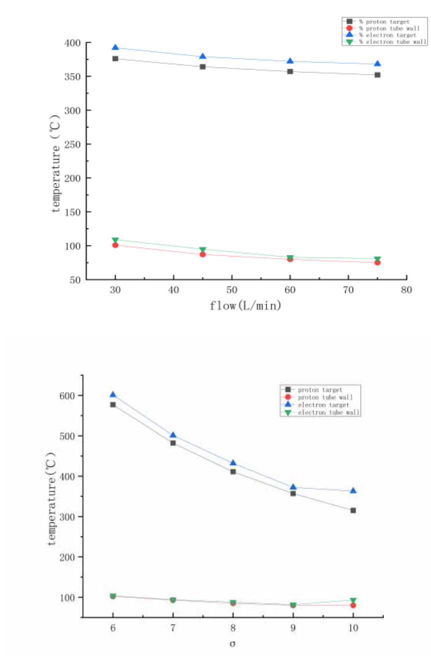

Figure 8: Curves of the Maximum Temperature, (a) different flow rate at beam size 9 mm, (a) different beam size at flow rate 1 kg/s.

The temperature almost has similar distribution, except for the condition where the electron beam size reaches 10 mm, which shows in Fig. 9. In this condition, the temperature distribution of the electron and proton target changes greatly, and the highest temperature of the electron appears in the region between 30° and 2.6°, that is, y = 0.33 m.

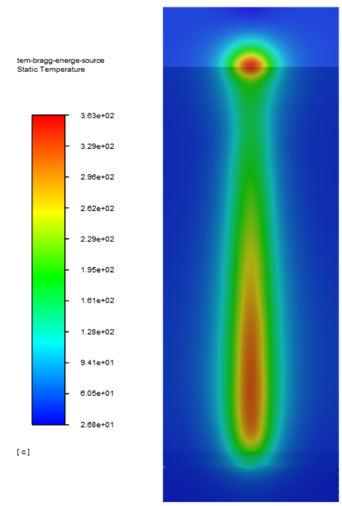

Figure 9: Temperature Distribution of the Electron Beam Size is 10 mm.

CONCLUSION

The design of a beam dump for 100 kW proton beam and 100 kW electron beam is described in this paper. The probability density of particle energy deposition in the depth direction was calculated by FLUKA, which is used as the input condition to calculate the temperature distribution of the beam dump. The cooling structure of the beam dump is optimized. The flow and beam size were used as variables to study the working conditions of the beam dump under different working conditions. The beam dump is currently being manufactured, the installation and test will be carried out in the near future.

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