Present Status of HBC Stripper Foil Development

By Isao. Sugai

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Talk:

- Requirement of Stripper Foil for RCS of J-PARC Accelerator
- Brief history of carbon foil developments
- Limits of Cluster Carbon Foils made by CADAD Method
- Development of HBC-Foils
- Lifetime Measurements of HBC, Diamond and CM-Foils by using 3.2 MeV Ne⁺, 650KeV H⁻ and 800MeV H⁻ Ion Beams
- Summary and Conclusions
Schematic view of J-PARC

Materials and Life Science Experimental Facility

Hadron Experimental Facility

Neutrino Experimental Facility

Linac (340m)

3-GeV RCS-Ring (25Hz, 1MW)

50-GeV-Ring (0.75MW)
Schematic layout of the Accelerator Complex of J-PARC and Stripper Foil Position

Configuration of the Accelerator Complex of J-PARC
Injection Beam and Stripper Foil Properties of 3GeV ring at J-PARC

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy</td>
<td>200 MeV (first stage)</td>
</tr>
<tr>
<td></td>
<td>400 MeV (second stage)</td>
</tr>
<tr>
<td>Beam pulse length</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Average beam current</td>
<td>0.333 mA</td>
</tr>
<tr>
<td>Beam Size</td>
<td>10 mm x 10 mm</td>
</tr>
<tr>
<td>Foil thickness</td>
<td>200-400 μg/cm²</td>
</tr>
</tbody>
</table>

Foil peak temperature ;  >1800K
(If average foil hitting number of bunched proton is >17 and Circulating bunched beam is 8.3x 10^{13}/bunch )
Schematic diagram of the charge exchange system for RCS of J-PARC
J-PARC 大強度負水素イオンビームの第1荷電変換用炭素フォイル取付け用チタン製ターゲットホルダー。スケールの単位はmmで表示。HBC-フォイル（幅40mm, 長さ110mm）は10μmのSiCファイバーでサンドイッチ状に取り付けられる。ポイント状で入射したビームは、図の左側に順次蓄積されてゆく。
Target Holder for Mounting of Ribbon Type Carbon Stripper Foil at J-PARC
Brief history of carbon foil development

- The first carbon foils were made by just evaporating carbon on a glass slide (e.g. foils from Arizona Carbon Foil Co.).
- Around 1985 Isao Sugai invented a new method to make carbon foils.
  - AC/DC discharge method, where carbon rods are alternately heated with DC and AC currents.
  - Creates a mixture of large and small carbon particles.
  - These foils are now used in the PSR.
- Around 2001 R. Shaw et al. at ORNL began developing diamond foils for the SNS.
  - Longer lifetimes based on test results at the BNL 750 keV H⁻ linac.
- However, the diamond foils have a crucial limit of crystalline change at around 1800K. So New foil against >1800K is strongly expected to be Innovated !!!
Arizona Carbon Foils

- The foils are extensively used in the world since 1964 due to high quality.
- The foils were made by high temperature evaporation-condensation on a glass slide.
- In order to investigate the lifetime of the foils, we measured the lifetime from a very thin 3\(\mu\)g/cm\(^2\) to thick 500 \(\mu\)g/cm\(^2\) using 3.2 MeV Ne\(^+\) DC ion beam of VDG accelerator.
3.2 MeV Ne⁺ DC ion beam VDG
Accelerator of Tokyo Institute of Technology
Lifetime Measurement

• Comparative measurements of the lifetime and other properties of this HBC-foil as well as DM-foil and CM-foil were performed with a 3.2 MeV Ne$^+$ and 3.0 $\mu$A ion beam of VdG accelerator.

• The lifetime of foil is defined total integrated beam current per unit area ($\text{C/cm}^2$)

  Note that low-energy heavy-ion beams could provide serious test conditions for the lifetime of foils because of their large energy deposition in the foils.
Energy deposition as a function of foil thickness for 200 and 400 MeV proton beams and a 3.2 MeV Ne\(^+\) DC beam.

Energy deposition of 3.2 MeV Ne\(^+\) beam is close to J-PARC RCS in terms of energy deposition in the foils.
Arizona Carbon Foils from 1\(\mu\text{g/cm}^2\) to 500 \(\mu\text{g/cm}^2\)

Lifetime versus Foil thickness (CM-Foils)
Arizona Foils were found to be “very short lifetime”

So, we developed a new cluster foil by Controlled AC/DC arc Discharge method (CADAD).
In “Controlled DC Arc-Discharge”,
Two kinds of Different Sized Carbon Clusters are emitted as,

Larger one; \(~500 \text{ nm}\) form *Cathode* (Very strong for high intensity beam, but fragile)
Smaller one; \(~3 \text{ nm}\) from *Anode* (Very strong mechanical shock, but very fragile for beam)

Life-Times of Foils are very Sensitive to The Ratio;

\[ R = \frac{W_c}{W_c + W_a} \]

where \( W_c \) and \( W_a \) are the Discharged Amounts of Carbons from Cathode and Anode, respectively.

We developed
“Combined System of DC and AC Arc-Discharges” which is easy control the \( R \) in simple way
DC and AC arc-discharge geometries for Cluster foil preparation
Cluster foils on Side Glass

- $R > 50\%$
  
  ($R = \frac{w_c}{w_c + w_a}$)

- Max, accessible foil thickness

- $130 \pm 40 \ \mu g/cm^2$
Foil Thickness Decreasing of the Cluster Foil during Beam Irradiation

- The foil thickness reduction at broken corresponds to $-93 \, \mu\text{g/cm}^2$ or $-73\%$ of the initial thickness.
In order to overcome these problems

- We have tried to mix the graphite rod with foreign atoms like Be, B, Al, Si, etc.

- Among these, the boron-mixed foil showed especially good results.

- Here, Stripper foils made by this method, which we can Hybrid Boron mixed Carbon stripper foil (HBC-foil)
Discovery of HBC-foil

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- We have tried to mix the graphite rod with foreign atoms like Be, B, Al, Si, etc.
- Among these, the boron-mixed foil showed especially good results.
- Here, Stripper foils made by this method, which we can Hybrid Boron mixed Carbon stripper foil (HBC-foil)
Anode of B(20%)
Cathode of B (20%)
Photographs of carbon layers on microscope slide glass substrates

(a) represent an HBC-foil of 320\(\mu\)g/cm\(^2\) and (b) is for a Cluster-foil of 180\(\mu\)g/cm\(^2\) made by the CADAD method.
Large area HBC-Foil

( FNAL-09/11/12)
## Sample foils for 3.2 MeV, Ne⁺ DC ion Beam of 3.5 mm beam spot

<table>
<thead>
<tr>
<th>Foil</th>
<th>S (Single) / D (Double)</th>
<th>Thickness (μg/cm²)</th>
<th>SiC fiber</th>
<th>Preparation Place</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBC</td>
<td>S</td>
<td>373</td>
<td>With</td>
<td>KEK</td>
<td>1600 ± 200K</td>
</tr>
<tr>
<td>HBC</td>
<td>D</td>
<td>180 x 2</td>
<td>With</td>
<td>KEK</td>
<td>1400 ± 200K</td>
</tr>
<tr>
<td>DLC</td>
<td>S</td>
<td>370</td>
<td>With</td>
<td>Canada (TRIUNF)</td>
<td>1600 ± 200K</td>
</tr>
<tr>
<td>ND</td>
<td>S</td>
<td>360</td>
<td>Without</td>
<td>USA (SNS)</td>
<td>1600 ± 200K</td>
</tr>
<tr>
<td>CM</td>
<td>S</td>
<td>402</td>
<td>With</td>
<td>USA (ACF)</td>
<td>1600 ± 200K</td>
</tr>
<tr>
<td>CM</td>
<td>D</td>
<td>207 x 2</td>
<td>With</td>
<td>USA (ACF)</td>
<td>1400 ± 200K</td>
</tr>
<tr>
<td>CNT</td>
<td>S</td>
<td>450</td>
<td>Without</td>
<td>Japan (AIST)</td>
<td>1300 ± 200K</td>
</tr>
<tr>
<td>MD</td>
<td>S</td>
<td>360</td>
<td>Without</td>
<td>Japan (Kobelco)</td>
<td>1600 ± 200K</td>
</tr>
<tr>
<td>GA</td>
<td>S</td>
<td>930</td>
<td>With</td>
<td>Japan (UBEKOSAN)</td>
<td>1700 ± 200K</td>
</tr>
<tr>
<td>B₄C</td>
<td>D</td>
<td>60 x 2</td>
<td>Without</td>
<td>KEK</td>
<td>1100 ± 200K</td>
</tr>
</tbody>
</table>
Photos of HBC, SNS-DM, CM foils at different stage of 3.2 MeV Ne⁺ Irradiation

(a) SNS/ORNL-ND-foil: Before (250mC/cm²) After (610mC/cm²)
(b) ACF-foil: Before (5mC/cm²) After (15 mC/cm²)
(c) Kobelco-MD: Before (60mC/cm²) After (120mC/cm²)
(d) KEK:S-HBC-Before (35000mC/cm²) After (8500 mC/cm²)
Comparison of the decreasing foil thickness of the HBC-foil and Cluster foil
Lifetime results of various foils measured with a 3.2 MeV, Ne⁺ ion Beam of 3.0 μA on 3.5 mm Φ
• KEK 650keV H⁻ DC ion Beam
Pictures of Various Foils Tested by using 650 keV H- and DC Ion Beam of 3.5 mmφ beam spot

**Single HBC-foil Sandwiched SiC fibers**

- Before beam irradiation
- Under irradiation (107h)
- Survived (256.5h)

10-4 (HBC: 390μg/cm²)

**Double-Layered HBC-foil Sandwiched SiC fibers**

- Before beam irradiation
- Under irradiation (104h)
- Survived (203.5h)

10-3 (HBC: 205x2=410μg/cm²)
Microcrystalline Diamond Sandwiched SiC fibers for SNS

3-2
(SNS #510: 383μg/cm²)

Before irradiation

Under irradiation (6h)

back bending (11h)

Irradiation after 3min

Under irradiation (5.0h)

back bending (14h)
Nanocrystalline Diamond without SiC fibers
4-2 (SNS #527: 433μg/cm²)

Before irradiation
Under irradiation (10.5h)
Inside curing (10.5h)

Inside curing (21h)
Inside curing (21h)
Multi-layered DLC for TRIUMF
8-5 (TRIUMF Multi-layered DLC: 2.3μm/ 480μg/cm²)
Carbon nano-tube for AIST
7-3 (CNT Sheet: 3~4μm/ 300~400μg/cm²)

Before irradiation       Under irradiation (5h)       Broken by a hole (9h)
CM-foil for ACF (Arizona)
10-1 (CM: 425μg/cm²)  2008/05/20,

Before irradiation  Under irradiation (0.5h)  Broken (1.5 h)
HBC No.31  410 μg/cm²

2007/11/27/18:30 --- 12/02/07:18  108h48m(-1h52m)

Total: 106h56m  120 μA/1900K

2007/11/27/18:15  0h

2007/11/27/18:35  0h 5m

2007/12/2/07:40  106h56m

2007/12/2/07:32  106h56m (Reverse side)
# Table-1 Lifetime of various foils

<table>
<thead>
<tr>
<th>Type of foil</th>
<th>Lifetime (h)</th>
<th>Initial thickness (µg/cm²)</th>
<th>Thickness Reduction (%)</th>
<th>Foil conditions</th>
<th>Beam Current (µA)</th>
<th>Foil Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>±10</td>
<td>±100</td>
</tr>
<tr>
<td>Single HBC sandwiched by SiC fibers (KEK)</td>
<td>256.5 survival</td>
<td>417</td>
<td>30.0</td>
<td>No deformation, but pin-holes</td>
<td>90</td>
<td>1970</td>
</tr>
<tr>
<td>Double Layered HBC sandwiched by SiC fibers (KEK)</td>
<td>203.5 survival</td>
<td>210 x 2</td>
<td>26.0</td>
<td>Small shrinkage and no pin-holes</td>
<td>90</td>
<td>1950</td>
</tr>
<tr>
<td>Microcrystalline Diamond sandwiched by SiC fibers (SNS)</td>
<td>10.5</td>
<td>349</td>
<td>3.0</td>
<td>Back bending and pin-holes</td>
<td>110</td>
<td>1930</td>
</tr>
<tr>
<td>Nanocrystalline Diamond without SiC fibers (SNS)</td>
<td>21.0</td>
<td>439</td>
<td>6.5</td>
<td>Back bending and pin-holes</td>
<td>130</td>
<td>1950</td>
</tr>
<tr>
<td>Nanocrystalline Diamond with Si frame (SNS)</td>
<td>62.0</td>
<td>541</td>
<td>2.1</td>
<td>Crack inside frame and No observed pin-hole</td>
<td>90</td>
<td>2100</td>
</tr>
<tr>
<td>Multi-DLC (TRIUMF)</td>
<td>1.0</td>
<td>480</td>
<td>Non-measurable due to a big hole</td>
<td>Broken</td>
<td>110</td>
<td>2260</td>
</tr>
<tr>
<td>Carbon nano-tube (AIST)</td>
<td>9.0</td>
<td>450</td>
<td>Non-measurable due to a big hole</td>
<td>Broken</td>
<td>90</td>
<td>1880</td>
</tr>
<tr>
<td>CM (Arizona) with SiC</td>
<td>1.5</td>
<td>425</td>
<td>Non-measurable due to a big hole</td>
<td>Broken</td>
<td>90</td>
<td>1920</td>
</tr>
<tr>
<td>Microcrystalline Diamond with Si frame (Kobelco)</td>
<td>61.5</td>
<td>540</td>
<td>5.7</td>
<td>Crack inside frame and Big a hole</td>
<td>90</td>
<td>2080</td>
</tr>
</tbody>
</table>

Lifetime of the foils was measured with a 650 keV H⁻ and DC ion beam and 3.5 ± 1.0 mm of beam spot.
( The reduction in thickness of the HBC-foil )
Comparison of Lifetime using 800 MeV H-Pulsed ion Beam in PSR Los Alamos

- LANL foils (Green), TRIUMF- DLC foil (Pink), SNS-DM foils (Blue) and KEK-HBC-foil (Orange)

- Total charge injected into PSR via various foils.
- Note that the HBC foil is still in use as of the writing of this article.
Left: The foil “thickness” variable, obtained by dividing a foil scattering loss signal by the foil current, changed dramatically within two weeks for the DLC foil, indicating strong wrinkling or curling.

Right: The foil “thickness” variable for the HBC foil does not yet indicate any deterioration.

Some problems, like pin-holes, are still being addressed by Sugai et al., and HBC foils tested in the future may prove yet superior to the one that is presently being tested.
Nanocrystalline diamond foil of SNS

Photograph of an NC foil before installation in PSR (left) and of a foil after several weeks of beam exposure (right).
TRIUMF-DLC foil

deformed at 50 C
HBC foil at final irradiation in PSR

1100 C Still OK for reuse in PSR
Property of the HBC foil

in comparison with other forms of carbon, Nano and Micro diamond, DLC and CNT
Element analysis of thin HBC-foil

- The spectrum was obtained by RBS with a 2 MeV He$^+$ ion, clearly showing the 10B and 11B nuclide peaks and several contamination. The thickness corresponds to approximately 24% of the carbon foil thickness.
Specific gravity, resistivity and thermal conductivity of HBC foil in comparison with other forms of carbon

<table>
<thead>
<tr>
<th>Sample</th>
<th>Specific gravity (g/cm³)</th>
<th>Resistivity (Ω·cm)</th>
<th>Thermal Conductivity (w/m·k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single crystal of graphite</td>
<td>2.26</td>
<td>10⁻⁴ perpendicular To C-axis</td>
<td></td>
</tr>
<tr>
<td>Fine grain graphite</td>
<td>1.75-1.9</td>
<td>~1 parallel to C-axis; 1.5-1.8 x 10⁻³</td>
<td></td>
</tr>
<tr>
<td>diamond</td>
<td>3.5</td>
<td>&gt; 10¹⁶</td>
<td>2000</td>
</tr>
<tr>
<td>Carbon nano-tube</td>
<td>4.7 x 10⁻⁴</td>
<td>2000-4000</td>
<td></td>
</tr>
<tr>
<td>Boron</td>
<td>2.36</td>
<td>1.5 x 10⁶</td>
<td>27.4</td>
</tr>
<tr>
<td>Boron carbide</td>
<td>2.51</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>Polygraphite</td>
<td>1.8-2.3</td>
<td>1.4 x 10⁻³</td>
<td>50-130</td>
</tr>
<tr>
<td>ACF-foil</td>
<td>1.94</td>
<td>1.5 x 10⁻²</td>
<td>1.41</td>
</tr>
<tr>
<td>Cluster foil</td>
<td>1.85±0.20</td>
<td>1.26</td>
<td>3.95</td>
</tr>
<tr>
<td>HBC-foil</td>
<td>1.10</td>
<td>2.34</td>
<td>0.24</td>
</tr>
<tr>
<td>DLC-foil</td>
<td>2.5</td>
<td>&gt;10⁹</td>
<td>200</td>
</tr>
</tbody>
</table>
• The DM-foils are irradiated by ion beam and laser. The CM (amorphous)-foil is irradiated by only ion beam. In all irradiated foils, we can clearly see broad peaks at around 1580 and 1350 cm⁻¹.

• The DM-foil irradiated by ion beam shows small peak at 1332 cm⁻¹, in contrast by laser irradiation.
Summary and Conclusions

1. We have measured the lifetime of various foils by using 3.2 MeV Ne$^+$, 650 keV H$^-$ DC ion beams and 800 MeV H$^-$ Pulsed ion beam.

2. Among these, the lifetime of the HBC foils showed rather long lifetime even at the three different beam irradiations, for example, 256 h for single and 203 h for double-layered HBC foils at the 650 keV H$^-$ beam, which correspond to about 170 (max) and 135(average) times longer than those of the CM foil. However, for the single HBC foil we observed small pinhole at the irradiated area at even $1900 \pm 100$K for 256 h.

3. Nano-diamond foils of SNS showed strongly back bending at the $2000 \pm 200$K, but lasted 20 h.

4. Further R&D should need especially to reduce the pinhole productions in the foil annealing process, and beam irradiation for the HBC foils at 2000 K.