The Irradiation Study of Carbon Stripper Foils by a 12MeV Ar Beam

Wen Jiang[1], Wolfgang Mittig[2], Frederique Pellemoine[3], Tan Ahn[4], Daniel Robertson[4], Edward Stech[4], Nalin Kumar[5]

1 Purdue University-Nuclear Engineering Department, 2 MSU-NUCL, 3 MSU-FRIB, 4 University of Nortre Dame, Department of Physics, 5 UHV Technologies, Inc.

MICHIGAN STATE UNIVERSITY

NSCL

Outline

- Background
- Materials
- Irradiation Study
- Post-Irradiation Swelling Study
- Summary

Background

- Carbon stripper foils :One of the dominant types of stripper foils
- Diamond Like Carbon(DLC) and Hybrid Boron doped Carbon (HBC) foils have been studied a lot
  - Multilayer HBC foils : long lifetime, good mechanical performance
- Most work focus on preparation methods and lifetime
- Characteristics of the layers

? ↕

Lifetime of the foils

- The irradiation performance of foils with more than 20 layers?

MICHIGAN STATE UNIVERSITY

Materials

- The stripper foils were all supplied by UHV Technologies, Inc.
- Nominal thicknesses :2-2.5μm (around 500 μg/cm2),
  - Exception: 1.6μm for 10% boron mix 90% carbon monolayer foil

Table 1. Types of the foils

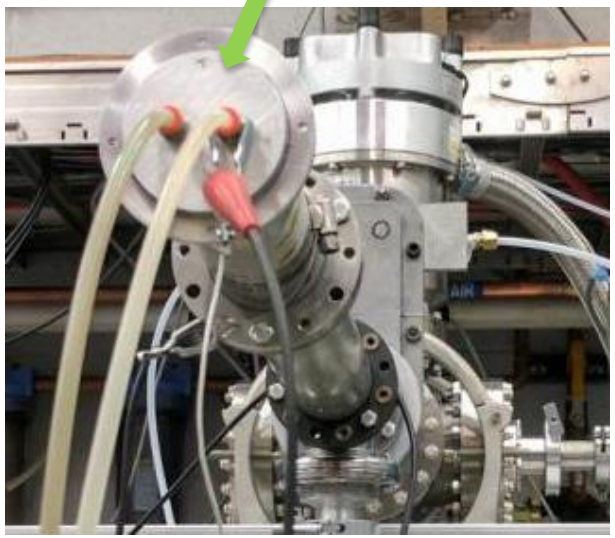
Code	Foil type
1	One layer DLC, type 3
2	One layer DLC, type 1
3	7 layers HBC, 4B+3C
4	9 layers HBC, 5B+4C
5	17 layers HBC, 9B+8C
6	48 layers HBC, 24B+24C
7	100 layers HBC, 50B+50C
8	One layer 10%B+90%C mixture

Irradiation Study-Setup

✓5U accelerator of University of Notre Dame.

✓4+ Ar beam of 12 MeV

- Foils were glued on brass frames
- The effective irradiation area of the foils : 0.25 × 0.23 inches
- Frames were mounted on copper plates to be irradiated→ 8 types of foils were mounted on 2 plates for each run's condition.
- Plates were loaded on a target holder of the accelerator with water-cooling system.



MICHIGAN STATE UNIVERSITY

Irradiation Study-Scheme and Outcome

- Intensity: 0.23μAe to 10μAe (0.06-2.5μAp)
- Fluence: 10^{11} to 10^{17} ions/cm^2
- Degree 6 damage

- Degree 4 damage

- Degree 3 damage

- Degree 2 damage

- Degree 1 damage

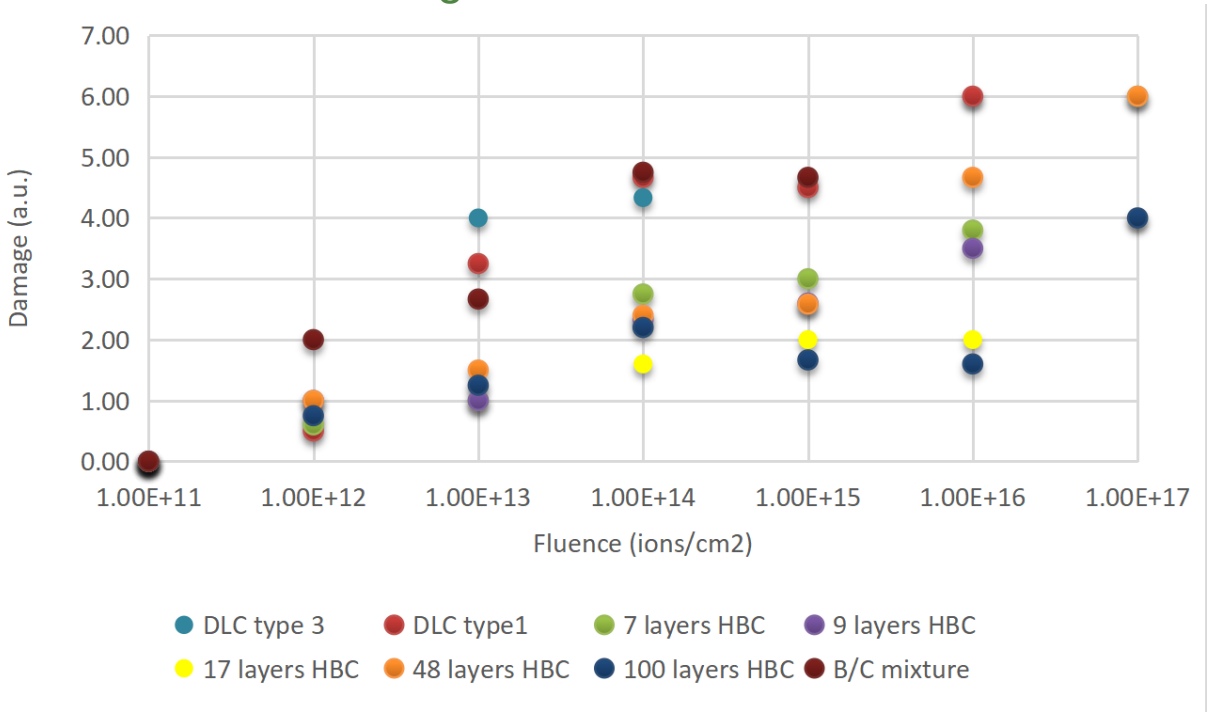
Intensity (μAe)	Fluence (ions/cm2)	(1)DLC, type 3	(2)DLC, type 1	(3)7 layers HBC	(4)9 layers HBC	(5)17 layers HBC	(6)48 layers HBC	(7)100 layers HBC	(8)B/C mix
0.23	2E+11	0	0	0	0	0	0	0	0
	1.22E+12	0	0	0	0	0	1	0	1
	2.01E+12	1	0	0	0				
	5.00E+12					1	1	0	1
	1E+13	2	1	0	0	1	1	0	2
	2E+13	4	4	0	0				
	5E+13	6	6	1	1	1	2	2	2
	1E+14	6	6	1	1	1	2	2	6
	1E+15	6	6	1	1	2	2	2	6
1.4	1.38E+12	2	2	2	4	1	1	2	4
1.4	1.40E+13	4	2	3	3	2	2	2	4
1.4	1.40E+14	4	4	3	3	2	2	3	3
1.4	7.00E+14	3	4	3	3	3	4	3	4
1.4	1.37E+15	3	4	3	3	2	2	3	4
1.4	2.43E+15					2	2	1	
	4.96E+15	4	4	2	2	2	2	1	
	7.45E+15	6	6	3	3	2	2	1	
	1.00E+16	6	6	3	3	2	2	1	
	1.40E+16	6	6	4	4	2	2	1	
1.4	2.92E+15		2			2	2	2	
	5.90E+15		4			2	2	2	
	8.91E+15		6			2	4	2	
	1.40E+16		6			2	6	2	
4	1.00E+15			2		3	3	1	
4	1.00E+16			2				1	
4	5.00E+16			4				2	
10	3.08E+12			1		2	1	1	
10	1.40E+15	4	4	4	4	2	2	3	4
10	1.20E+13			1		1	1	1	
	1.01E+14			4		1	2	1	
	1.00E+15			6		1	6	1	
	1.00E+16			6		2	6	2	
	1.00E+17			6		4	6	4	

MICHIGAN STATE UNIVERSITY

Irradiation Study-Analysis

- Three variables were used for evalutaion: intensity, fluence and the type of foil.
  - →Ignore the intensity based on correlation analysis: less significant

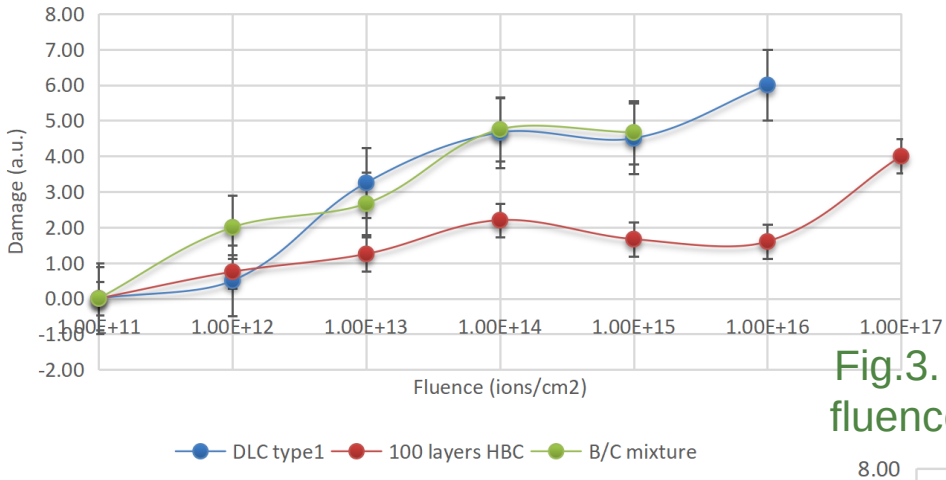
Fig.1. The damage degree of 8 types of foils under different magnitudes of ion fluence.



MICHIGAN STATE UNIVERSITY

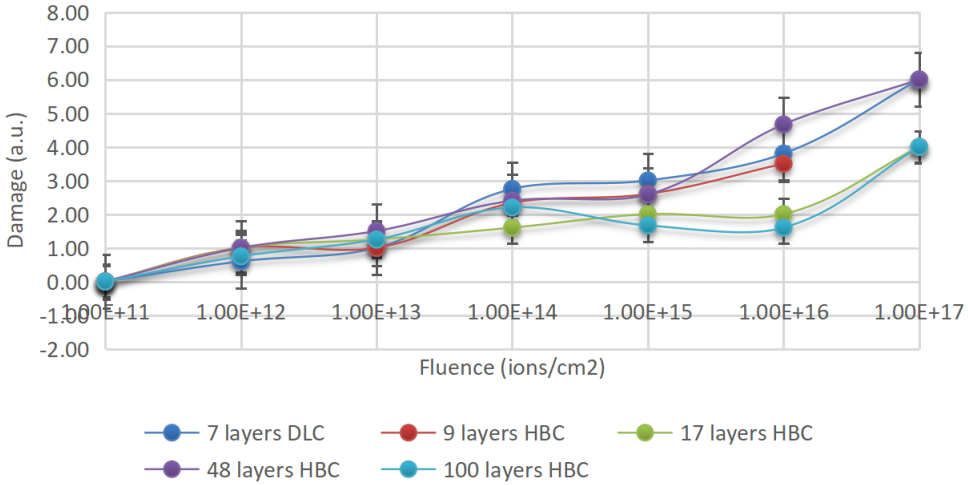
Irradiation Study-Analysis

Fig.2. Comparison of the damage with respect to fluence of DLC, HBC and B/C mixture



- DLC foil and B/C mixture foil became damaged rapidly above 10^{13} ions/cm^2, and are both near to failure at 10^{14} ions/cm^2.
- 100 layers HBC foil remained relatively undamaged up to 10^{17} ions/cm^2.

Fig.3. Comparison of the damage with respect to fluence of HBC foils of different number of layers.



- Below 10^{14} ions/cm^2, the performance of all the HBC foils is similar, and starts to deviate after 10^{14} ions/cm^2.
- Not until 10^{16} ions/cm^2 when some foils start to fail.
- Damage degree ? layers of foils

MICHIGAN STATE UNIVERSITY

Irradiation Study-Hypothesis

- The 100 layers HBC foils performed best among all the tested foils in terms of lifetime, also with respect to their structural steadiness--no layer debonding even under high intensities or high fluences.
- Total thickness of 100 layers HBC foils~ 1 μm, the thickness of each layer is about 10nm→Nanoscale effects

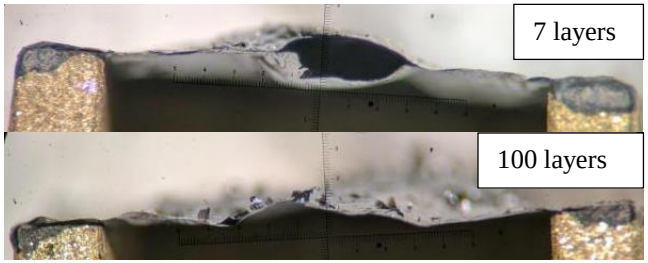


Fig.6. A view of the border of 7 layers and 100 layers HBC foils after 1.4μAe and $7*10^{14}$ions/cm^2 irradiation.

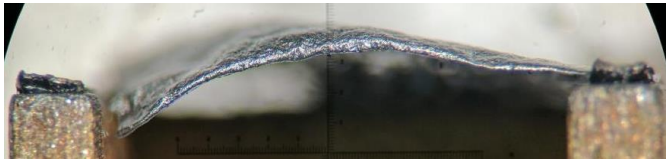


Fig.7. The border view of 100 layers HBC foils after 4μAe and $5*10^{16}$ions/cm^2 irradiation.

MICHIGAN STATE UNIVERSITY

Irradiation Study-Hypothesis

- DLC structure in the carbon layers of all the multilayer HBC foils. DLC structure → nanographite structures upon irradiation[1][2]
- "Wigner Effect"--The interstitial defects caused by lattice atom displacement and interstitial-vacancy recombination[3]→ crystallite distortion → initiation of the cracks
- Boron atoms may act as interstitials which diffuse into diamond lattice and recombine with vacancies, forming a stable interface tolerant to irradiation[4]
  - In fewer layer foils, carbon layers are thicker → Wigner Effect dominate, the resistance to irradiation declines.
  - In 100 layer foils, layer thickness~ 10nm, interstitials enhanced interfaces dominate → high tolerance to irradiation
- Nevertheless, the multilayer foils overall have longer lifetime than monolayer ones

Post-Irradiation Swelling Study

- Quantify the irradiation performance of the foils→ swelling
- Alpha-particle attenuation were used to determine the thickness of the foils, which was expected to be influenced by the swelling.
- Alpha source: Am-241, 3μCi
- *Swelling=(thickness of the irradiated samples- thickness of the unirradiated sample)/thickness of the unirradiated sample*100%*

Post-Irradiation Swelling Study

Table 2. Analysis of the measurements of 100 layer HBC foils

Irradiation fluence (ions/cm2)	Irradiation intensity (μAe)	Thickness evaluated by SRIM (μg/cm2)	Thickness (μm)	Swelling(%)
0	0	261.03	1.16	
10^{15}	0.23	267.34	1.19	2.29
$1.40*10^{12}$	1.4	263.83	1.17	0.95
$1.40*10^{13}$	1.4	252.12	1.12	-3.53
$1.40*10^{14}$	1.4	267.87	1.19	2.49
$7.01*10^{14}$	1.4	259.19	1.15	-0.83
$1.40*10^{15}$	1.4	269.01	1.19	2.93
10^{16}	4	262.87	1.17	0.58
$3*10^{12}$	10	267.52	1.19	2.36
$1.55*10^{15}$	10	259.25	1.15	-0.80

Table 3. Analysis of the measurements of DLC foils

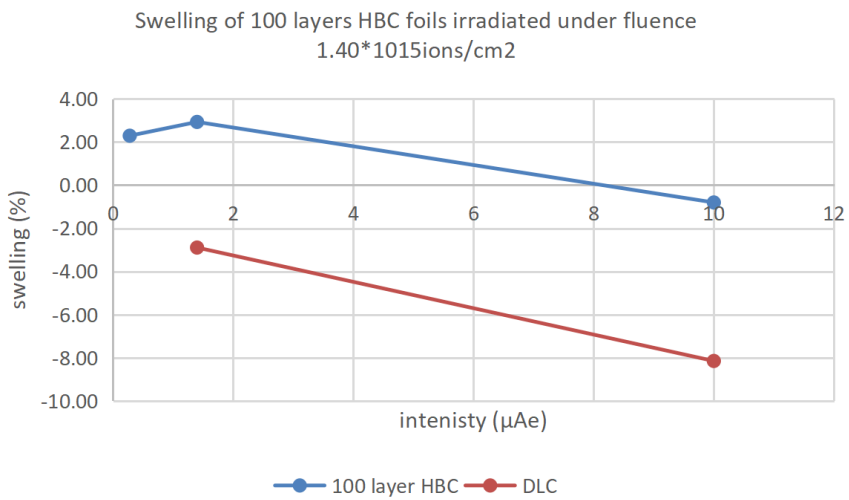
Irradiation fluence (ions/cm2)	Irradiation intensity (μAe)	Thickness evaluated by SRIM (μg/cm2)	Thickness (μm)	Swelling(%)
0	0	585.08	2.60	
$1.40*10^{12}$	1.4	600.33	2.67	2.38
$1.40*10^{13}$	1.4	593.16	2.64	2.32
$1.40*10^{14}$	1.4	584.61	2.60	-0.30
$7.01*10^{14}$	1.4	588.14	2.42	0.01
$1.40*10^{15}$	1.4	569.70	2.53	-2.89
$5.02*10^{15}$	1.4	580.15	2.58	-0.80
$1.40*10^{16}$	1.4	544.97	2.42	-5.78
$1.55*10^{15}$	10	532.39	2.36	-8.15

- **For the α particles of Am-241 in carbon foils, dE/dx= 783.27KeV/mg/cm2. The density of the foils is taken as 2.25g/cm3.*
- The thickness of 100 layers HBC foils irradiated under different conditions did not change too much. The thickness of DLC foils changed obviously, and shows thickness reduction instead of increase.

MICHIGAN STATE UNIVERSITY

Post-Irradiation Swelling Study

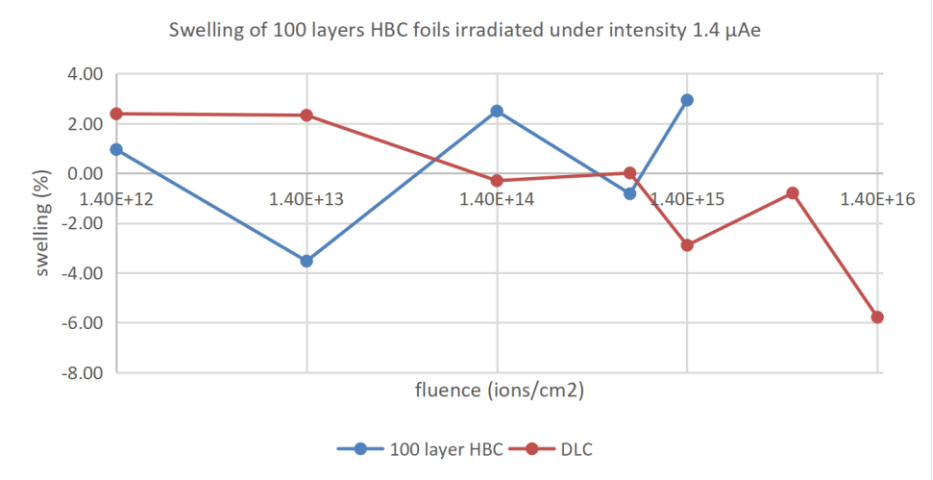
Fig.4. Swelling of 100 layers HBC and DLC foils irradiated under 0.23 (N/A for DLC foils), 1.4, 10 μAe intensities and the same fluence $1.40*10^{15}$ions/cm2.



- **The swelling here indicates the increasing in thickness, while in real cases refers to the expansion of the surface area, accompanied by the attenuation in thickness.*

- The swelling of 100 layers HBC foils fluctuates in a relatively small range with respect to radiation conditions
- DLC foils show a regular trend-- the thickness decreases in higher intensities and fluences

Fig.5. Swelling of 100 layers HBC foils irradiated under 1.4 μAe intensity and the increasing fluence.



MICHIGAN STATE UNIVERSITY

Post-Irradiation Swelling Study

- "Swelling" is a comprehensive result of many effects:
- The expansion of the surface area of the foils is majorly caused by thermal effect[5][6]
- The thickness could also reduce due to the "ion hammering effect"-- add to surface swelling[7]
- The reduction in measured thickness is very possibly due to the sputtering of surface atoms or the cracks on the foil as well.
- *-- Despite the complication, multilayer foils maintain better their sizes than DLC foils and are more resistant to irradiation.*

Summary

- Below 10^{13} ions/cm^2, regardless of beam intensity, all the foils are “safe”. Then non-multilayer foils start to show heavy damage and eventually fail.
- Among all the foils, 100 layer HBC foils performed best upon irradiation, not only having longest lifetime (10^{17} ions/cm^2 under 2.5μAp), but also having the most steady multilayer structure as well as the size.
- Multilayer foils performed generally better than the monolayer ones.
- Boron layer may help to increase the resistance of the foils to irradiation damage, elongating their lifetimes.

Acknowledgement

- The author would like to give thank to John Yurkon from NSCL, MSU, for his help in training to use and setting up the equipment.

MICHIGAN STATE UNIVERSITY

Thank you!

Questions?

References

- 1. Huang-Chin Chen et al. Diamond & Related Materials 18 (2009)
- 2. C. Popescu et al. Applied Surface Science 390 (2016)
- 3. Shuo-Cheng Tsai a, E-Wen Huang b, Ji-Jung Kai a, Fu-Rong Chen . Journal of Nuclear Materials 434 (2013)
- 4. Franco Cataldo, Giancarlo Angelini, Zsolt Révay, Eiji Osawa & Tibor Braun . Fullerenes, Nanotubes, and Carbon Nanostructures, 22(2014)
- 5.I. Sugai et al. Nuclear Instruments and Methods in Physics Research A 613 (2010)
- 6.Hiroo Hasebe et al. Nuclear Instruments and Methods in Physics Research A 613 (2010)
- 7. Charge Strippers of Heavy Ions for High Intensity Accelerators, Reviews of Accelerator Science and Technology Vol. 6 (2013)