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DESIGN OF HIGH-POWER GRAPHENE BEAM WINDOW*

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Abstract

Beam window is a key device in high-intensity hadron beam applications, and it is usually used to separate air or other gas environments in the end of beam vacuum duct. Compared with the usually-used window materials such as Inconel alloy, Aluminum alloy and so on, the graphene has extremely high thermal conductivity, high strength and high transparency to high-energy ions. With the maturation of large-size graphene manufacturing technology, we have studied this new-type window for MW-class proton beam. The thermal analyses by the theoretical formula and simulations based on FEA are presented in this paper. Simultaneously, the scattering effect and the lifetime are also discussed. The preliminary results are promising. The same material can also be possibly applied to other devices such as charge-exchange stripping foils, beam monitors and so on.

INTRODUCTION

For high-power hadron beam applications such as spallation neutron sources, accelerator-driven systems, beam window is a key device. It separates the high vacuum region in the accelerator from air or other gas environments. The beam passes through the window to impinge the target or beam dump. The commonly-used materials of hadron beam window are aluminum alloy, Inconel alloy and so on. For a beam dump window usually with reduced beam power, the cooling method can be air cooling [1]. However for the window in front of the target, the main cooling method is water cooling, though different cooling structures can be used according to beam power, such as surface cooling at SNS and J-PARC [2-3], side cooling at CSNS [4], and multi-pipe cooling at ESS and C-ADS [5-6]. Table 1 lists some window designs.

Table 1: Beam Windows for Some Accelerators

Location	Material	Cooling structure	Beam power (MW)
CSNS	A5083	Side cooling	0.1
SNS	Inconel718	Surface cooling	1.0
J-PARC	A5083	Surface cooling	1.0
ISIS	Inconel718	Surface cooling	0.16
ESS	A6061-T6	Multi-pipe cooling	5
C-ADS	A6061-T6	Multi-pipe cooling	15

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As high power accelerators are developing rapidly, there are much stricter requirements on the hadron beam window. Important concerned issues include cooling, scattering effect, radiation damage, mechanical strength and so on, especially cooling. Therefore, it is important to find new types of materials to solve these problems.

In this paper, graphene is introduced and studied as a candidate material for multiple-MW beam power, as it has extremely high thermal conductivity [7], high strength [8], high transparency to high-energy ions [9] and impermeability for gases including helium [10]. The study will show that the temperature in a graphene window is so low that there is no need for cooling water even for MW-class beams, and the scattering effect can also be neglected due to its very thin structure. Besides, the radiation damage effect in term of DPA (displacement per atom) is calculated and the lifetime is discussed.

THERMAL AND STRESS ANALYSES OF GRAPHENE WINDOW

The thermal conductivity of monolayer graphene can reach 4840-5300 W/(m.°C) at room temperature [7], which outperforms the conventional window materials. Thermal analyses are performed to demonstrate the splendid thermal properties of a graphene window.

Suppose a proton beam of 1.6 GeV in energy and 10 MW in beam power and 60 mm×60 mm in beam size with a uniform distribution is used. The window is air cooled on one side. For a graphene window of a square foil, the temperature distribution can be calculated using the method of separation of variables.

$$T(x,y,z) = T_f + \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} C_{mn} \frac{ch[\eta_{mn}(b-z)] + \alpha sh[\eta_{mn}(b-z)]}{sh(\eta_{mn} b) + \alpha ch(\eta_{mn} b)} \sin(\beta_m x)\sin(\gamma_n) \quad ,(1)$$

in which,

$$\beta_m = \frac{m\pi}{2L}, m = 1,2,3...$$

$$\gamma_n = \frac{n\pi}{2L}, n = 1,2,3...$$

$$\alpha = \frac{h}{k\eta_{mn}}$$

$$C_{mn} = \frac{H_f}{kL^2\eta_{mn}\beta_m\gamma_n}\{\cos[\beta_m(L+a)] - \cos[\beta_m(L-a)]\} \cdot \{\cos[\gamma_n(L+a)] - \cos[\gamma_n(L-a)]\}$$

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In Eq. 1, L is half of the side length of the square, here L=0.075 m; a is the beam size as mentioned above, here a=0.06 m; b is the thickness of graphene foil, here b=0.335μm (100 layers); H_f is the energy deposition, and heat flux is used here because the foil is very thin; h is the convection coefficient of natural air, 5W/(m^2.°C) at 30 °C; k is the thermal conductivity of graphene, 4840 W/(m. °C).

The temperature distribution can be calculated by using Eq. (1) and the highest temperature is 73.3 °C. This is consistent to the thermal analysis using ANSYS which shows that the highest temperature is 73.7 °C. The temperature distribution by ANSYS is shown in Fig. 1.

If the beam is changed to a round one with 2D Gaussian distribution and the rms size or σ is 20 mm, which is 1/3 of a, we find that the highest temperature is 55.1 °C(Fig. 1), which is lower than that of the uniform distribution beam. This is to say, even if the beam is not uniform, there is no bad effect on temperature in a grahene window.

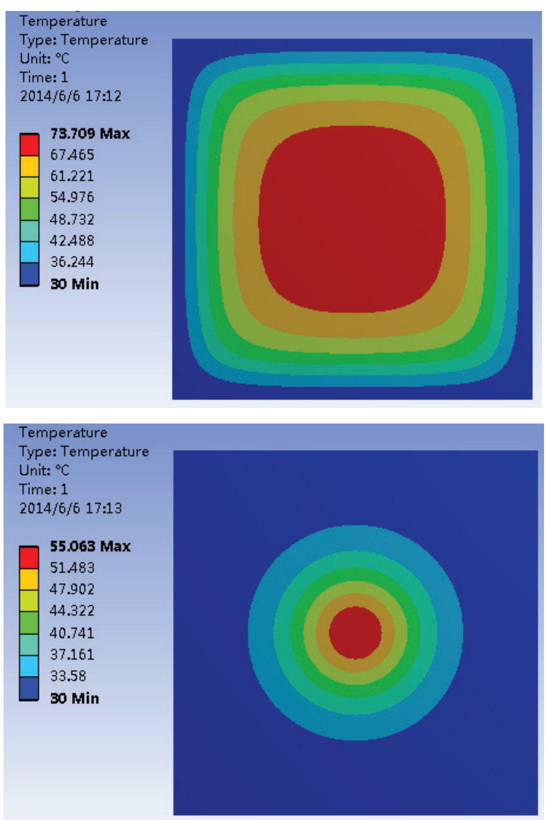

Figure 1: Temperature distribution in a graphene window with 10 MW in beam power (Up: uniform squared beam, a=0.06 m; Down: 2D Gaussian round beam, σ=0.02 m).

The highest temperature increases when the beam power is larger. Table 2 shows the highest temperatures in the window with the corresponding beam power. The beam is the 2D Gaussian round beam as mentioned above. Surprisingly, the highest temperature in the graphene window is only 155.3 °C even if the beam power reaches to 50 MW, still far below the melting point of the material.

Table 2: The Highest Temperatures in the Graphene Window with Different Beam Powers

Beam power (MW)	1	10	30	50
Highest temperature (°C)	32.5	55.1	105.2	155.3

A very low temperature also means that the thermal stress is small, so the main cause of the stress in the window is the Hooke stress of air pressure, which can be calculated using the formulae in Table 3. It is evident that a curved window is helpful to decrease the stress. Suppose the air pressure is 1 ATM, the window has cylinder shape with a diameter of 150 mm, and the window is of 100 layers of graphene (0.335 μm in thickness), the highest Hooke stress is about 22.4 GPa, far less than the breaking strength of about 130 GPa [8]. As the window is very thin, there may be other problems, such as wrinkling, which should be considered in further studies.

Table 3: Expressions for Highest Hooke Stress of Different Window Shapes

Window shape	**Highest Hooke stress**
Flat (circular)	$\sigma_{\max} = \pm 0.188 p(D/\delta)^2$
cylinder	$\sigma_{\max} = pD/2\delta$
sphere	$\sigma_{\max} = pD/4\delta$

BEAM SCATTERING EFFECT

Graphene has a property of high transparency to high-energy ions due to the composition of light elements, so it is an ideal material for beam window. To simply estimate the beam scattering effect in the window which will degrade the beam and may produce abnormal beam distribution at the target, we considered the window as carbon foil and the beam as the 2D Gaussian round proton beam mentioned above. Suppose the non-normalized emittance is 10 π.mm.mrad. The beam scattering effect in the window with different thickness is calculated by FLUKA, the model is shown as Fig. 2 and the results are shown as Fig. 3.

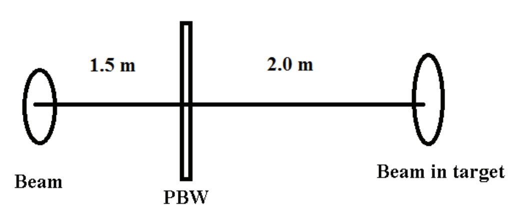

Figure 2: Calculation model for the beam scattering effect.

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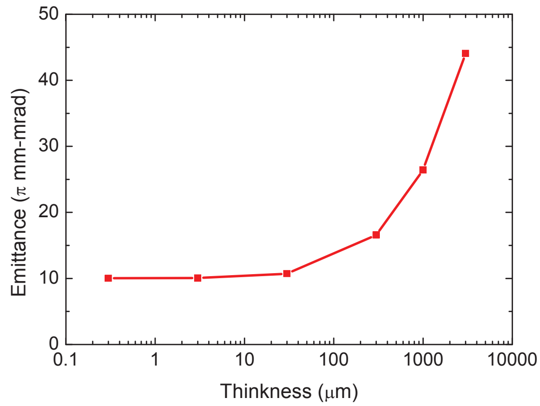

Figure 3: Beam emittance with respect to the thickness of graphene window due to the beam scattering effect.

Figure 3 shows that when the thickness is smaller than 100 μm, the increase in beam emittance due to the beam scattering effect is quite small, but increases rapidly afterwards. As a comparison, for the windows made of the other materials, the thickness is in the order of about 1 mm, the increase in the beam emittance must be considered.

DISCUSSION ON LIFETIME

The beam passing through the beam window can cause defection of the window. The DPA effect in the window has been calculated by using FLUKA. Once again, the beam is defined as the 2D Gaussian round beam defined above. Suppose the operation time is 7200 hours per year, the DPA distribution is shown in Fig. 4. The peak current density here is 251 μA/cm^2 and the max DPA is about 8.1/y.

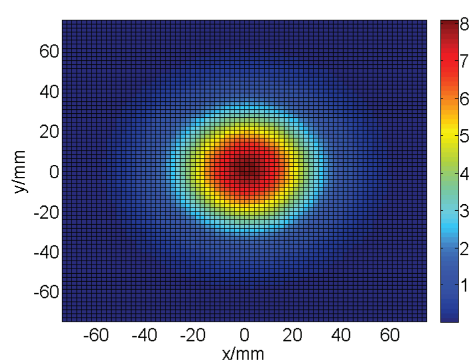

Figure 4: DPA distribution in the graphene window.

The actual DPA should be smaller because the result calculated by algorithm developed for bulk solids is larger than that of two-dimensional systems [9].

There is no conclusion about what the max DPA graphene can endure yet, but it is sure that graphene has certain resistance to irradiation. It has high mechanical stability and good impermeability for small atoms such as helium even with a high vacancy concentration [11]. The applicable lifetime for graphene needs further investigation.

CONCLUSION

A new type beam window made of graphene for MW-class proton beams is proposed and studied. Thermal and stress analyses show that graphene is a potential material to replace usually-used materials for beam windows in extremely high power beams. The beam scattering effect is also estimated, and it turns out that the light elements composition and thin thickness make the graphene window less problematic. The DPA effect due to irradiation has been calculated and the lifetime of a graphene window is discussed. It looks very promising for using graphene windows for high power beams. Many detailed investigations need to pursued before the material can be exploited in real beam window applications.

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