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Electron Strippers for Compact Neutron Generators

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Abstract. The next generation of compact tandem-type DD or DT neutron generators requires a robust electron stripper with high charge exchange efficiency. In this study, stripping foils of various types were tested, and the H^- to H^+ conversion efficiency, endurance to the heat load, and durability were investigated in terms of suitability in the tandem-type neutron generator. In the experiments, a H^- beam was accelerated to about 180 keV, passes through a stripping foil, and produces a mixed beam of H^-, H^0, and H^+. These ions were separated by an electric field, and detected by a movable Faraday cup to determine the conversion efficiency. The experimental results using thin foils of diamond-like carbon, gold, and carbon nano-tubes revealed issues on the robustness. As a new concept, a H^- beam was injected onto a metal surface with an oblique angle, and reflected H^+ ions are detected. It was found that the conversion efficiency, H^+ fraction in the reflected particles, depends on the surface condition, with the maximum value of about 90%.

Keywords: neutron generator, tandem accelerator, electron stripper, stripping foils
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INTRODUCTION

There has been growing demand for compact and high intensity neutron generators in various fields, such as application to security systems, land mining, and structural evaluation of tankers or nuclear reactors. A tandem acceleration concept has been proposed for a DD or DT neutron generator [1-2]. In this approach, a D^- beam is accelerated up to several-hundreds keV toward a high voltage stage for electron stripping, and the D^+ beam produced is re-accelerated and injected to a D- or T-target with almost doubled energy. This type of accelerator requires a compact, mechanically robust electron stripping system, which can endure high heat load. There are generally two types of electron stripping system, a gas stripping cell and a thin stripping foil. A stripping foil is preferable, because it is simple and the generator would be more compact. In order to produce neutrons by DD or DT reactions, D^- ions need to be accelerated to the few hundred kilovolt range, but there has been almost no research of stripping foils applicable in this energy range.

In this study, various types of stripping foil, including diamond-like carbon, gold, and foils made from carbon nano-tubes, and from graphene were tested experimentally in the energy range of 60 – 150 keV. The foils were evaluated for their application to a tandem-type neutron generator in terms of H^- to H^+ conversion efficiency, heat load, and durability. As a new concept, a solid plate electron stripper was tested, and the experimental results, and comparison with the theoretical prediction were reported.

EXPERIMENTAL SETUP

A test stand previously developed for an alpha particle diagnostics method, Advanced Beam Source 103 (ABS103) [4-7], was used as a H^- beam source. Figure 1 shows the schematic diagram of the ABS103. An H^+ beam extracted from a compact bucket type source was focused at the center of a lithium charge exchange cell, and a H^- beam produced was charge-separated and bent toward the accelerator column.

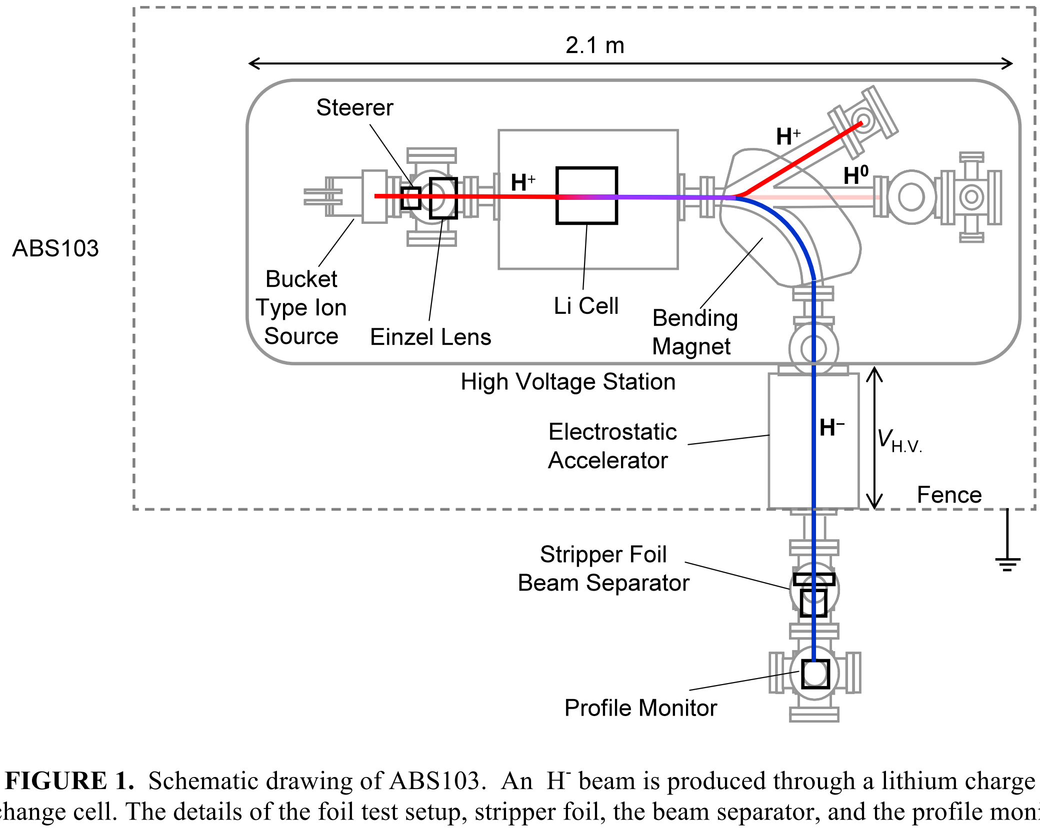

FIGURE 1. Schematic drawing of ABS103. An H^- beam is produced through a lithium charge exchange cell. The details of the foil test setup, stripper foil, the beam separator, and the profile monitor are shown in Fig. 2.

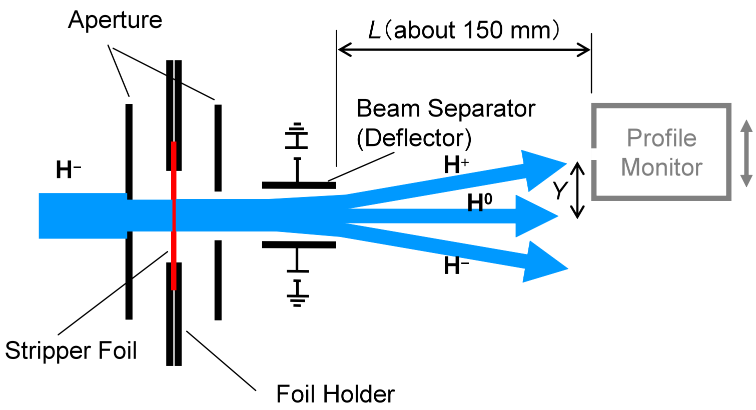

FIGURE 2. Schematic drawing of the experimental setup for the stripping foil test. The outgoing beam fractions from a foil are charge-separated by an electrostatic deflector in the beam separator, and detected by a movable Faraday cup (profile monitor).

Figure 2 shows the experimental setup for the stripping foil test. The H^- beam was extracted through a 4 mm-aperture is injected onto and passed through a test foil. The outgoing beam was charge-separated by an electrostatic deflector (36 mm in length) and detected by a movable Faraday cup (1 mm entrance slit). The distance between the center of the deflector and the entrance slit was 163 mm.

EXRERIMENTAL AND CALCULATION RESULTS

Stripping Foils

By using this apparatus, 5 types of stripping foils were tested, including a foil of evaporated amorphous carbon [8], a gold foil, a carbon nano-tube sheet [9], a double wall carbon nano-tube (DWCNT) on copper mesh and a graphene sheet. The thickness of each foil, the beam energy tested and results are summarized in Table 1. The H^+ beam current was detected only from the amorphous carbon foil of 55 $\mu g/cm^2$ and the gold foil of 480 $\mu g/cm^2$. With other foils neither H^+ beam current nor H^+ beam current was detected because the beam energy was too low to penetrate them.

TABLE 1. Electron stripping foils tested.

Foil	Thickness	Beam Energy	Electron Stripping
amorphous carbon foil (Arizona Carbon Foil)	55 $\mu g/cm^2$	105 – 147 keV	50 – 90 %
Gold	480 $\mu g/cm^2$	127 keV	94 % , but beam divergence is large.
CNT sheet (specially provided by ANI)	unknown(~ 10 μm)	127 keV	not detected
DWCNT on Cu mesh	unknown(~ 10 μm)	147 keV	not detected
Graphene	unknown(~ 10 μm)	150 keV	not detected

The conversion efficiency from H^- to H^+ was evaluated, by comparing theoretical prediction of outgoing beam profiles calculated using the TRIM code [3], where charge exchange probability was not taken into account. The beam profile at the faraday cup of the present geometry was calculated by using the energy loss, energy and angular straggling obtained from TRIM calculation. In Fig. 3 is shown the calculated beam profile from an amorphous carbon foil assuming all particles from the foil are H^+, together with the measurement results. The conversion efficiency from H^- to H^+ was calculated by integrating the measured beam currents profiles divided by that of theoretical prediction. The results are shown in Fig. 4.

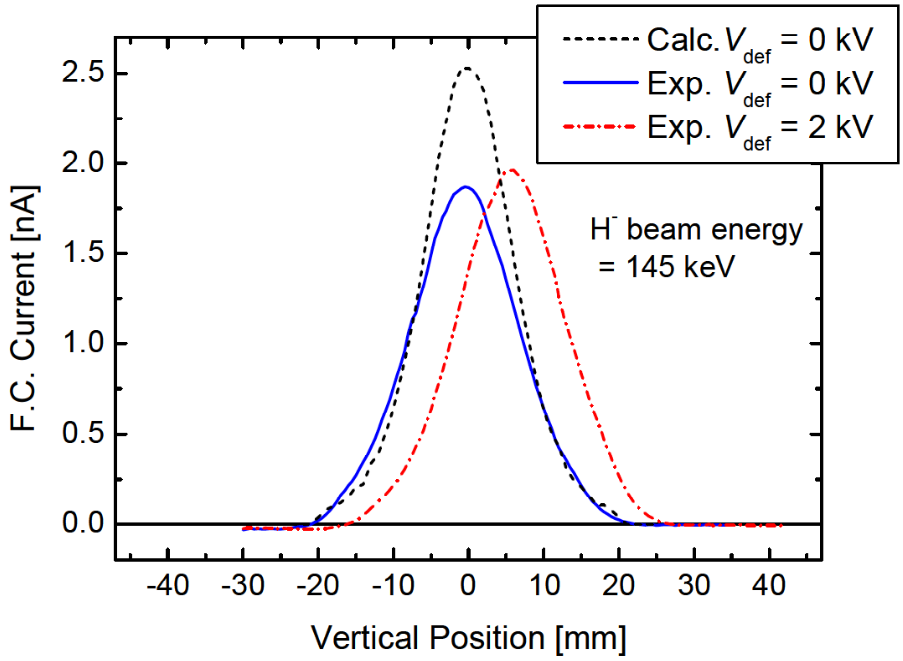

FIGURE 3. The H+ beam profiles from an amorphous carbon foil. Dashed line shows the theoretical profiles obtained by TRIM calculation assuming the same geometrical conditions, and solid lines show the measurement results. The peak shifted by 7 mm when the deflector voltage, V_{def}, of 2 kV was applied at the charge separator. It is consistent with the geometrical prediction.

Although the amorphous carbon foil showed high conversion efficiency, it is not suitable for the application to a compact neutron generator, because it is fragile, and is not able to withstand high heat load. For this reason, a gold foil was tested. The thinnest foil available was 480 μg/cm^2 in thickness. The measured spectrum is shown in Fig. 5. The output beam was dispersed due to the multiple scattering. The measured conversion efficiency for the gold foil was 94 %.

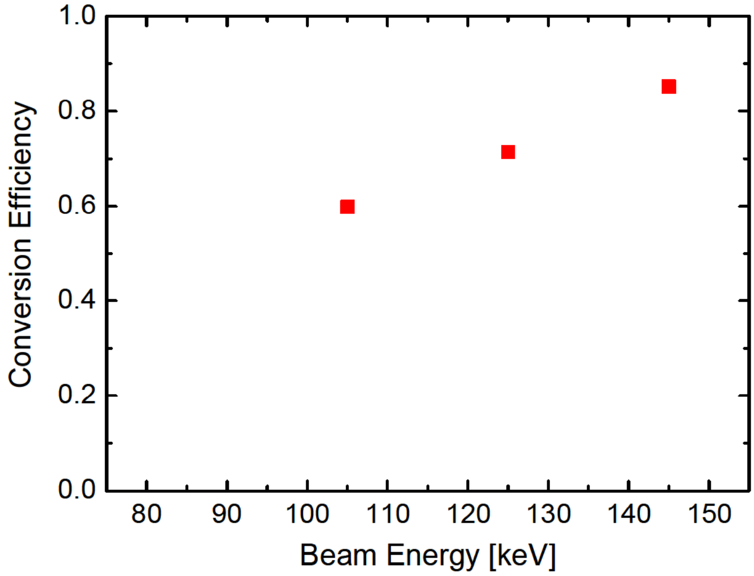

FIGURE 4. The H^- to H^+ conversion efficiency from an amorphous carbon foil as a function of beam energy.

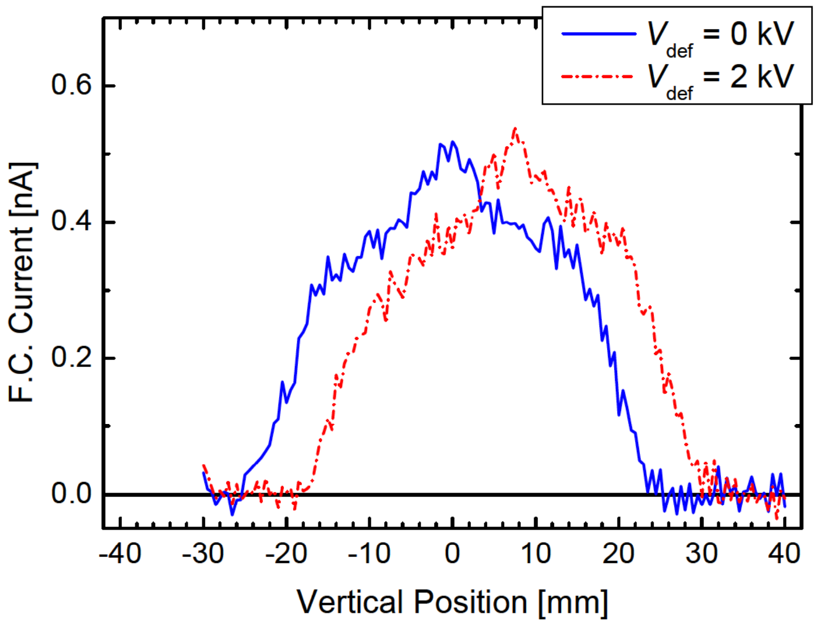

FIGURE 5. The beam profile from an gold foil. The 7 mm shift at the deflector voltage of 2 kV is consistent with the geometrical prediction.

Stripping Plates

As a new concept, a layered stripping plate was proposed by Terai et al. [10][#]. In this system, a H^- beam is injected onto a metal surface with an oblique angle. The schematic view of the arrangement is shown in Fig. 6.

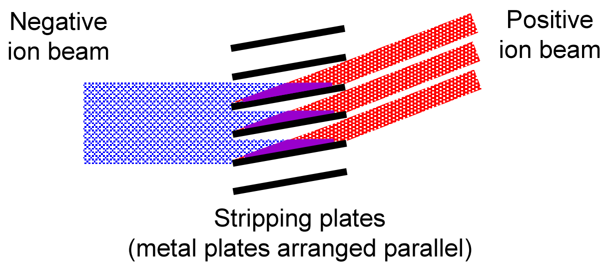

FIGURE 6. Schematic view of the stripping plate concept.

In order to test this concept, an experiment was performed using the present setup. The plates were highly polished molybdenum of 0.4 mm in thickness, 31mm wide and 25 in length to the beam direction. A set of 25 parallel plates separated by 0.2 mm in gap was tilted to the beam direction so that the beam incident angle to the plates was 89 degrees. The reflected H^+ ions were detected by the movable faraday cup. . Figure 7 shows the measured H^+ beam profile. The negative currents in the experimental profiles were caused by negative ions that passed through the small gap of plate. The conversion efficiency from H^- to H^+ was evaluated, in a similar manner to the carbon foil above. The beam profile at the faraday cup of the present geometry was calculated by using the energy loss, energy and angular straggling from a TRIM calculation. The calculated H^+ beam profile is shown in Fig. 7, by a dashed line, indicating the good agreement with the measured results. The conversion efficiency from H^- to H^+ was calculated by integrating the measured beam currents profiles divided by that of theoretical prediction. The results are shown in Fig. 8, as a function of beam energy. Here experimental results of two cases are shown. One was obtained with a factory supplied molybdenum plate (triangles), and the other was obtained with polished molybdenum plate (circles) [10], indicating that the reflected H^+ current depends on the surface condition. With the polished molybdenum plate, the conversion efficiency was about 90% at145 keV.

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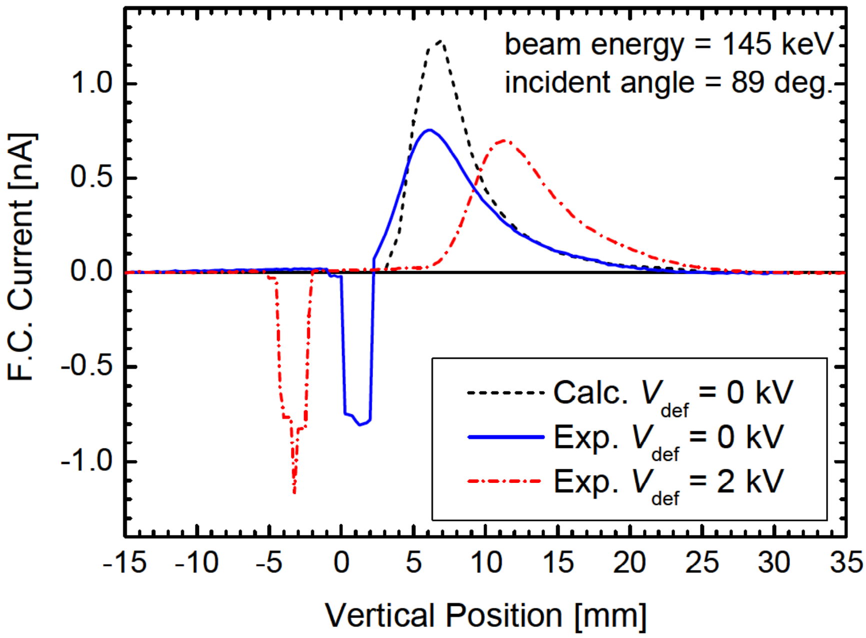

FIGURE 7. The H^+ beam profile from the stripping plate. Dashed line shows the theoretical profiles obtained by TRIM calculation assuming the same geometrical conditions, and solid lines show the measurement results. The peak shifted by 7 mm when the deflector voltage, V_{def}, of 2 kV was applied in the charge separator. It is consistent with the geometrical prediction. The minus signals of the experimental profiles were caused by negative ions that passed through the small gap of plates.

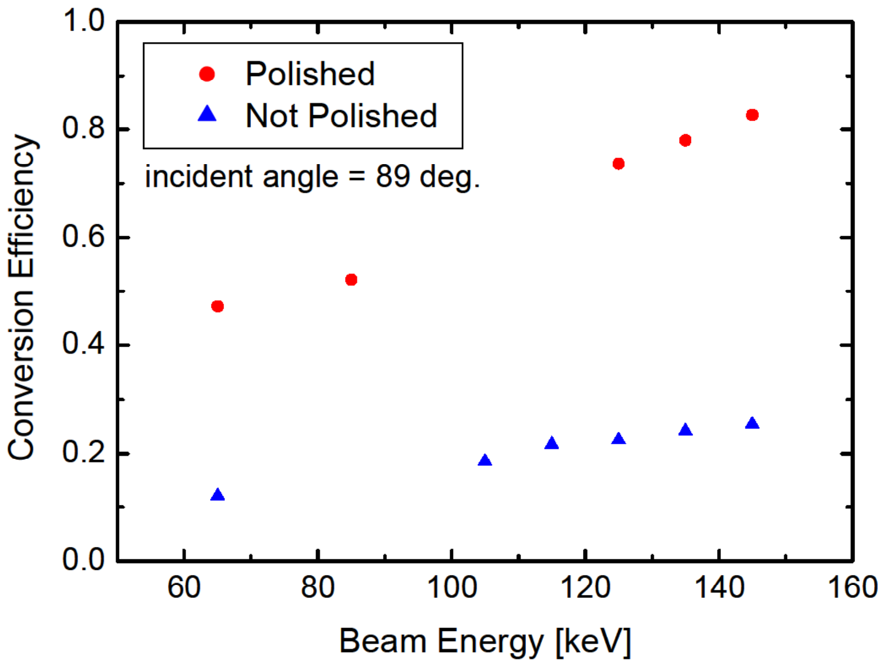

FIGURE 8. The H^- to H^+ conversion efficiency from stripping plates as a function of beam energy. Triangles are obtained with a factory supplied molybdenum plate, and solid circles are obtained with polished molybdenum plate [10].

CONCLUSION

Stripping foils of various types including a foil of evaporated amorphous carbon, a gold foil, a carbon nano-tube sheet, a double wall carbon nano-tube (DWCNT) on copper mesh and a graphene sheet were tested in the energy range up to 150 keV for the application of a tandem type compact DD or DT neutron source. The H^+ beam current could only be detected from ~~the only from~~ an amorphous carbon foil of 55 μg/cm^2 or a gold foil of 480 μg/cm^2. The experimental results using these foils revealed issues on the robustness.

Measurements for a solid plate electron stripper consisted of bombarding a H^- beam onto a stripping plate at an oblique angle. The reflected H^+ ions were detected and the reflected H^+ current was found to depend on the surface condition of the metal plates. The conversion efficiency of H^- to H^+ is nearly linear with the incident beam energy and, at 145 keV, has a value close to 90%.

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