PRIMARY STUDY OF HIGH POWER GRAPHENE BEAM WINDOW

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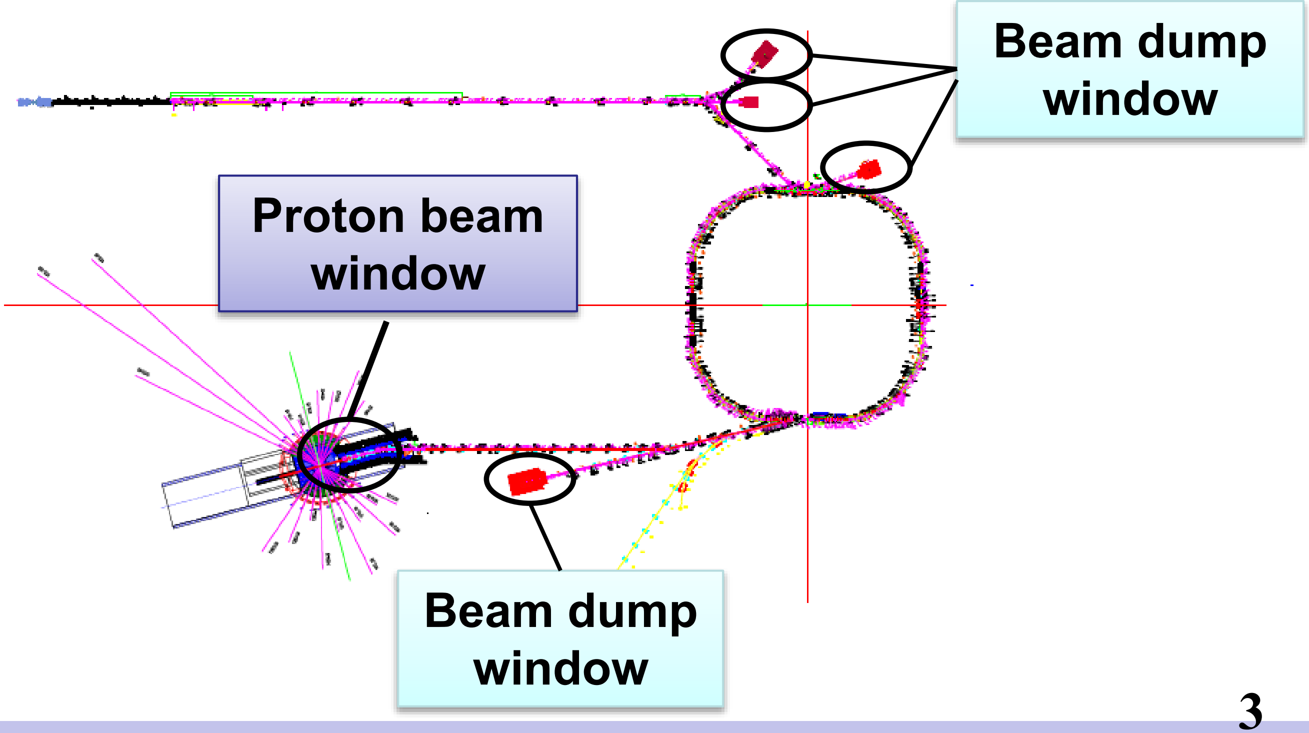
Outline

- Backgrounds
- Primary studies of high power graphene beam window
  - Vacuum performance
  - Thermal performance
  - Anti-pressure ability
  - Scattering effect
  - Radiation lifetime
- Summary

Backgrounds

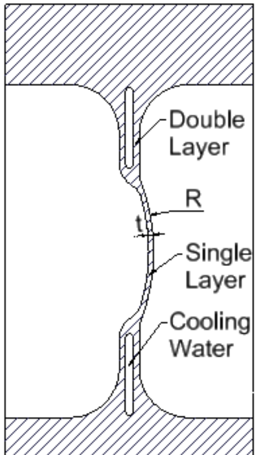
- What is high-power beam window?
  - Used to separate high vacuum region from other atmospheres.
  - Key device for high-power hadron beam accelerators.
  - Beam passes through the window to impinge the target or beam dump.



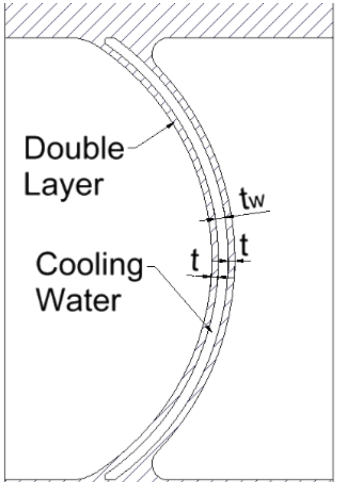
Backgrounds

Proton beam windows of some accelerators

- Side cooling (forced water)
  - CSNS (0.1 MW): A5083-O
- Surface cooling (forced water)
  - SNS (1MW): Inconel 718
  - J-PARC (1MW): A5083-O
  - ISIS (0.16MW): Inconel 718
- Multi-pipe cooling (forced water)
  - ESS (5MW): A6061-T6

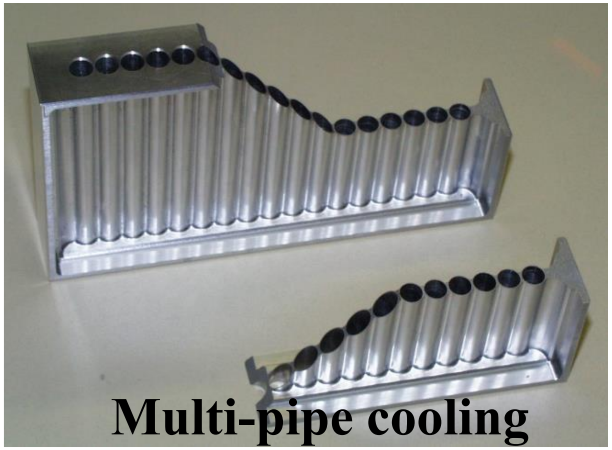


Side cooling



Surface cooling

Different structure (cooling), similar materials (metal)



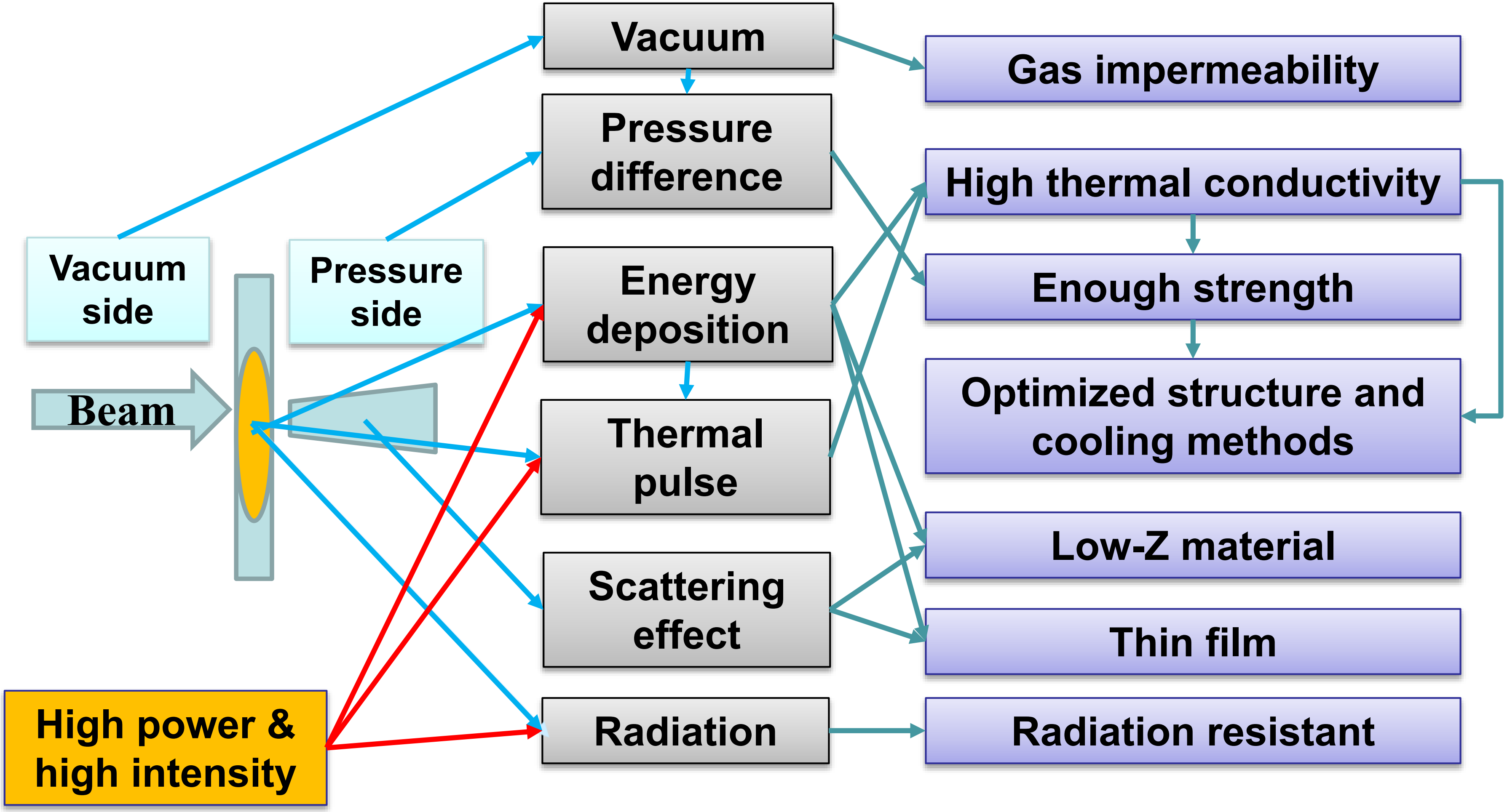
Multi-pipe cooling

Backgrounds

- High power high intensity (hadron) accelerators are more and more needed for different fields of science.
  - Spallation neutron source (eg. ESS 5MW, 2.5 GeV)
  - Accelerator-driven system (eg. CADS ~10 MW, 1GeV)
  - Neutrino facility (eg. MOMENT 15 MW, 1.5 GeV)
  - High intensity leads to high energy deposition. High power beam windows meet bottlenecks in heat dissipation and thermal stress.
- Beam window in study
  - Plasma window: in experimental stage

Backgrounds

- Requirements



Vacuum side

Pressure side

Beam

High power & high intensity

Vacuum

Pressure difference

Energy deposition

Thermal pulse

Scattering effect

Radiation

Gas impermeability

High thermal conductivity

Enough strength

Optimized structure and cooling methods

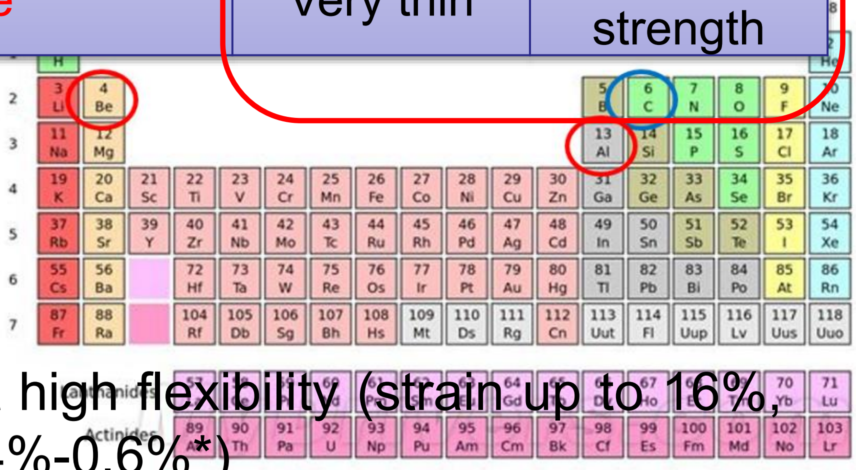
Low-Z material

Thin film

Radiation resistant

Backgrounds

Common-used materials	A6061-T6	Inconel 718	Beryllium	GlidCop Al-15
Thermal conductivity (W/(m·°C))	167	14.7	216	365
Questions	Thermal conduction problem			
Not-used materials	**Graphitized polyimide film (GPI)**	**Diamond film**	**Graphene**	**Graphene film**
Thermal conductivity (W/(m·°C))	Up to 1750	Up to 900-2320	Up to 4840-5300	Up to 1940
Questions	Brittle		Very thin	Low strength

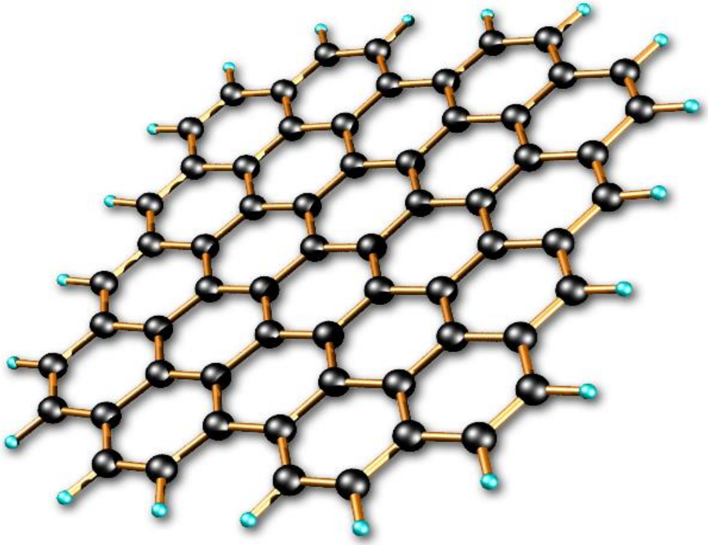


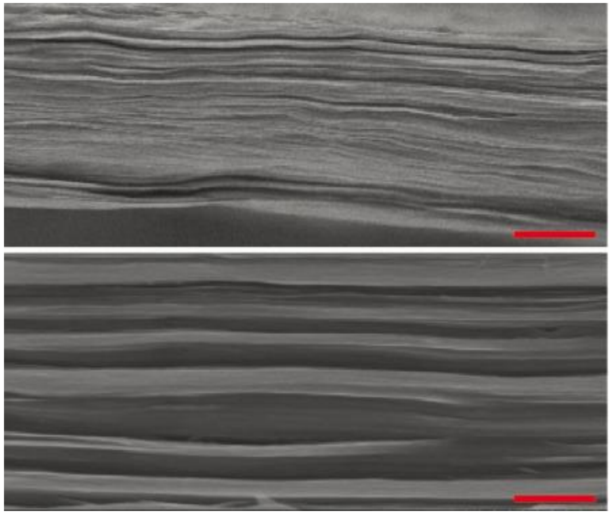
- Why Graphene?
  - Low-Z.
  - High thermal conductivity.
  - Graphene film: low strength but high flexibility (strain up to 16%, while GPI~3%, diamond film 0.4%-0.6%*)

* Li Peng et al. , *Adv. Mater.* 2017, *29*, 1700589

Backgrounds

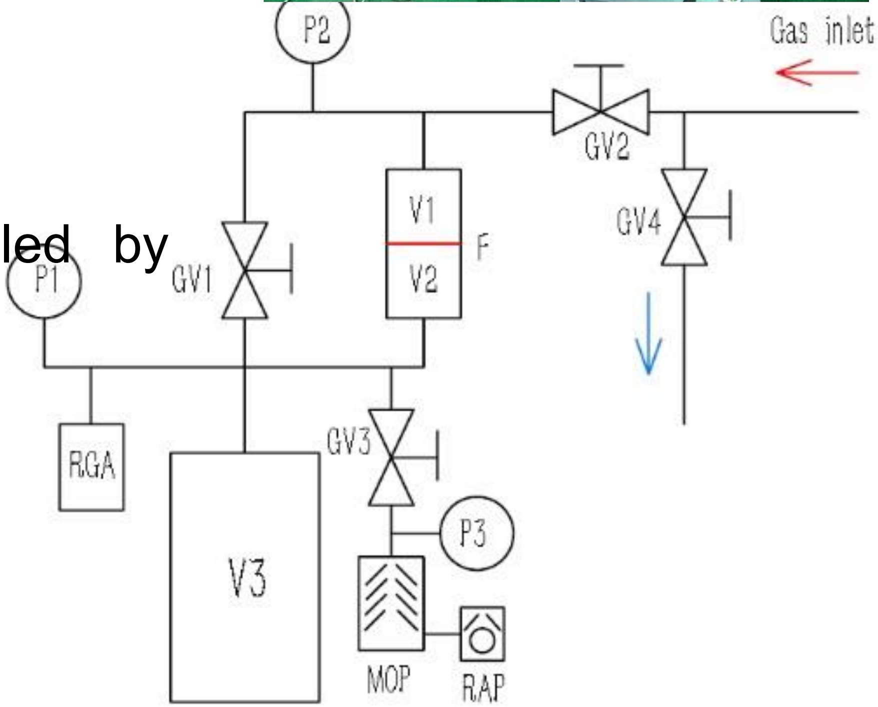
- Definition in this talk
  - Graphene:
    - Monolayer or multilayer 2D graphene such as CVD graphene.
    - Too thin to be used as a macroscopic material.
  - Graphene film:
    - Graphene-based materials such as reduced graphene oxide.
    - Can be macroscopic used.





Vacuum performance

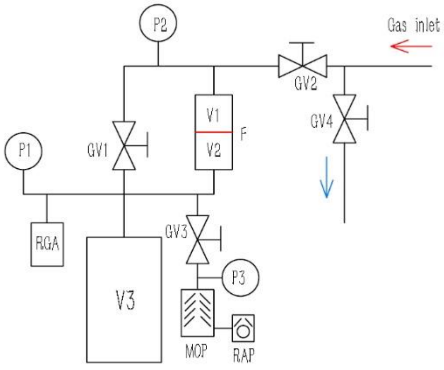
- Differential pressure method
- Facility:
  - V1: High pressure chamber.
  - V2 + V3: measured chambers much larger than V1.
  - P1/P2: Vacuum gauges.
  - RGA: residual gas analyzer.
  - F: Film to be tested, sealed by fluorine rubber.
  - GV 1-3: Metal angle valves.
  - GV4: Safety valve.



Pengcheng Wang et al., "GAS Permeability Measurement of Graphene Films", IPAC'18, this conference.

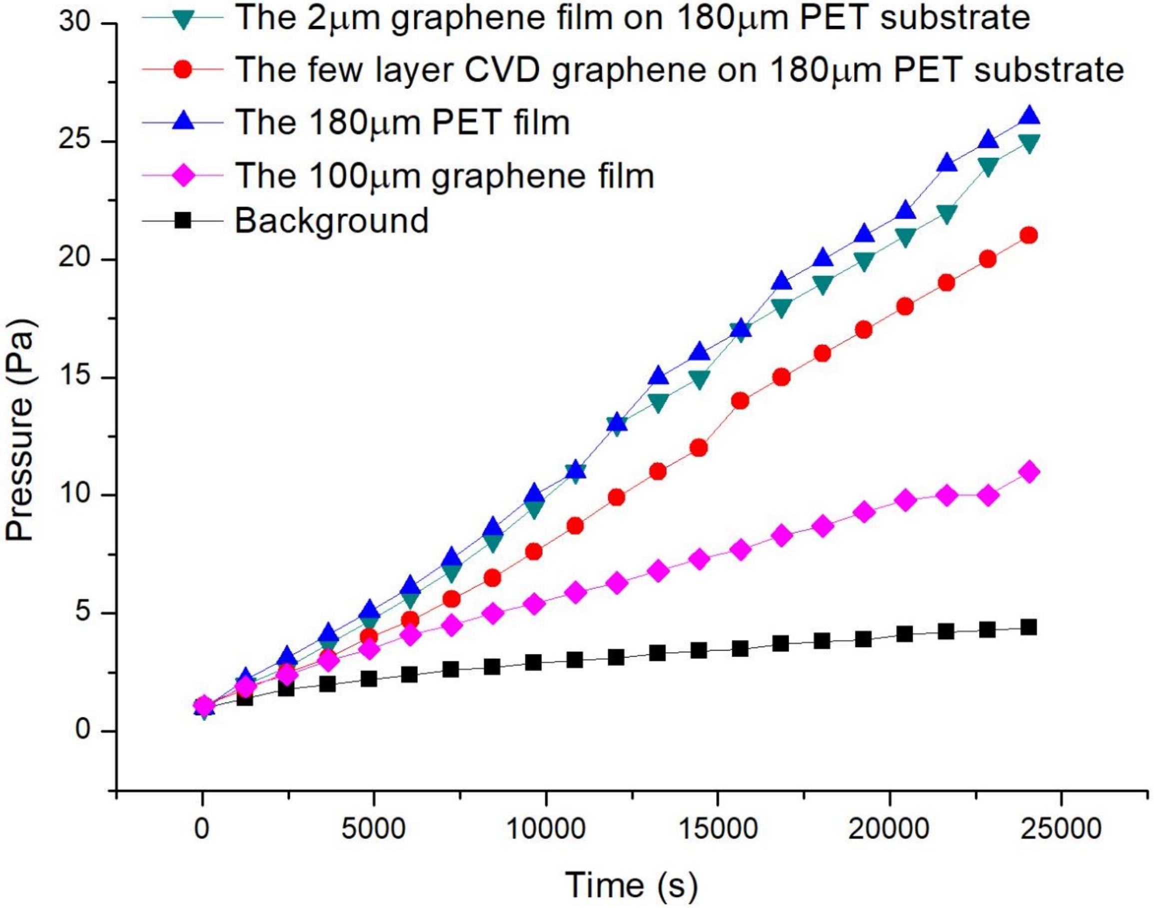
Vacuum performance

- Procedures:
  - Installation and leak detection.
  - Start pumps and bake for 24 hours.
  - Measure background P-t curve.
  - Measure P-t curves for different cases.
  - Data processing.



- 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
  - The 100 μm graphene film

Vacuum performance



Vacuum performance

Results comparison

- Leak rate difference from calculation and detection. The tested ones are recorded 30 minutes after vacuumizing. The P-t curves are recorded two days after the vacuumizing.
- For 100 μm graphene film, the saturation is too soon to test for our facility.

	The 2 μm graphene film on 180 μm PET substrate	**The few layer CVD 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}	----

Vacuum performance

Results comparison

- Both the few layer graphene and the graphene film have impermeability for helium.
- For all the films tested, the 100μm graphene film has the best vacuum performance.

	The 2 μm graphene film on 180 μm PET substrate	The few layer CVD 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}
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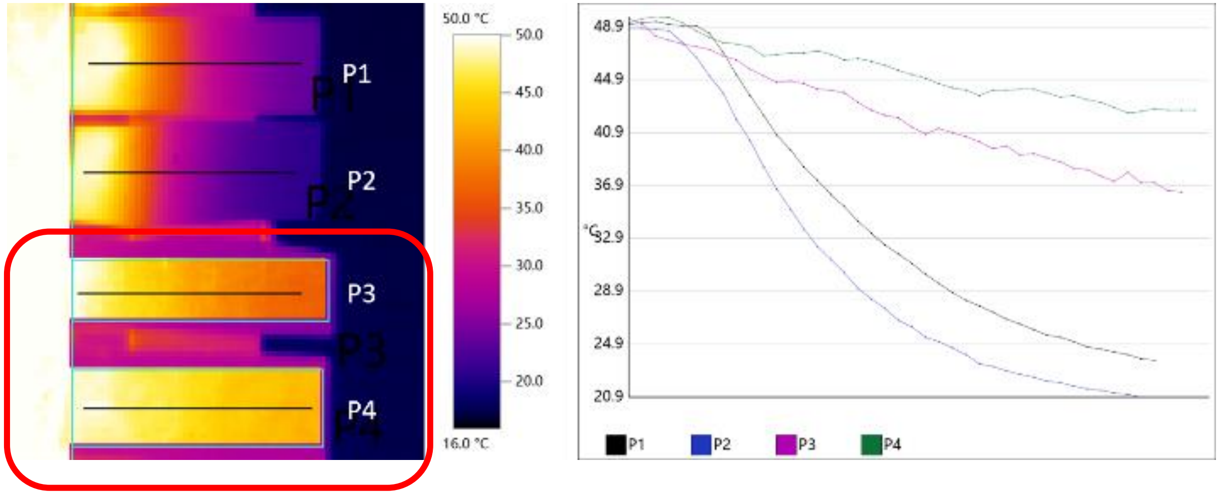
Thermal performance

Thermal diffusion coefficient test of some commercially available materials

Materials	Thermal diffusion coefficient (mm²/s)			
	Location 1	Location 2	Location 3	Average
25 μm Nickel foil	27.944	31.817	30.633	30.141
300 layers graphene on 25 μm nickel foil*	41.422	35.126	38.455	38.334
30 μm graphene film	728.94	710.845	741.151	726.979

***Tested 27% enhancement of nickel foil *vs* calculated 23% enhancement.**

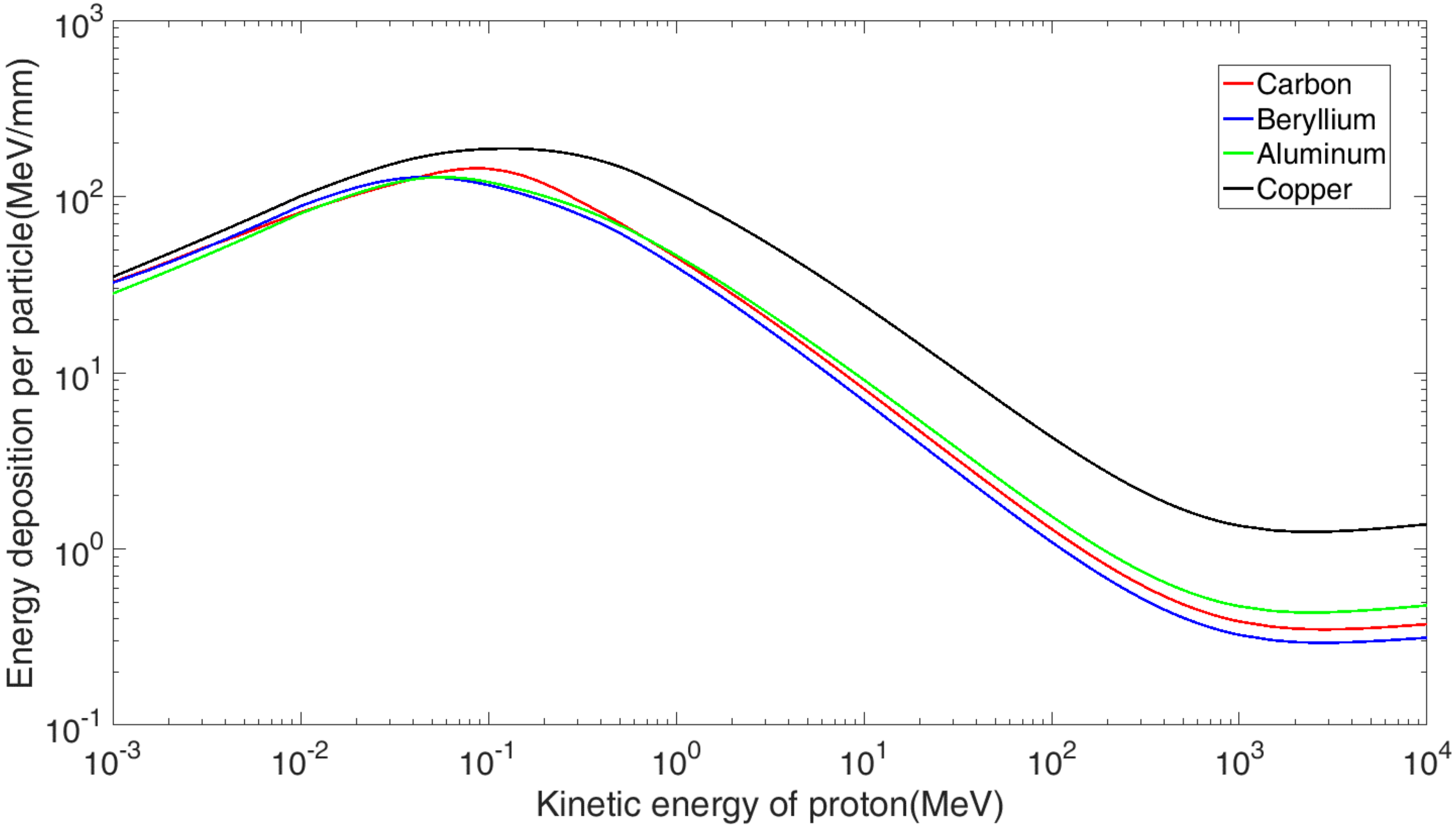
Thickness of graphene is too small to enhance the thermal conductivity largely.



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 performance

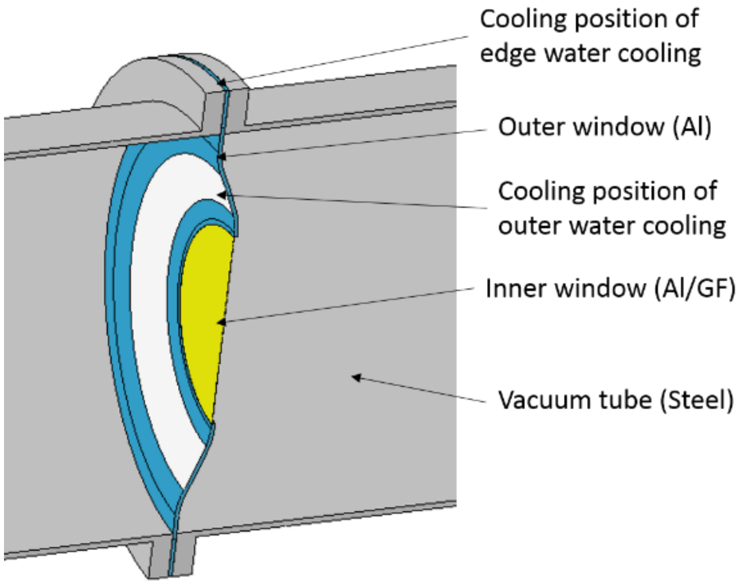
- Stopping power of Carbon is relatively low.



Thermal performance

Assumed window

- Inner window: A6061 vs GF
- Diameter of inner window: 100 mm
- Diameter of vacuum tube: 214 mm
- Thickness of inner window: 0.1 mm
- Thickness of outer window: 2 mm



Assumed beam

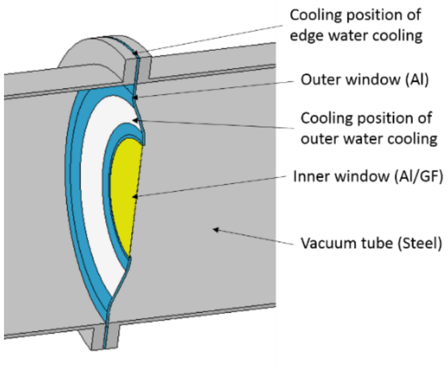
- Kinetic energy: 1.6 GeV
- Uniform at the inner window

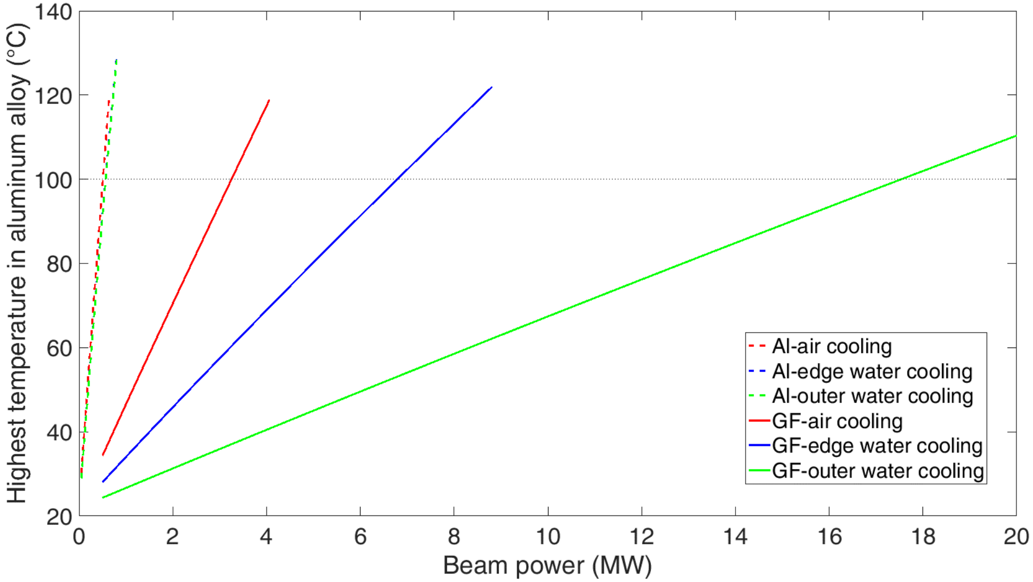
Cooling conditions:

- The air cooling: 3 W/(m^{2}K) at the nonvacuum side.
- The edge water cooling: 5000 W/(m^{2}K) at the edge of outer window.
- The outer water cooling: 5000 W/(m^{2}K) at the curve part of outer window.

Thermal performance

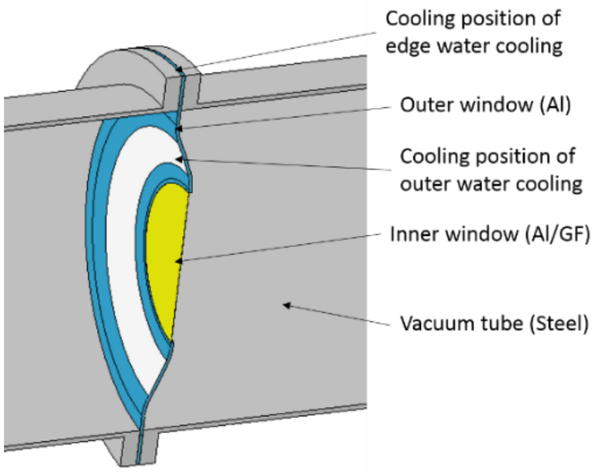
- Assigned thermal conductivity coefficient
  - GF: 1200 W/m°C
  - A6061: 167 W/m°C
- Endurable beam power
  - Inner window A6061: less than 0.5 MW
  - Inner window GF: up to 17 MW
  - Assumed window, assumed beam. The values are not real, but can indicate the effect.

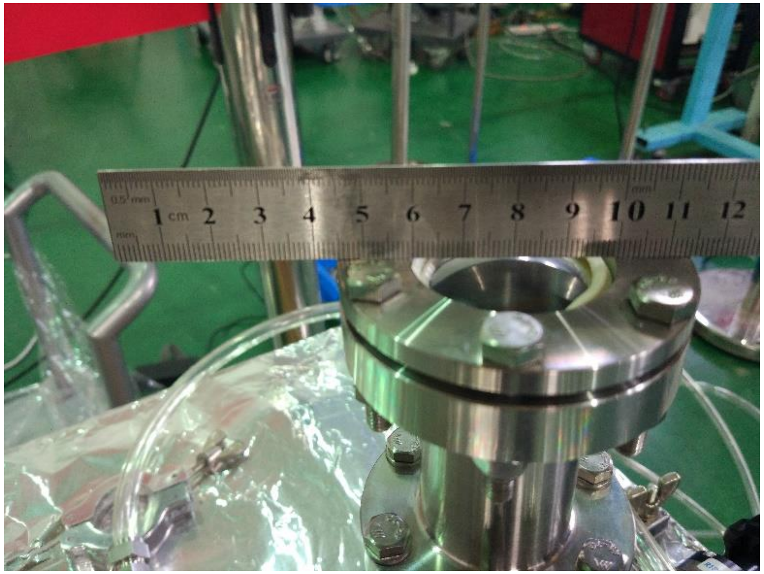




Anti-pressure ability

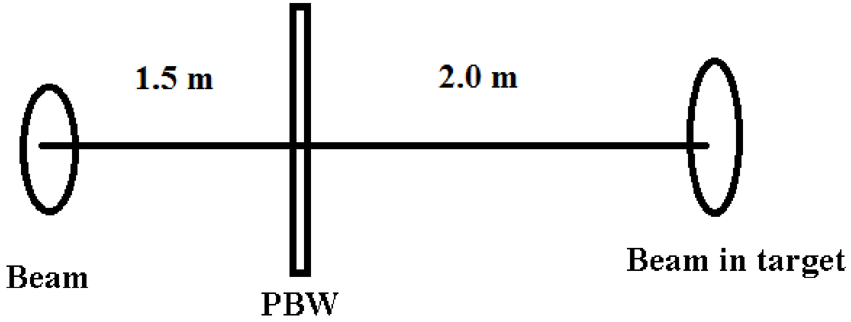
- Graphene film: diameter 38 mm, thickness 0.1 mm
- The failure pressures are 9.5×10^4 Pa, 1.64×10^5 Pa, 1.32×10^5 Pa, 1.84×10^5 Pa. Basically higher than 1 atm.
- For the assumed window, if the connection can be solved, the stress will be smaller because the edge of graphene film is not fixed but connected to the metal film, which is allowed deformation.

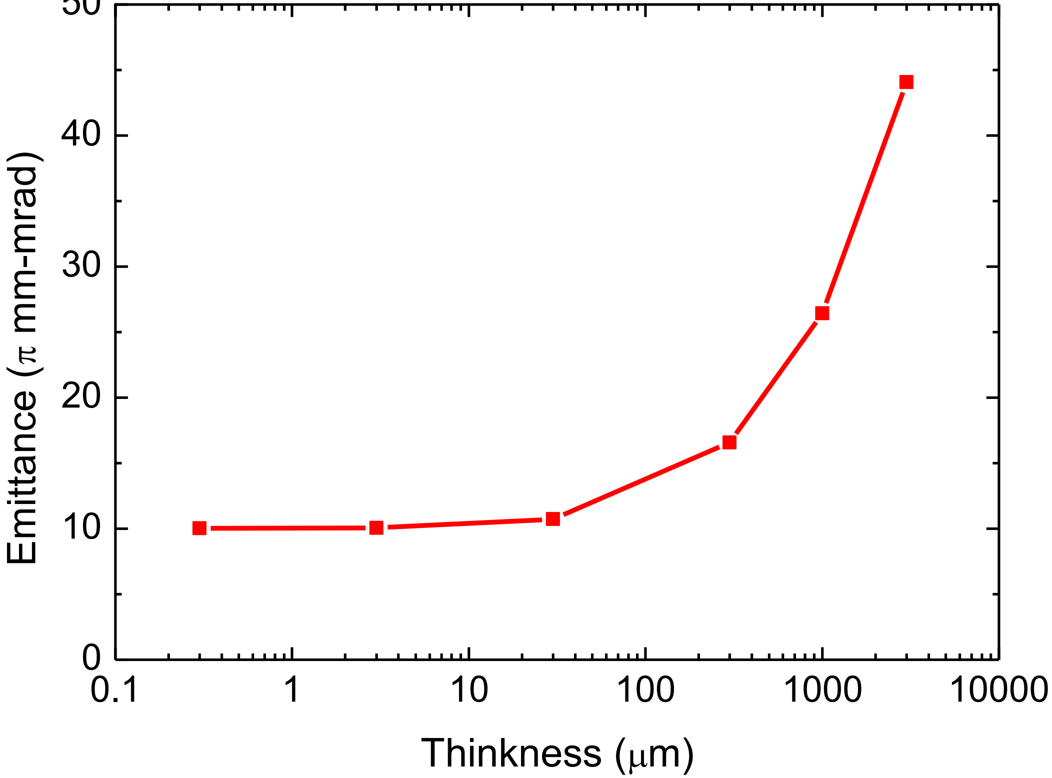




Scattering effect

- Scattering effect is low due to small thickness.

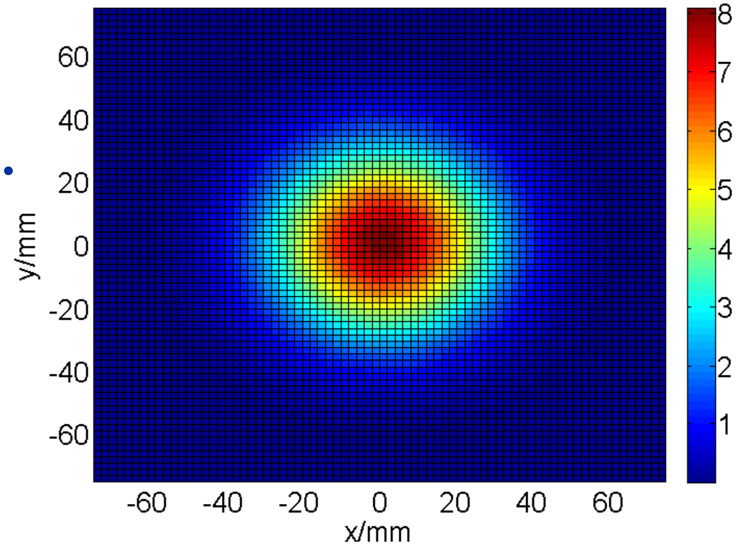




H. Wang et al., "Design of High-power graphene beam window", IPAC'14

Radiation Lifetime

- Graphene has certain resistance to irradiation
  - High mechanical stability and good impermeability for small atoms even with high vacancy concentration.#
- Calculation
  - Peak current density: 251 μA/cm2.
  - Max DPA is about 8.1/y*.
- Needs further investigation.



E. H. Åhlgren et al., Appl. Phys. Lett. 100, 233108 (2012).

* H. Wang et al., "Design of High-power graphene beam window", IPAC'14

Distance to application

Items	Status
Vacuum performance	100 μm graphene film has a relatively high impermeability for helium.
Thermal performance	Very good. Can enhance the endurable power by 1-2 magnitude of order.
Strength	Can endure 1 atm with the diameter of 38mm
Scattering effect	Good because of thin film
Radiation lifetime	Has certain resistance to irradiation

- More detailed works should be done before application.
  - New technology for better materials.
  - The connection between graphene film and other (metal) materials.
  - Radiation resistance analyses and experiments.

Summary

- Graphene beam window for MW-class or even higher hadron accelerators is being primary studied.
- The graphene film is a good candidate material for high power beam window. The performances are tested or analyzed, including vacuum performance, thermal performance, anti-pressure ability, scattering effect and radiation.
- Many detailed investigations need to be pursued before the graphene film can be exploited in real beam window for high power hadron accelerators.

Thanks for your attention!