PRIMARY STUDY OF HIGH POWER GRAPHENE BEAM WINDOW *

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Abstract

Beam windows are usually used to isolate vacuum or other special environments, which is a key device for high-power accelerators. Graphene has extremely high thermal conductivity, high strength and high transparency to high energy ions. It is highly suitable for beam windows if the technology is allowable. This paper will discuss the primary tests of graphene films, including vacuum performance and thermal conductivity performance, as well as the simulated performance of an assumed graphene window.

INTRODUCTION

Beam window is a key device for the high-power hadron beam accelerators such as neutrino factory, spallation neutron sources and accelerator-driven systems. It is used to separate different atmospheres. The commonly used materials are Aluminium alloy [1-4], Inconel alloy [5], Beryllium/ AlBeMet [6], and so on. The cooling methods can be air cooling [5], side water cooling [1], surface water cooling [2] or multi-pipe water cooling [3-4], according to the beam power. Among the ever-fabricated beam windows, the multi-pipe water cooling window made of the Aluminium alloy has the best cooling ability, which can endure about 5 MW beam power while the beam size is double Gaussian with ± 2σ·within footprint of 200 × 60 mm.

Generally, the low-Z materials are preferred for the beam window, because they have low scattering effect, which may change the distribution of the beam [7]. The energy deposition generalized by the beam can lead the temperature and stress increases of the window, which are the two bottlenecks of high-power beam windows. Beryllium has good thermal and mechanical properties among the commonly used metals, but is has some usage restrictions and cannot improve the endurable beam power largely. Some graphitized polyimide film such as GPI has very high thermal conductivity up to 1750 W/mK but it is too brittle to be used (tensile strain about 3%), as well as the diamond film (thermal conductivity 900-2320 W/mK and strain 0.4%-0.6%) [8].

Graphene is a monolayer 2D carbon allotrope which has extremely high thermal conductivity up to 5300 W/mK [9], high strength up to 130 GPa intrinsic strength [10], and high transparency to high-energy ions [11]. Owing to these ideal material performance, we proposed the concept of high-power graphene beam window [12]. This paper will focus on the recent progress of our study, including the vacuum performance tests, the thermal conductivity performance and the simulated performance of an assumed window.

Particularly, the monolayer or multilayer graphene by now are too thin to be used as a macroscopic material, in this paper we call them graphene. Meanwhile, there are some graphene-based macroscopic materials such as reduced graphene oxide, in this paper we call them graphene film.

VACUUM PERFORMANCE TESTS

An experiment facility has been built for the vacuum performance tests, which is shown in Fig. 1. After a 24 hours baking and the detection of background, the GV2 was opened and the 1 atm helium was connected. The P-t curve of the sample film was recorded, the helium leak rate can be calculated as well. The detailed principles and data processing in in Reference 13 [13].

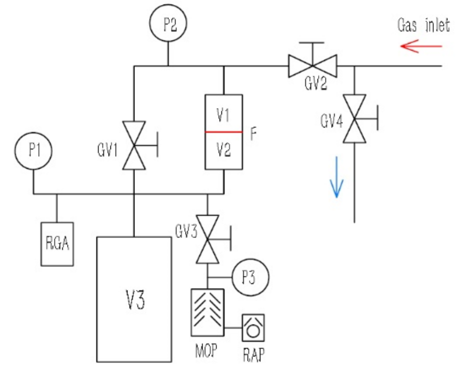

Figure 1 : Diagram of the vacuum test facility.

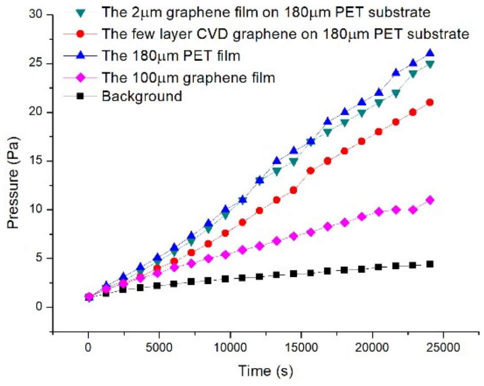

Figure 2 : P-t curves of the vacuum test.

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Table 1 : Detailed Results of the Vacuum Tests

	The 2 µm graphene film on 180 µm PET substrate	**The few layer graphene on 180 µm substrate**	**The 180 µm PET film**	**The 100 µm graphene film**
Helium leak rate tested by helium leak detector (Pa.m^3/s)	1.8×10^{-7}	4.2×10^{-7}	4.9×10^{-7}	8.4×10^{-9}
Helium leak rate calculated from P-t curves (Pa.m^3/s)	2.62×10^{-6}	2.37×10^{-6}	2.79×10^{-6}	1.01×10^{-6}
Diffusion coefficient（Pa.m^3/s）	8.86×10^{-12}	3.46×10^{-12}	1.35×10^{-11}	----
Solubility（mol/Pa/m^3）	1.92×10^{-4}	4.39×10^{-4}	1.33×10^{-4}	----
Permeant rate（mol/Pa/m/s）	1.7×10^{-15}	1.52×10^{-15}	1.79×10^{-15}	3.62×10^{-16}

Table 2 : Test Results of Thermal Diffusion Coefficient

Materials	**Thermal diffusion coefficient (mm^2/s)**			
	Location 1	**Location 2**	**Location 3**	**Average**
Nickel foil	27.944	31.817	30.633	30.141
Multilayer graphene on nickel foil	41.422	35.126	38.455	38.334
30 µm graphene film	728.94	710.845	741.151	726.979

There are four films tested, the 2µm graphene film on 180 µm PET substrate, the few layer CVD graphene on 180 µm substrate, the 180 µm PET film and the 100 µm graphene film respectively. The P-t curves are shown in Fig. 2.It demonstrates that both the few layer graphene and the graphene film have certain impermeability for helium. For all the films, the 100µm graphene film has the best vacuum performance. The leak rate is at the same level of the proton beam window requirement of CSNS, so it is likely the graphene film might be used if it can meet other requiremnts.

The few layer graphene is even better than the 2 µm graphene film. This may be because the graphene film is not as uniform and compact as the few layer graphene. The calculated leak rates from P-t curves are different from those test by helium leak detector, this may be because the tested ones are recorded 30 minutes after the vacuumizing, while the P-t curves are recorded two days after the vacuumizing, there may have some state change of the film. The detailed results are listed in Table 1.

THERMAL CONDUCTIVITY PERFORMANCE

Thermal Conductivity Tests

The ideal 2D graphene has a thermal conductivity up to 5300 W/mK, but it is hard to use directly. The graphene film is a good choice because it has certain thickness which can be used individually and has a thermal conductivity up to 1940 W/mK [8]. Some tests have been done to compare the thermal conductivity.

Table 2 shows the thermal diffusion coefficient tested of different films. For the multilayer graphene on nickel foil, the 105 nm multilayer graphene (about 300 layers) introduced a 27% enhancement of thermal diffusion coefficient of nickel foil of 25 µm. The proportion is expected to be 23% which we calculated using the equivalent thermal resistance method. It demonstrates that the thickness of graphene is too small to enhance the thermal conductivity performance largely. But for the graphene film, the thermal diffusion coefficient is much higher, which indicates the graphene film is more appropriate for beam windows by now. Figure 3 shows the thermal conductivity performance of different films. The four samples are adhered to a constant temperature platform, the thermal conductivity of graphene films are much better than nickel and aluminium.

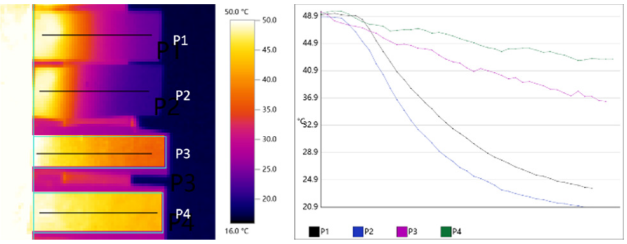

Figure 3: Thermal imagery (L) and temperature line (R) of four samples. (P1: 20 µm Aluminium, P2: 20µm nickel, P3: 20 µm graphene film, P4: 100 µm graphene film).

Thermal Analyses of an Assumed Graphene Window

To estimate the thermal conductivity performance of the graphene film, an "assumed" window model has been built, which is shown as Fig. 4. The window is composed of outer window and inner window. The outer window is made of aluminium alloy while the inner window is made of graphene film. The Vacuum tube is made of steel. To compare the performance, the one with an aluminium alloy inner window is analysed meantime. The proton beam is assigned as a uniform beam at the area of the inner window, which diameter is 100 mm. The kinetic energy is assigned to be 1.6 GeV. The inner diameter of the vacuum tube is assigned to be 214 mm. The thickness of the outer window is 2 mm and that of the inner window is 0.1 mm.

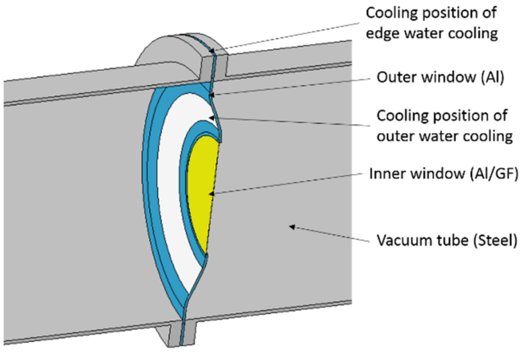

Figure 4: Window model for thermal analyses.

For each window, three cooling conditions have been analysed. The air cooling is that the convection coefficient is 3 W/(m^{2}K) at the nonvacuum side. The edge water cooling is that the convection coefficient is 5000 W/(m^{2}K) at the edge of outer window. While the outer water cooling is that the convection coefficient is 5000 W/(m^{2}K) at the curve part of outer window. The thermal conductivity coefficient of the graphene film is assigned to be 1200 W/m°C.

The operating temperature of graphene film can be up to 400 °C [14], so the highest temperatures of the aluminium alloy are compared to determine the endurable beam power. The comparison is shown in Fig. 5. For the assumed window, beam and cooling methods, the endurable beam power of aluminium window is less than 0.5 MW when the highest temperature of aluminium reaches 100 °C, which we think is unsafe. But for the window with graphene film at the centre, the endurable beam power can be enhanced by one or two orders of magnitude, up to 17 MW.

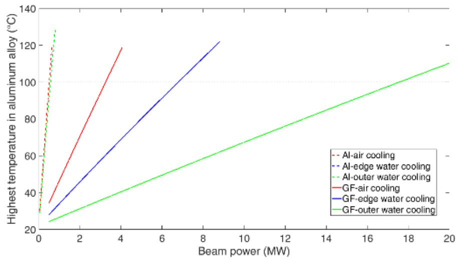

Figure 5: The comparison thermal conductivity performance of graphene window and aluminium window.

ANTI-PRESSURE ABILITY

Four graphene films of the diameter of 38 mm and thickness of 0.1 mm are tested. The edge of the graphene films are fixed by flanges. The failure pressures are 9.5 ×10^4 Pa, 1.64×10^5 Pa, 1.32×10^5 Pa, 1.84×10^5 Pa respectively. It shows that the graphene film can sustain 1 atm pressure. The differences may come from the nonuniform of the material or the manual operation.

For the window shown in Fig. 5, the stress will be smaller because the edge of graphene film is not fixed but connected to the metal film, which is allowed deformation. If the graphene film can be connected with other materials like aluminium, the anti-pressure ability can be better.

CONCLUSION

Graphene is an ideal material for high power beam window. But owing to the tiny thickness, it can't be used directly by current technology. Graphen film which has relatively high impermeability for gases like helium and high thermal conductivity, is a good candidate material. This paper described the vacuum tests, the thermal conductivity performance and the anti-pressure ability of graphene film. The results show that the graphene film can enhance the endurable beam power by one or two orders of magnitude. For the cases where the graphene film can sustain the pressure owing to small pressure or small diameter, it can be directly used as a beam window. For the cases where the graphene film cannot sustain the pressure, it might be used in the future with the development of the connection technology of graphene film and metals or the manufacture technology of higher performance materials.

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