Thermal analysis and optimization of proton beam window for the CSNS

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Abstract: The proton beam window (PBW) is one of the key devices of China Spallation Neutron Source (CSNS). It is the boundary between transport line and target. This paper will present a new PBW structure and detailed thermal-stress analysis. The energy deposition and scattering effect need to be low when the beam passes through the PBW, so proper selection of material and structure is important. According to the study of energy deposition, A5083-O is selected as the PBW material. A single-double layer structure is first proposed based on the study of cooling structures. Thermal analysis and structural optimization are discussed, and transient analysis is done to show the effect of the beam pulse. Besides, safety is confirmed for cases of cooling tunnel blockage, beam profile shrinkage, or centroid orbit offset. All these analyses show the newly designed PBW structure can meet the requirements of the CSNS well.

Key words: proton beam window, energy deposition, A5083-O, thermal analysis, structure optimization, safety confirmation

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1 Introduction

The China Spallation Neutron Source (CSNS) is an accelerator-based high power project under construction in China [1]. The proton beam window (PBW) is one of the key devices of the CSNS. It is the boundary between the high vacuum region of the transport line and the helium atmosphere around the target assembly. There are several design demands of the PBW: energy deposition, scattering effect, radiation damage, cooling method, mechanical strength, etc. [2–5]. Table 1 shows some relevant PBW beam parameters. According to the beam character of the CSNS, a single-double layer structure is first proposed, and A5083-O is selected as the PBW material. Energy deposition, cooling structure and mechanical properties are discussed and analyzed, the optimization based on ANSYS analysis is presented, and safety is confirmed for cases of adverse circumstances.

Table 1. Beam parameters of PBW of CSNS.

beam power	100 kW
beam energy	1.6 GeV
beam distribution	2D Gaussian distribution σ(27 mm, 6.3 mm)
pulse length	500 ns
repetition frequency	25 Hz

2 Material selection

The material should make the scattering effect and energy deposition low, the highest temperature and stress should be below the allowable value.

Inconel alloy and aluminum alloy are common materials for PBW. SNS and ISIS used Inconel alloy for its resistance for corrosion and adaptability to extreme environments [6, 7]. J-PARC and ESS used aluminum alloy for its low energy deposition, low scattering effect, and good thermal conductivity [2, 3]. In this study, corrosion-resistant materials Inconel718 and A5083 are considered and contrasted. Table 2 lists the energy deposition when a single 1.6 GeV proton passes through each material, which is calculated using SRIM. It comes from ionization and Coulomb scattering, and is mainly related to density when the proton energy is the same. The results show that the energy deposition per proton on A5083 is one third of that on Inconel718. Besides, the scattering effect of A5083 is better than that of Inconel718 [8]. These are the two main reasons for the CSNS to choose A5083 as the PBW material. Considering that the annealing state can persist at a constant strength [9], A5083-O was finally chosen. To have enough margin, the designed allowable temperature $[T]$ is set to

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below 82.5 ℃, the designed allowable stress [S] is set to below 72 MPa.

Table 2. Energy deposition of 1.6 GeV single proton.

material	density/ (g/cm^3)	($\mathrm{d}E_\mathrm{e}/\mathrm{d}x$)/ (MeV/mm)	($\mathrm{d}E_\mathrm{n}/\mathrm{d}x$)/ (MeV/mm)
Inconel718	8.19	1.216	1.208×10^{-4}
A5083	2.67	0.4387	4.383×10^{-5}

3 Energy deposition and structure analysis

Because of the high energy deposition of the PBW and the temperature limit, water cooling is important and introduced, the convection of He and thermal radiation are ignored.

3.1 Energy deposition distribution

The deposition power of a 100 kW proton beam passing through the PBW is calculated using Eq. (1), which is 32.91 W/mm. The beam is of 2D Gaussian distribution, and the center of the beam overlaps with the PBW center. The energy deposition distribution can be expressed as Eq. (2).

$$q = \frac{nP}{E}\times(\mathrm{d}E_\mathrm{e}/\mathrm{d}x+\mathrm{d}E_\mathrm{n}/\mathrm{d}x). \quad (1)$$

$$Q = t\cdot C\mathrm{e}^{-\left(\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right)}. \quad (2)$$

P is the beam power, E is the proton energy, Q is the energy deposition distribution, q is the power loss per millimeter in PBW, n is the safety factor, and t is the thickness of PBW.

According to sufficient design and calculation by our physical design colleagues, the beam standard deviation is (27 mm, 6.3 mm), then the peak value of energy deposition $3.08\times10^7\mathrm{W/m^3}$ is obtained. The energy deposition distribution is plotted as shown in Fig. 1 with a 2 mm thickness PBW.

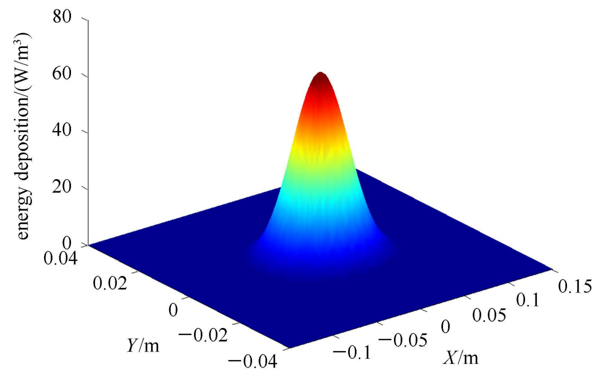

Fig. 1. Energy deposition distribution on a 2 mm thickness PBW.

3.2 Cooling structures analysis

There are mainly two PBW cooling structures in existence: the sandwiched structure and the multiple pipes structure [2–4]. Only ESS used a multiple pipes structure because its power is too high for a sandwiched structure. The sandwiched structure is a reasonable method for SNS and J-PARC, but the energy deposition and scatting effect are high and the activation of cooling water is serious. Because CSNS has lower beam power, a single layer structure with edge water cooling is considered, which has low energy deposition, a small scattering effect

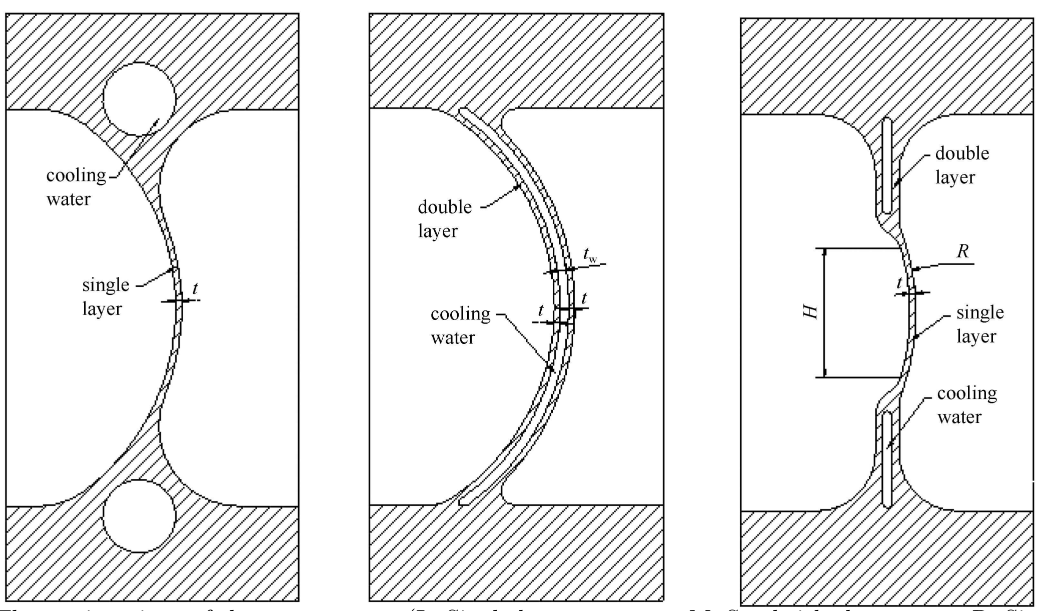

Fig. 2. The section views of three structures. (L: Single layer structure; M: Sandwiched structure; R: Single-double layer structure).

and little water activation, but the simulated temperature is too high for A5083-O. Then single-double layer structure is introduced with both advantages of the two structures. The middle 180 mm×38 mm region is single layered, which is larger than 3 times of the standard deviations region of the proton beam; the up and down sides are double layered.

Figure 2 displays the section views of these structures. Fig. 3 shows the temperature calculated from these structures. Obviously, there is no need to use sandwiched window, and the single-double layer structure can meet the temperature demand well.

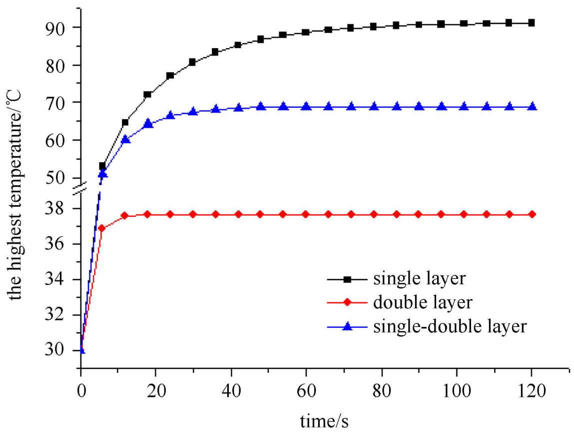

Fig. 3. Temperature comparison of cooling structures.

3.3 Structure optimization

The thickness of the single layer has little effect on temperature because the cooling water is at the sides of the beam area. The scattering effect has been simulated, which recommended a thin window, the results are shown in Fig. 4 [8]. However, thin window will enhance the machining difficulty. By overall consideration, a thickness of 2 mm is selected.

Table 3. Highest temperature and stress of three shapes.

	flat	cylinder	ellipse
the highest temperature/℃	67.1	68.8	72.8
the highest von mises stress/MPa	69.4	56.9	42.4

The conventional shapes of PBW are cylinder (SNS/ISIS), sphere (SINQ) and multiple pipes (ESS). Here three single layer shapes are considered, which are flat, cylinder and ellipse, with the same height of 38 mm (about $3\sigma_y$). Table 3 lists the comparison. For the cylinder and ellipse, the radii have been roughly optimized. The temperature distributions of the three structures are almost the same, but the stresses have differences. The stress of the ellipse shape is the lowest, and that of the flat shape is the highest, this is because the curving shapes of cylinder and ellipse enhance the rigidity, then the press-resistant ability is better than the flat one.

All three shapes can meet the design demands. Considering the machining difficulty, safety and design margin, the cylinder structure is used. Thus the height of the single layer can be optimized further.

To get the optimal structure, the height H and radius R are discussed. According to the calculation, the rate of a beam passing through the single area is 99.7% when the height of single area is 38 mm. When the height is 44 mm ($3.5\sigma_y$), that rate is 99.9%, the highest temperature is 72.5 ℃, and the highest stress is 60.5 MPa, which meet the material demands well. So the height of the single area is adjusted to 44 mm.

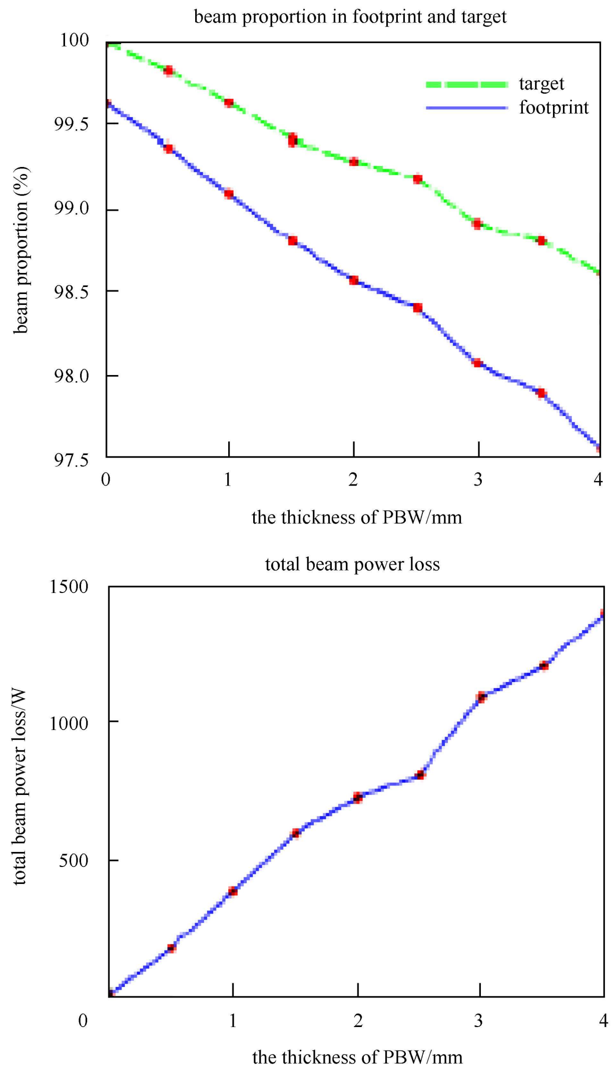

Fig. 4. The scattering effect varies with thickness.

Figure 5 shows the effect of cylinder radius. The highest temperature and stress hardly vary, the radius of 80 mm is chosen mainly depending on the thickness at the sides of single layer (which is 2.08 mm and the designed one is below 2.1 mm) and the largest displacement. The distributions of temperature, stress and displacement of the final structure are shown in Fig. 6.

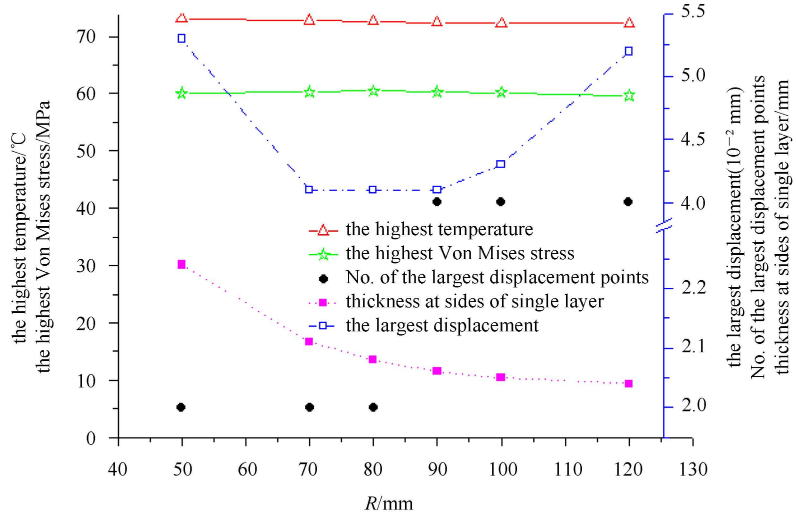

Fig. 5. The selection of radius.

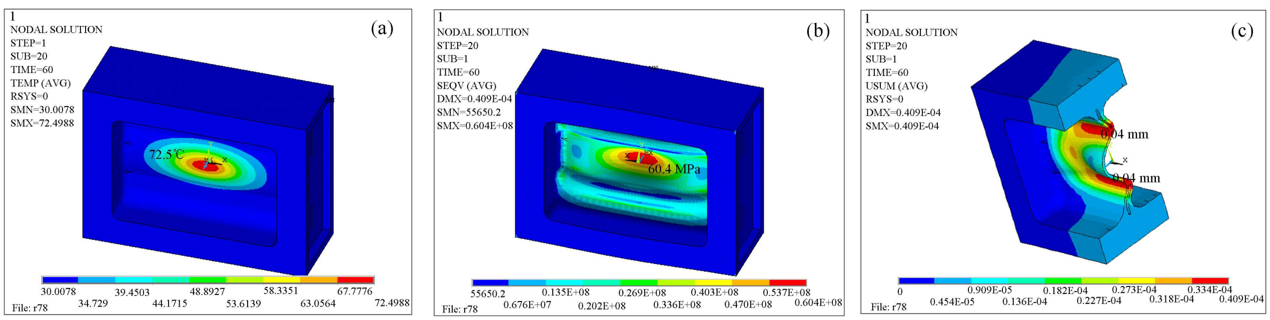

Fig. 6. The analysis results of final structure. (a) The temperature distribution; (b) the Von Mises stress distribution; (c) the displacement distribution.

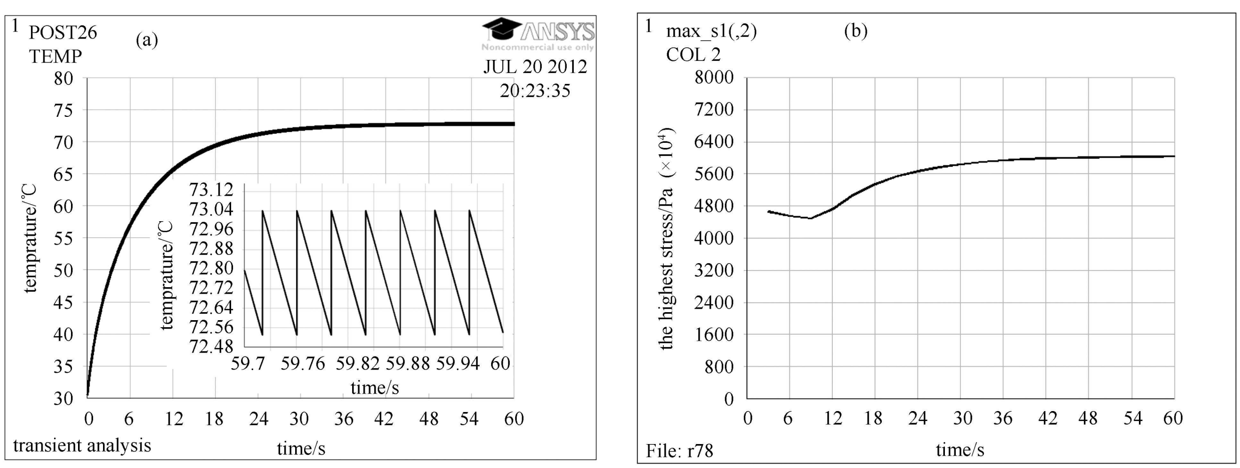

Fig. 7. The highest temperature and stress vary with time. (a) The highest temperature varies with time; (b) the highest Von Mises stress varies with time.

3.4 Transient analysis

The balance state is also important for the project. Fig. 7 shows that the highest temperature and stress vary with time. The equilibrium time is about 50 s, the highest temperature varies by about 0.5 ℃ per pulse, which means the fatigue effect can be ignored.

4 Safety confirmations

ANSYS uses the finite element method, thus the quality of elements is very important. The peak value of energy deposition displayed by ANSYS is 3.06×10^7 W/m^3 (Fig. 8), and the statistical power is 65.74 W, which are almost the same as the designed values. The element partition has no problem.

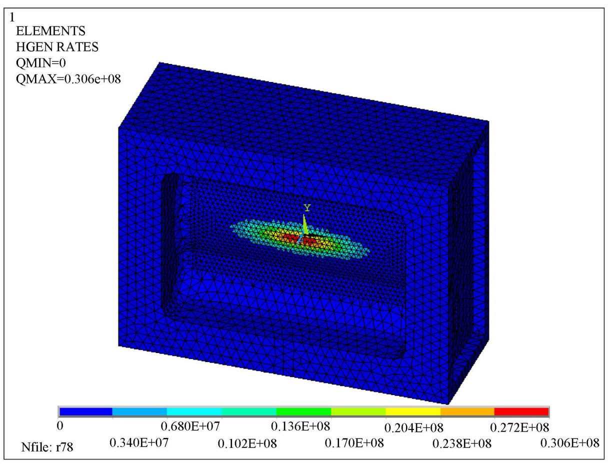

Fig. 8. Energy distribution in the ANSYS model.

When working, the PBW may meet many harsh environments, the PBW design must make sure that the PBW can work properly under these environments.

4.1 Effect of the convective coefficient

The actual convective coefficient (K) may not reach the designed value because of tube blockage. The effect of K is analyzed. Meanwhile, one side of cooling water blockage is considered where K is set to be 0. Fig. 9 shows the highest temperature and stress variation with the value of K.

Figure 9 shows that the PBW can bear a certain blockage of cooling water, the highest temperature is below 80 ℃ even when the value of K is 1000 W/(m^2·℃). When K is over 3500 W/(m^2·℃), the highest temperature and stress hardly vary, that is to say, the selected 5000 W/(m^2·℃) is proper.

4.2 Effect of beam parameter changes

The beam may not work as the designed profile and orbit, thus the analysis of the effects of beam profile and beam centroid orbit is necessary.

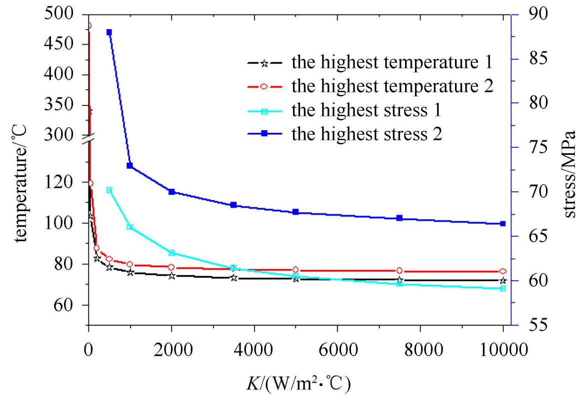

Fig. 9. The highest temperature and stress of the PBW vary with K. (1 denotes the values of K of two sides are equal, 2 denotes that of one side are 0).

Table 4 demonstrates that when the beam profile shrinks to standard deviation (21 mm, 6.5 mm), the highest temperature and highest stress reach the allowable value [T] and [S]. So, the beam standard deviation must be larger than (21 mm, 6.5 mm). Fig. 10 indicates there is no problem in the case of centroid orbit shifts, which may happen during beam commissioning or because of installation error.

Table 4. Effect of beam profile.

beam profile (σ_x, σ_y)/mm	the highest temperature/℃	the highest stress/MPa
100%* (27,6.3)	72.6	60.5
95% (25.7,6)	74.4	62.6
90% (24.3,5.7)	76.2	64.7
85% (23,5.36)	78.3	67.2
80% (21.6,5)	81.0	70.6
75% (20.3,4.7)	83.8	74.0

*beam profile shrinks to scale along x and y directions

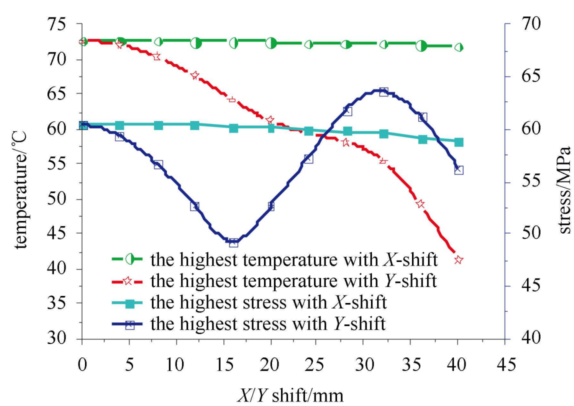

Fig. 10. The effect of X/Y shift on the highest temperature and stress.

5 Conclusions

The properties of the PBW is crucial to the CSNS, and the analysis gives a reference to PBW design. According to the beam characteristic, the energy deposition is simulated, based on which A5083-O is selected as the PBW material. The single-double layer structure is first proposed based on thermal simulation. Using the ANSYS code, different structures are contrasted, which shows the optimized structure can meet the temperature and stress demands well. Besides, the balancing state shows fatigue can be ignored. Safety is confirmed according to its status in cases of cooling tunnel blockage, beam profile shrinkage, or centroid orbit offset. It provides a judgment of the designed structure. Meanwhile, the scattering effect and radiation damage have been analyzed and confirmed. The PBW is now under technological design.

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