DESIGN OF HIGH-POWER GRAPHENE BEAM WINDOW

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outline

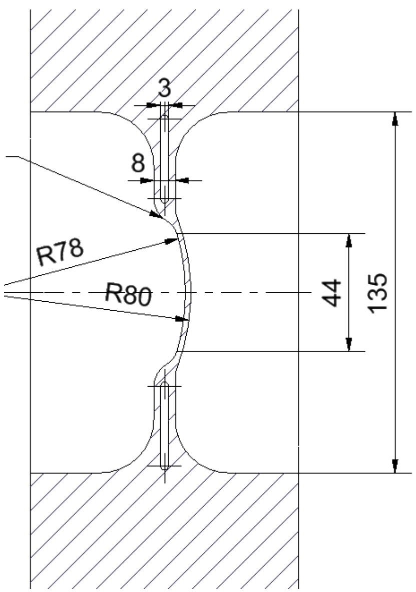
- What is hadron beam window?

Hadron beam window

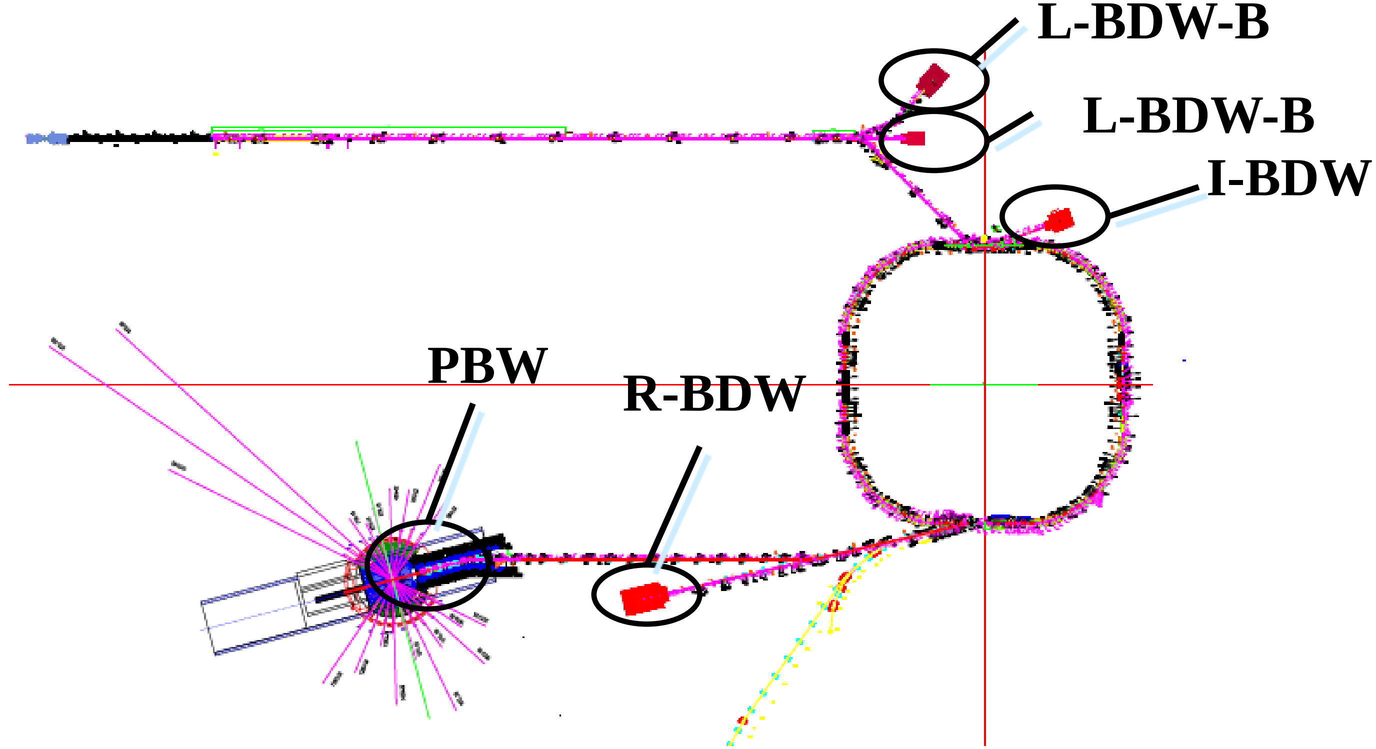
- Key device in high-intensity hadron beam applications.
- Separating the high vacuum region in the accelerator from air or other gas environments.
- The beam passes through the window to impinge the target or beam dump.
- Commonly-used materials: aluminum alloy, Inconel alloy and so on.
- Low power windows: usually air cooling (in front of beam dump).
- High power windows: usually forced water cooling (in front of target).

Hadron beam window

- Take CSNS as an example
  - PBW: Proton beam window, material A5083-O, side cooling (forced water) .
  - BDW: Beam dump window, material GlidCop Al-15, natural air cooling.

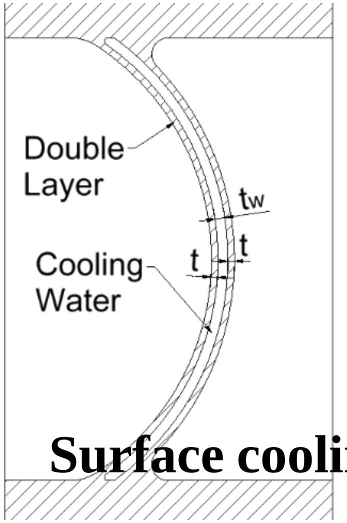


Side cooling

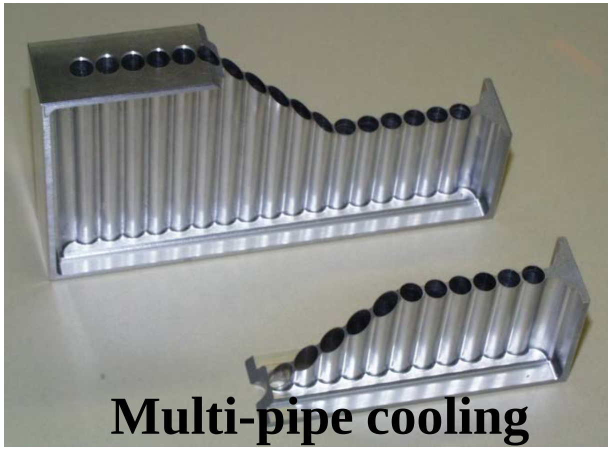


Hadron beam window

- Proton beam windows of some accelerators
  - Surface cooling (forced water)
    - SNS (1MW): material Inconel 718
    - J-PARC (1MW): material A5083-O
    - ISIS (0.16MW): material Inconel 718
  - Multi-pipe cooling (forced water)
    - ESS (5MW): material A6061-T6
    - C-ADS (15MW): material A6061-T6
- Beam window in study
  - Plasma window: in experimental stage



Surface cooling



Multi-pipe cooling

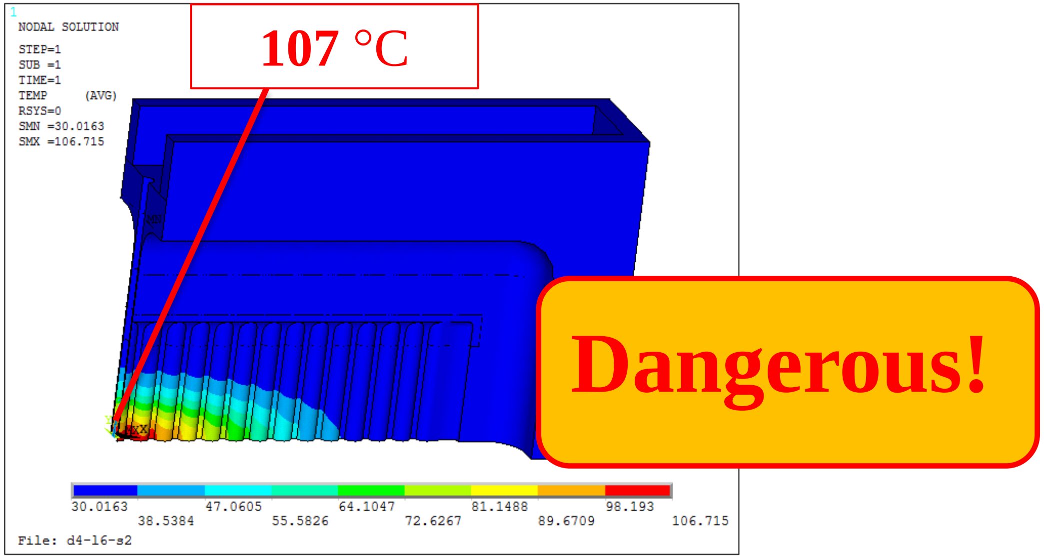
outline

What › **Why** › **How**

- Why to find other material for hadron beam window?
- Why graphene?

Why to find other material for hadron beam window?

- High power accelerators are developing rapidly.
- Much stricter requirements on the hadron beam window.
  - Cooling
  - Scattering effect
  - Radiation damage
  - Mechanical strength



- Example
  - Structure: multi-pipe, material: A5083-O.
  - Proton beam distribution: 2D Gaussian, rms size (27, 6.3)mm (same as CSNS).
  - Beam power: 2.5MW, highest temperature: 107 °C.

Why graphene?

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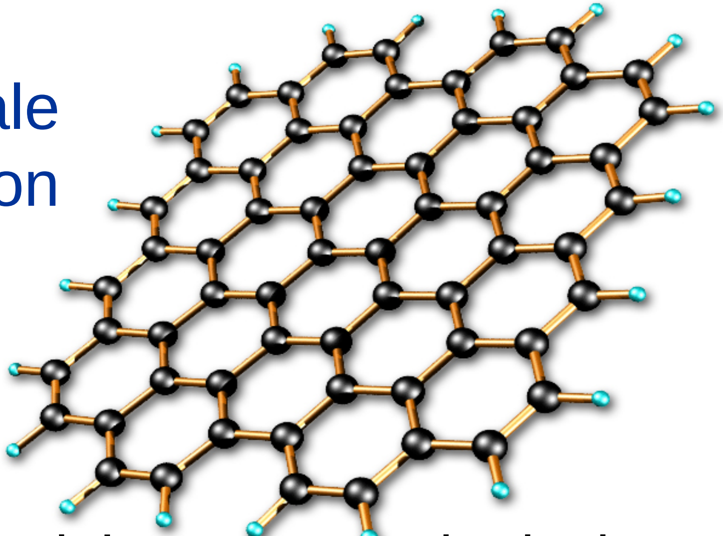

- Graphene is an atomic-scale honeycomb lattice made of carbon atoms.
- First isolated in the lab in 2004.
- Splendid properties:
  - The strongest material: Young's modulus E=1TPa, intrinsic strength σ_{int}=130GPa.
  - High thermal conductivity: 4840-5300 W/(m·°C) at RT.
  - High transparency to high-energy ions.
  - Impermeability for gases including helium.
  - Certain resistance to irradiation.
- Large-size graphene manufacturing technology has matured.

Why graphene?

	A5083-O	Inconel 718	S316 (hardening)	GlidCop Al-15	Graphene
Young's modulus (Gpa)	70.3	199.9	193	110	~1000
Breaking strength (MPa)	290	1375	1280	480-610	~130000
Yielding strenth (MPa)	145	1100	965	255-300	
Thermal conductivity (W/(m·°C))	117	14.7	16.2	365	4840-5300

outline

- Thermal and stress analyses
- Beam Scattering effect
- Discussion on lifetime

Thermal and stress analyses

- Suppose two proton beams:
  - 1.6 GeV in energy and 10 MW in beam power.
  - Beam 1: 60 mm×60 mm in beam size with a uniform distribution.
  - Beam 2: 2D Gaussian round beam, rms size or σ is 20 mm.
- Suppose a graphene window:
  - A square foil.
  - Air cooling on one side.
- The temperature distribution can be calculated using the method of separation of variables.

Thermal and stress analyses

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- For beam 1:

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

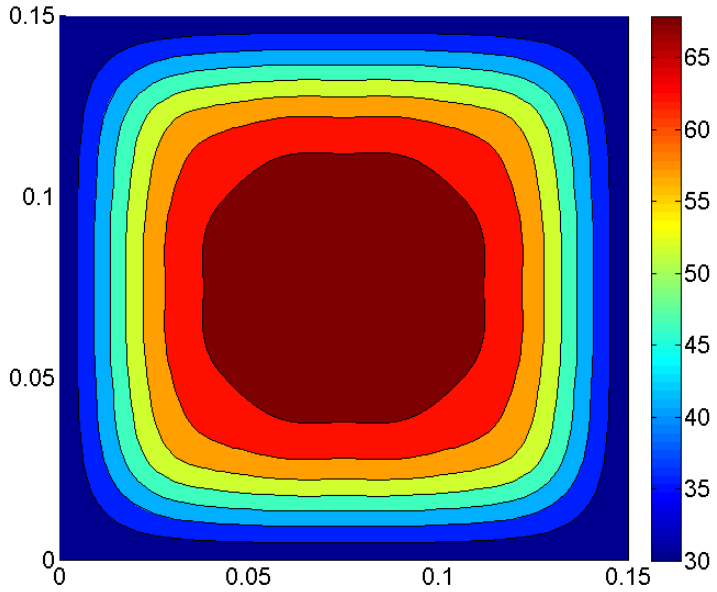
$$\beta_m = \frac{m\pi}{2L}, m = 1,2,3\ldots \qquad \gamma_n = \frac{n\pi}{2L}, n = 1,2,3\ldots \qquad \alpha = \frac{h}{k\eta_{mn}}$$

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

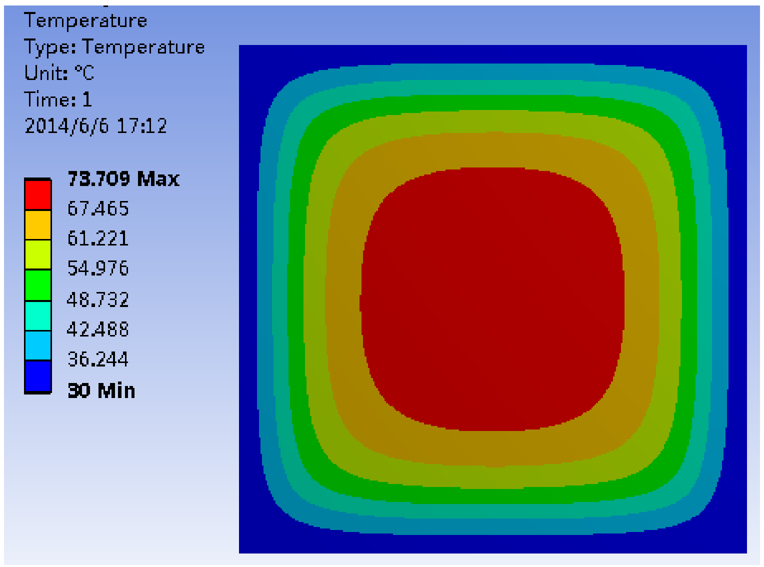
- *L*: half of the side length of the square, *L*=0.075 m;
- *a:* the beam size as mentioned above, *a*=0.06 m;
- *b*: thickness of window, b=0.335μm (100 layers);
- H_f : energy deposition, and heat flux is used;
- *h* : convection coefficient, *h*=5W/(m^2.°C) at 30 °C;
- *K*: thermal conductivity of graphene, 4840 W/(m. °C).

Thermal and stress analyses

- The highest temperature calculated by Matlab is 73.3 °C. It is consistent to the results of thermal analysis using ANSYS which shows that the highest temperature is 73.7 °C.



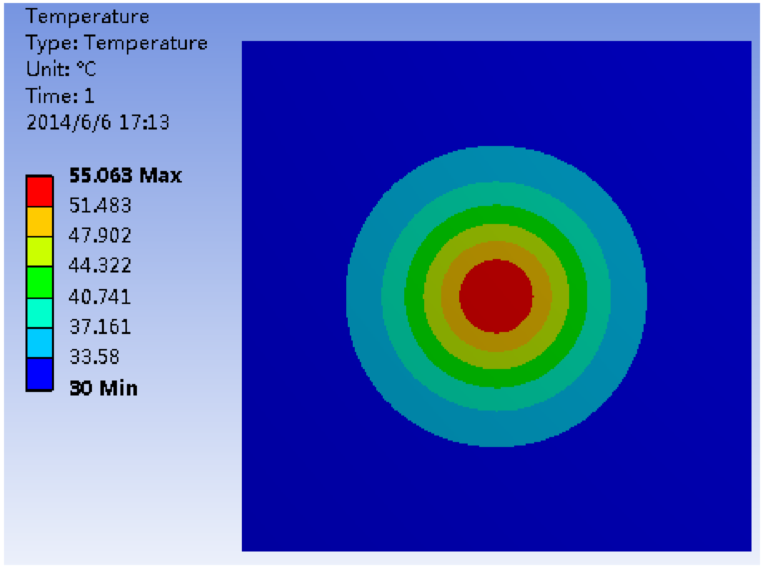
Analytical by Matlab



FEA by ANSYS

Thermal and stress analyses

- For beam 2:
  - σ is 20 mm, namely is 1/3 of *a*, the highest temperature is 55.1 °C, which is lower than that of the uniform distribution beam.
  - There is no bad effect on temperature in a grahene window when the beam is 2D Gaussian distribution (peak currency is higher).



Thermal and stress analyses

- The highest temperature increases when the beam power is larger.
- For beam 2: the highest temperature is only 155.3 °C even if the beam power reaches to 50 MW, far below the melting point of graphene.

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

Thermal and stress analyses

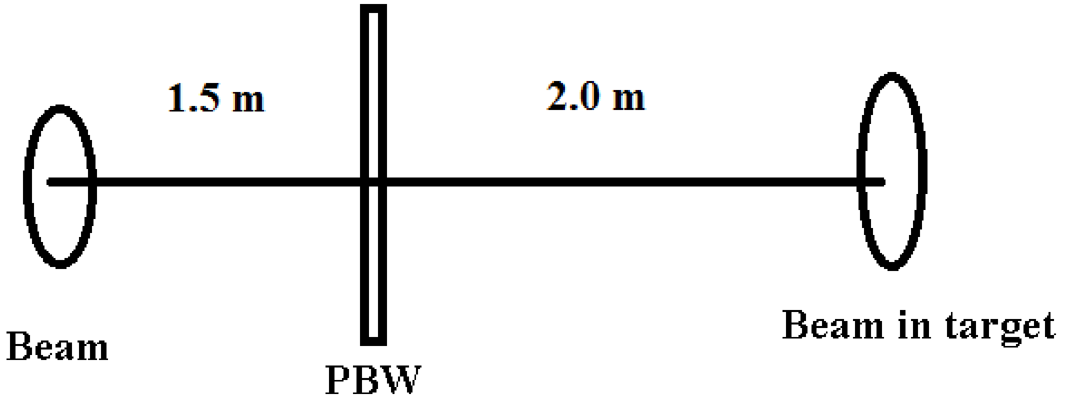
- Thermal stress is small due to low temperature.
- The main cause of the stress is the Hooke stress of air pressure.
- A curved window is helpful to decrease the stress.

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

  - Suppose *p*=1 ATM, *D*=150 mm, *δ*=0.335 (100 layers).
  - The highest Hooke stress is about 22.4 GPa, far less than the breaking strength of about 130 Gpa.
- Other problems, such as wrinkling, should be considered in further studies.

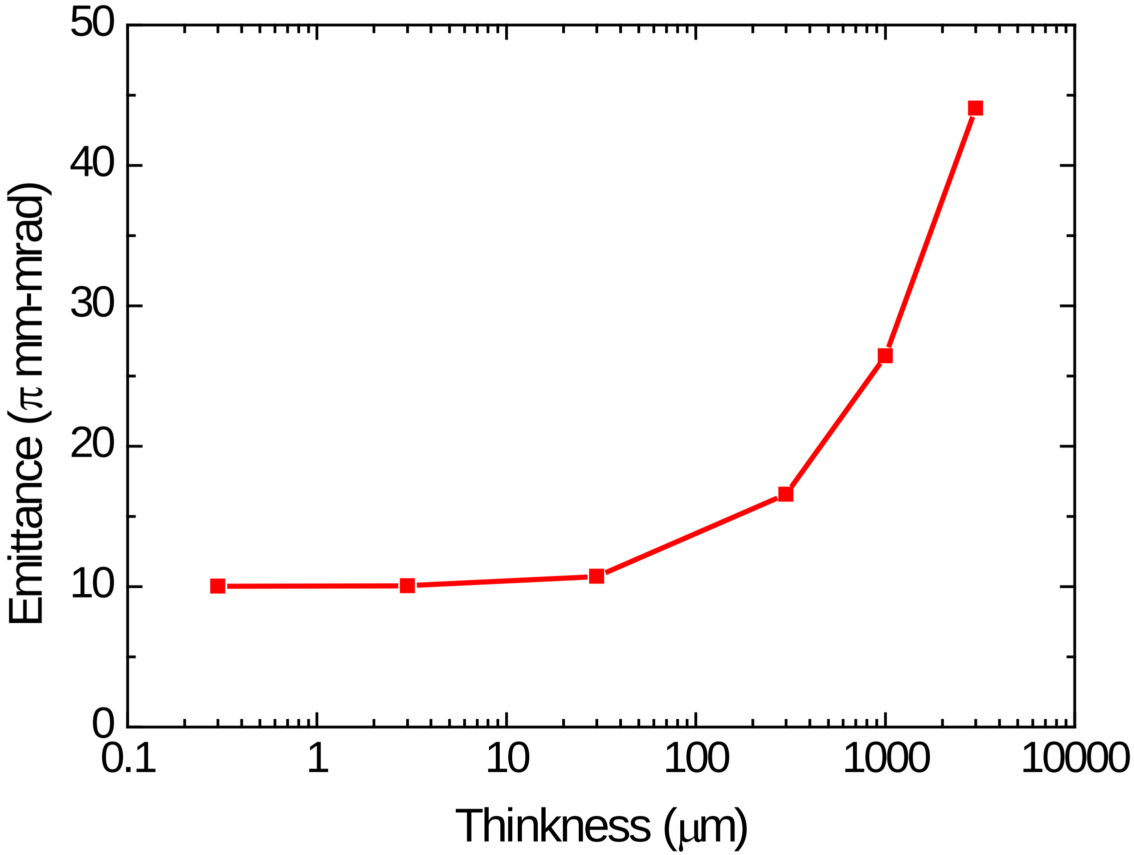
Beam Scattering effect

- High transparency to high-energy ions, an ideal property for beam window.
- Scattering effect is estimated.
  - Considering the window as a carbon foil.
  - Suppose the beam is beam 2, and the non-normalized emittance is 10 π.mm.mrad.



Beam Scattering effect

- Graphene window: thinner than 100 μm.
- Traditional window: the order of about 1 mm.



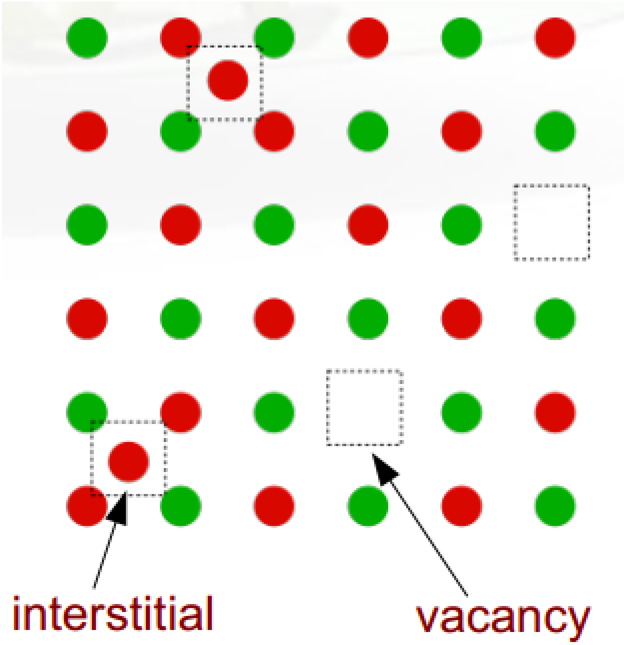
Discussion on Lifetime

- The beam passing through the beam window can cause defection of the material.
- The DPA has been calculated by FLUKA.
  - DPA: displacement per atom, a major index of the radiation damage.

$$N_d = \phi \cdot t \cdot n_0 \cdot \sigma_d \cdot \upsilon$$

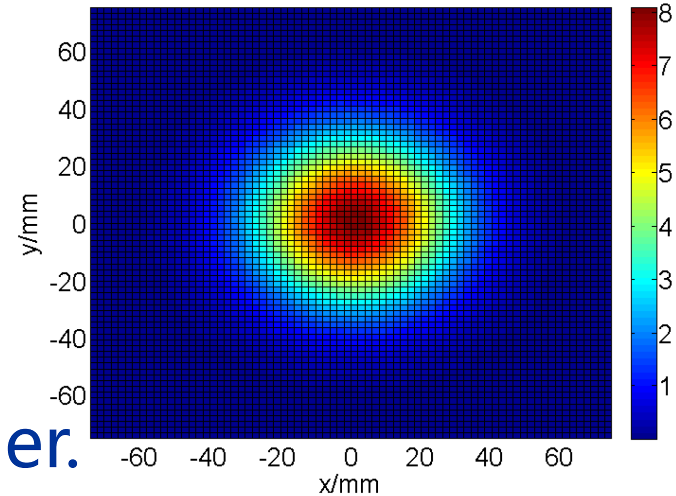
$$DPA = N_d / n_o$$

N_d: total displacement atoms;
Φ: incident particle flux;
n_0: atoms/cm^3;
σ_d: cross section;
υ: displacement damage function;
t: time.



Discussion on Lifetime

- Calculation.
  - Use beam 2, suppose operation time is 7200h/y.
  - Peak current density: 251 μA/cm^2.
  - Max DPA is about 8.1/y.



- The actual DPA should be smaller.
  - The result calculated by algorithm developed for bulk solids is larger than that of two-dimensional systems.*
- Graphene has certain resistance to irradiation.
  - High mechanical stability and good impermeability for small atoms even with high vacancy concentration.#
- Applicable lifetime needs further investigation.

***O. Lehtinen et al., Phys. Rev. B, 153401 (2010).**
 # E. H. Åhlgren et al., Appl. Phys. Lett. 100, 233108 (2012).

summary

- Graphene beam window for MW-class hadron beams is proposed and studied.
- Thermal and stress analyses show that graphene is a very potential window material in extremely high power beams.
- The simulation denotes that the beam scattering effect can be ignored.
- The DPA has been calculated and the lifetime of a graphene window is discussed.
- The results are promising.
- Many detailed investigations need to be pursued before the graphene can be exploited in real beam window applications.

references

1. G. Murdoch et al., “Beam Dump Window Design for the Spallation Neutron Source”, PAC’03, Portland, May 2003, p.1467 (2003).
2. T. McManamy, “SNS Proton Beam Window Design”. In: Institute of Theoretical Physics, CAS, 2008.
3. S. Meigo, “Proton beam window assembly”, https://j-parc.jp/researcher/MatLife/en/committees/documents/IV-02-Meigo_Rev2.pdf
4. WANG Hai-jing et al., Chinese Physics C, Vol. 37, No. 7 (2013) 077001.
5. Michael Butzek et al., “Proton beam window for high power target application”, 4th High power Targetry Workshop, Malmö, 2011.
6. Wu Hongli et al., High Power Laser and Particle Beams, 1001-4322(2013)10-2675-07.
7. Alexander A. Balandin et al., Nano Letters, Vol. 8, No. 3, 902-907 (2008).
8. Changgu Lee et al., Science 321, 385 (2008).
9. O. Lehtinen et al., Phys. Rev. B, 153401 (2010).
10. J. Scott Bunch et al., Nano Lett., Vol. 8, No. 8, 2458-2462(2008).
11. E. H. Åhlgren et al., Appl. Phys. Lett. 100, 233108 (2012).

Thanks for your attention!