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# Measurement of 181 MeV $H^-$ ions stripping cross sections by carbon stripper foil

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**Abstract**

The stripping cross sections of 181 MeV $H^-$ (negative hydrogen) ions by the carbon stripper foil are measured with good accuracy. The present experiment was carried out at the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex). The stripping cross sections for different charge states, also known as electron loss cross sections of $H^-$ ion are denoted as $\sigma_{-11}$, $\sigma_{-10}$ and $\sigma_{01}$, for both electrons stripping ($H^- \rightarrow H^+$), one-electron stripping ($H^- \rightarrow H^0$) and the 2nd-electron stripping ($H^0 \rightarrow H^+$) proceeding $\sigma_{-10}$, respectively. We have established very unique and precise techniques for such measurements so as also to determine a foil stripping efficiency very accurately. The cross sections $\sigma_{-11}$, $\sigma_{-10}$ and $\sigma_{01}$ are obtained to be $(0.002 \pm 0.001) \times 10^{-18} cm^2$, $(1.580 \pm 0.034) \times 10^{-18} cm^2$ and $(0.648 \pm 0.014) \times 10^{-18} cm^2$, respectively. The presently given cross sections are newly available experimental results for an incident $H^-$ energy below 200 MeV and they are also shown to be consistent with recently proposed energy ($\frac{1}{\beta^2}$) scaled cross sections calculated from the previously measured data at 200 and 800 MeV. The present results has a great importance not only at J-PARC for the upgraded $H^-$ beam energy of 400 MeV but also for many new and upgrading similar accelerators, where $H^-$ beam energies in most cases are considered to be lower than 200 MeV.

*Keywords:* `H⁻ ion, stripper foil, stripping cross sections`

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## 1. Introduction

In the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex), we have precisely measured the stripping cross sections for $H^-$ (negative hydrogen) ions of 181 MeV by the carbon stripper foil. In order to achieve higher beam current in a circular proton accelerator, a multi-turn $H^-$ stripping injection is commonly utilized [1, 2, 3]. Solid stripper foils are widely used for stripping $H^-$ ion beam to proton ($H^+$) beam by removing two bound electrons from the $H^-$ ion. The proton beam is injected in the circular machine for several hundred to thousand turns until it occupied the full design emittance. The $H^-$ ion beam interacting with a foil leads three production channels. Namely, stripping of both electrons leads to an $H^+$ beam, stripping of a single electron leads to an $H^0$ beam and some of them uninteracted and thus remain as $H^-$. The stripping efficiency for a particular foil material is a function of foil thickness as well as kinetic energy of the $H^-$ ion. The stripping cross sections also known as electron loss cross sections, are denoted as $\sigma_{-11}$, $\sigma_{-10}$ and $\sigma_{01}$, where $\sigma_{-11}$ is for both two-electron stripping in a single step ($H^0 \rightarrow H^+$), $\sigma_{-10}$ is for the 1st-electron (outer most) stripping ($H^- \rightarrow H^0$) and $\sigma_{01}$ is for the 2nd-electron stripping ($H^0 \rightarrow H^+$) proceeding $\sigma_{-10}$.

There exist only two earlier measurements of the $H^-$ stripping cross sections by carbon foils at 200 and 800 MeV of the $H^-$ ion beam energies. [4, 5]. The earlier experiment at 200 MeV unfortunately gave an uncertain value for the $\sigma_{-11}$ cross section, while the measurement errors were also as high as 10%. The value of $\sigma_{-11}$ cross section itself is very small and it was thus treated to be zero for calculating the production yields. The later experiment at 800 MeV clearly determined three cross sections with significantly improved measurement errors. However, the cross sections at lower $H^-$ energies in particular around 200 MeV have particular interest not only for J-PARC $H^-$ beam energy of 181 MeV at the 1st phase but also for many newly constructing and upgrading accelerators worldwide [6, 7, 8]. The $H^-$ beam energy at J-PARC has already been upgraded to the design of 400 MeV and the present experimental result was thus very important to determine an appropriate foil thickness.

It is worth mentioning that an energy scaling of the cross sections by using $\frac{1}{\beta^2}$ was proposed recently, where $\beta$ is the relativistic factor of the $H^-$ ion [9]. Based on the 800 MeV measurement, an energy scaled cross sections given for 200 MeV was shown to reproduced those measured ones at 200 MeV within a few percent errors. The higher the $H^-$ ion energy, the higher the scaling accuracy was also claimed. It is thus very important to carry out accurate measurements, especially at the lower energies. The first motivation of the present study is to make a precise measurement of all three charge state cross sections, $\sigma_{-11}$, $\sigma_{-10}$ and $\sigma_{01}$ of 181 MeV $H^-$ ions incident on carbon foils, where no experimental data exists. It is also important to determine an appropriate foil thickness for the J-PARC design $H^-$ ion beam energy of 400 MeV in order to achieve a desired stripping efficiency. Because, a thinner foil than the appropriate one would increase the waste beam (particularly $H^0$) and could be an issue for the already constructed waste beam dump with a limited capacity. A thicker foil would increase the stripping efficiency but then the uncontrolled foil scattering beam loss of the circulating beam at the injection region during multi-turn injection would be a big concern. The energy deposition or heat load in the foil is increased for a thicker foil and is also an issue concerning foil lifetime for machine operation. Other than J-PARC, precisely measured cross sections at 181 MeV would also be useful for many previously mentioned new and upgrading similar accelerators worldwide [6, 7, 8].

## 2. Brief Overview of the 3-GeV RCS of J-PARC

Fig. 1 shows a schematic view of the 3-GeV RCS of J-PARC. The RCS is a 25 Hz rapid cycling proton synchrotron designed for a beam power of 1 MW [1]. The design injection and extraction energies are 400 MeV and 3 GeV, respectively. The injection energy was just upgraded to the design 400 MeV in 2013 from the initial 181 MeV. A multi-turn $H^-$ stripping injection system is adopted in order to fill the ring with as much as $8.33\times10^{13}$ protons for 1 MW. The accelerated 3-GeV beam is simultaneously delivered to the muon and neutron production targets in the MLF (Material and Life Science Experimental Facility) as well as to the MR (50-GeV Main Ring). RCS beam power for the operation before the 2014 summer shutdown was 300 kW ($2.5\times10^{13}$ particles per pulse) for both MLF and MR.

Fig. 2 shows a layout of the RCS injection and the successive injection beam dump. The primary stripper foil named $1^{st}$ foil is placed at the middle of 4 injection chicane magnets named shift bump magnets (SB1-4). The role of SBs are to merge injected $H^-$ and circulating protons at the $1^{st}$ foil for the multi-turn injection. A more than 99.7% of the $H^-$ are stripped to $H^+$ and injected into the ring. The partially stripped $H^0$ leaving the 1st foil and un-stripped $H^-$ (if any) are called waste beam. They are further stripped to $H^+$ by two secondary foils named $2^{nd}$ and $3^{rd}$ foils, respectively and transported to the injection beam dump located nearly 15 m downstream from the $1^{st}$ foil. The $H^-$ beam energy in the present experiment was 181 MeV. The $1^{st}$ stripper foil material was used as carbon with 5 different thicknesses between 48 $\sim$ 193 $\mu g/cm^2$.

## 3. Experimental setup and Measurement Principle

Fig. 3 shows a layout the present experimental setup as well as the measurement principle. We measured partially stripped $H^0$ and the un-stripped $H^-$ at the injection dump by using two independent and completely different type of monitors. One of them is a current transformer (CT) named H0CT, while the other one is a multi-wire profile monitor (MWPM) named MWPM7 placed at the entrance of the injection beam dump.

The H0CT is usually used for monitoring the waste beam current in the injection dump. In order to extract the real beam signal from the huge background we have already established a precise technique and has proven to be very efficient for monitoring even a small quantity of the waste beam [11]. The time domain signal measured by the H0CT is taken by an on-line controlled oscilloscope and then a Fast Fourier Transformation (FFT) analysis is done. As a result, picking up amplitude of the power spectrum corresponding to the frequency of the intermediate pulses (chopping frequency), which depends on the frequency of the RCS rf system gives the beam signal [12]. In the usual RCS operation, the frequency of the intermediate pulses at 181 MeV injection for RCS rf with dual harmonic (h=2) is typically 0.940 MHz.

In addition to the H0CT, we have also made it possible to perform the same study by measuring partially stripped $H^0$ and the un-stripped $H^-$ beam profiles by the MWPM7. In this case the integrated yield of the each beam profile is used for the analysis.

We utilized two modes of the RCS, which are basically used for beam studies. The first mode is the single-pass extraction mode as shown on the top (a) of Fig. 3, where all three foils are set in place. In this case the fully stripped $H^+$ beam is injected into the ring but it is transported only one third of the RCS circumference and extracted to the extraction beam dump. The partially stripped (un-charged) $H^0$ and un-stripped $H^-$ (if any) are further stripped to $H^+$ by using secondary foils named $2^{nd}$ and $3^{rd}$ foils, respectively and are transported to the injection beam dump. The $H^0$ and $H^-$ yields are measured by the H0CT and MWPM7 separately. However, in order to obtain charge fractions of the partially stripped $H^0$ and un-stripped $H^-$, the injected beam is measured by the injection beam dump mode as shown in the bottom (b) of Fig. 3. In this case, the $1^{st}$ foil is removed from the beam line and thus the incoming $H^-$ is stripped to $H^+$ by the $3^{rd}$ foil and transported to the injection beam dump. A ratio of the signal measured by mode (a) to mode (b) gives $H^0$ and $H^-$ charge fractions for a corresponding thickness of the $1^{st}$ stripper foil. It is worth mentioning that the secondary foils are thicker (500 $\mu g/cm^2$) and thus the stripping efficiencies are expected to be almost 100% (99.9999%). For a design $1^{st}$ foil thickness of 200 $\mu g/cm^2$, a 99.7% of the incoming $H^-$ is stripped to $H^+$ injected into the ring. The remaining 0.3% are ideally the partially stripped $H^0$, where the un-stripped $H^-$ are negligibly small. In the present experiment we used rather big size foils as compared to the size of the injected beam. The foils were also with two layered in order to reduce any pinholes in the foil. Any measurable un-stripped $H^-$ is thus believed to determined by the production cross section.

Fig. 4 shows a typical carbon foil dimension used for the present experiment sketched with typical size of the injected $H^-$ beam. The foil size, especially in the vertical direction was twice wider than that usually used for the operation. In order to avoid foil missing $H^-$, the injected beam center to the foil edge was kept about 20 mm for both horizontal and vertical directions, where a measured full size ($4\sigma$) of the injected beam at the foil location was about 16 mm for both dimensions.

The $H^0$ and $H^-$ components can be simultaneously measured by the MWPM7 as two beam profiles are separated enough to get each integrated yield. As for the H0CT, we measured each component of the $H^0$ and $H^-$ by removing $3^{rd}$ and $2^{nd}$ foils, respectively from the beam line. A removal of the $3^{rd}$ allows only $H^0$ component to transported to the injection beam dump (after stripping to $H^+$ by the $2^{nd}$ foil). The un-stripped $H^-$ (if any) in this case hit the beam pipe and lost few meter downstream at the branch between dump line and the circulating beam line. In the similar way, removal of the $2^{nd}$ foil guaranties a measurement of the any un-stripped $H^-$ component. In order to take into account any fluctuation of the incoming $H^-$ beam during the measurement, the injected beam intensity was also measured by the last SCT (Slow Current Transformer) placed in the $H^-$ injection beam transport line, which was just a few meters upstream of the $1^{st}$ foil. A no beam data was also always taken in order to subtract the background from the measurement. The results of the $H^0$ and $H^-$ yields are normalized to the incoming $H^-$ beam intensity to obtain the $H^0$ and $H^-$ charge fractions. By measuring the $H^0$ and $H^-$ charge fractions together or independently, the $H^+$ charge fraction which is injected into the ring can thus be obtained as 1 - ($H^0$ + $H^-$).

The linearity of H0CT and MWPM7 for a required intensity range of the injected beam corresponding to the expected signals with and without foils were key issues for the present experiment. The H0CT acts as an online monitor for the waste beam during RCS operation and its linearity has already been shown to be very good as was reported earlier [11]. The linearity of the MWPM7 was measured in the injection beam dump mode. In this case injected $H^-$ beam was stripped to $H^+$ beam by the $3^{rd}$ foil and the beam profile was measured by the MWPM7. A response of the integrated yields of the measured beam profiles as a function of the injected beam intensity was obtained. The number of injected $H^-$ beam pulses were optimized to controlled injected beam intensity. In contrast to the H0CT, the maximum allowable intensity for which the beam profile measured by the MWPM7 not saturated was around $6{\times}11^{11}$, where the minimum was about $0.5{\times}11^{11}$. The above intensity range well covered the expected partially stripped $H^0$ and un-stripped $H^-$ yields for all foils used for the present experiment. Figure 5 shows a response of the integrated yields obtained from the measured MWPM7 beam profiles as a function of the injected beam intensities. The symbols are the profile yields with corresponding measurement errors for five different intensities of the injected beam, while the solid line is a linear fitting of the data. The mean value of the profile yield and the error in one standard deviation were obtained from multiple measurements for each intensity. The linearity of the MWPM7 is also obtained to be very good for a beam intensity range used in the present experiment.

## 4. Experimental data

In this section a detail of the experimental data measured by the H0CT and MWPM7 as well as analysis procedures are presented. The quality of the measured data is also discussed. The thickness of five carbon foils used in the present experiment were 48, 84, 115, 125 and 193 $\mu g/cm^2$.

### *4.1. Measurement by the H0CT*

Fig. 6 shows the FFT spectra of the H0CT time domain signal for 4 carbon foils measured in the single pass extraction mode. The H0CT signals obtained for 4 foils are plotted along with the signal with no foil (all beam to the injection beam dump) as well as with no beam. The signal at the expected fundamental frequency of 0.94 MHz and successive higher order harmonics at rf multiples are clearly seen even for the heaviest foil. The coincidence of the peak positions for the data with foil to that with no foil guaranties the real signal for each foil as in the later case (with no foil) all of the injected beam was transported to the injection dump. The duration of the injected beam was 0.5 ms with a total of about $2.5\times10^{13}$ $H^-$ particles. In order to remove the background, the time domain no beam data is subtracted from the data with beam before FFT analysis is done. For the analysis, FFT peak height corresponding to the fundamental frequency (0.94 MHz) is used. An expanded view of the FFT spectra near the fundamental frequency region are shown in Fig. 7, where clear signals for all foils can easily be identified. No such a signal can be seen with no beam as a typical FFT spectrum is shown by the broken line in black.

The signal height with any foil in this case corresponds to the measured partially stripped $H^0$ and un-stripped $H^-$ yields together as both $2^{nd}$ and $3^{rd}$ foils were set in place. The ratio of the signal height with foil to that of no foil thus gives $H^0$ and $H^-$ charge fractions together. As a result, we separately measured $H^0$ and $H^-$ yields by removing $3^{rd}$ and $2^{nd}$ foils, respectively as explained for the measurement principle in the previous section. As an example, Fig. 8 show the FFT spectra for the $H^0$ and $H^+$ yields together and $H^0$ yield only (measured by removing $3^{rd}$ foil) for the thinnest and thickest foils of 48 and 193 $\mu g/cm^2$, respectively. The difference of the signal heights between two spectra ($H^0$ and $H^+$ together and $H^0$ only) for each foil gives the corresponding un-stripped $H^-$ yield. As expected, there was certain amount of the un-stripped $H^-$ for the former one, where as no significant amount of that for the later one. The $H^0$ and $H^-$ charge fractions are obtained by taking a ratio of each FFT peak heights to that with no foil. The $H^+$ charge fraction which was the rest of the total injected beam and was injected into the ring was thus easily calculated. The $H^-$, $H^0$ and $H^+$ charge fractions for a 48 $\mu g/cm^2$ carbon foil are obtained to be 0.0209±0.0002, 0.3206±0.0070 and 0.6575±0.0134, respectively. The errors of the $H^-$ and $H^0$ charge fractions are the measured statistical errors in one standard deviation as obtained from the multiple measurements of each data.

The measured errors of the H$^-$ and H$^0$ yields as well as error of the injected H$^-$ yield are taken into account in order to calculate errors for the H$^-$ and H$^0$ charge fractions. The H$^-$ and H$^0$ yields measured together and the corresponding error is used to calculate the H$^+$ charge fraction and its error. The data taking and the analysis were carried out in the same manner for all foils.

*4.2. Measurement by the MWPM7*

The partially stripped H$^0$ and the un-stripped H$^-$ can be simultaneously measured by the MWPM7 in the single-pass extraction mode because of no overlap at all of the two beam profiles at the MWPM7. Similar to the H0CT, the injected beam itself was also measured in the injection beam dump mode so as to obtained each charge fraction. Fig. 9 shows the measured H$^0$ and H$^-$ beam profiles for 4 foils together with the injected H$^-$ beam profile (open circles), which is scaled to one third of its original height. The center of H$^-$ and H$^0$ beam profiles are nearly 80 mm separated with no overlap each other. As a result, integration for H$^-$ and H$^0$ yields can thus be easily obtained by measuring them together in the single-pass extraction mode. Similar to the H0CT data, the H$^0$ beam profile even for the heaviest foil of 193 $\mu g/cm^2$ (solid circles) was also clearly measured by the MWPM7. The H$^0$ and H$^-$ charge fractions were obtained by a ratio of the integrated yields of the H$^0$ and H$^-$ beam profiles measured with each foil in the single-pass extraction mode to that with H$^-$ profile measured with no foil in the injection beam dump mode. The H$^+$ charge fraction was thus easily calculated. Based on the MWPM7 results, the H$^-$, H$^0$ and H$^+$ charge fractions for a 48 $\mu g/cm^2$ carbon foil are obtained to be 0.0229±0.0004, 0.3194±0.016 and 0.6577±0.0346, respectively.

## 5. Experimental results

In this section we attempt to obtain stripping cross sections of 181 MeV H$^-$ ion by the carbon foil based on the directly measured H$^0$ and H$^-$ charge fractions. We used differential equations for three charge fractions in the H$^-$ beam given by Tawara et al. [13] and integrating those to the following forms:

$$N^- = e^{-(\sigma_{-10}+\sigma_{-11})x} \tag{1}$$

$$N^0 = \frac{\sigma_{-10}}{\sigma_{-10}+\sigma_{11}-\sigma_{01}}[e^{-\sigma_{01}x} - e^{-(\sigma_{-10}+\sigma_{-11})x}] \tag{2}$$

$$N^+ = 1 - N^- - N^0 \tag{3}$$

Where $N^-$, $N^0$ and $N^+$ are respectively, the fractions of negative hydrogen atoms ($H^-$), neutral hydrogen atoms ($H^0$) and protons ($H^+$) in the beam. The parameter x is the number of target atoms per $cm^2$, $\sigma_{-10}$ and $\sigma_{-11}$ are the single and double electron loss cross sections of an $H^-$, respectively. The $\sigma_{01}$ is the stripping cross section of an $H^0$ to $H^+$ proceeding $\sigma_{-10}$.

The measured charge fractions for all foils are given in Table 1. The $H^-$ and $H^0$ together were measured by setting both $2^{nd}$ and $3^{rd}$ foils in place. However, for the H0CT the $H^-$ and $H^0$ were also separately measured by removing the $2^{nd}$ and $3^{rd}$ foil, respectively. The $H^+$ was obtained as 1 - ($H^0$ + $H^-$). For each setting, the data was taken for at least 3 times. A mean value and the corresponding measurement error in one standard deviation obtained from the multiple measurements are presented in the table. The measurement results by the H0CT and MWPM7 are obtained to be consistent with each other as given in the upper and lower part of the table, respectively.

In order to obtain cross sections, a total of the $H^-$ and $H^0$ charge fractions for each foil and data for both H0CT and MWPM7 were fitted together by combining Eqs. 1 and 2 for three free parameters, $\sigma_{-10}$, $\sigma_{-11}$ and $\sigma_{01}$. For minimizing the fitting function error, we used MINUIT program in the PAW (Physics Analysis Workstation) developed at CERN [15]. The best fitting values for the three cross section with fitting errors are obtained to be as follows:

$\sigma_{-11} = (0.002\pm0.001)\times10^{-18}\text{cm}^2$

$\sigma_{-10} = (1.580\pm0.034)\times10^{-18}\text{cm}^2$

$\sigma_{01} \quad = (0.648\pm0.014)\times10^{-18}\text{cm}^2$

Fig. 10 shows the measured charge fractions plotted as symbols together with calculated ones (solid lines) by using present cross sections in theoretical expressions given by Eqs. 1 $\sim$ 3. As also presented in the Table 1, the charge fractions measured by both H0CT and MWPM7 for all foils are obtained to be quite consistent with each other as they can be seen completely overlapped in the figure. The difference of the results between two monitor systems can only be seen in the size of error bars (lower for the H0CT). The measurements errors of the $H^0$ and $H^-$ charge fractions in most cases are even smaller than the size of the symbols representing the yields. The dotted and dashed lines are also the same calculated ones for 181 MeV obtained by using energy scaled cross sections of the previously measured data at 200 MeV [4] and 800 MeV [5], respectively. The energy scaling was done by using $\frac{1}{\beta^2}$ hypothesis [9]. The $\sigma_{-11}$ cross section was considered to be zero for the 200 MeV case as it was given a negative value and was also treated in the same way by the authors. The calculated charge fractions based on the present cross sections are found to be quite consistent to those calculated ones based on the previously measured data, especially the later one at 800 MeV.

The thickness of each foil was measured by various methods like weighting, alpha-ray gauge, Rutherford Backscattering Spectroscopy (RBS) as well as by Scanning Electron Microscopy (SEM). The RBS and SEM measurements were conducted at the TIARA (Takasaki Ion Accelerators for Advanced Radiation Application), which is one of the other laboratories of Japan Atomic Energy Agency located in the Takasaki prefecture [14]. A purity test of the of the foil material was also carried out and there was no any significant unexpected elements other than carbon was observed. The thickness of the foils measured in four different methods were consistent each other, resulting a maximum foil thickness error of less than 4% even for the worst case.

The numerical values of three charge state cross sections obtained in the present experiment at 181 MeV are summarized in table 2. The previously measured cross sections for 200 and 800 MeV, scaled to the 181 MeV, are also included for comparison. The present cross sections for all charge fractions are measured to be consistent with expected scaled cross sections as obtained from the previous measurements. The agreement is found to be comparatively better for the 800 MeV measurements. The measured errors of the cross sections in the present experiment are obtained to significantly better than previous experiment at 200 MeV. The $\sigma_{-11}$ cross section is also determined as a finite value and as expected it is obtained to be negligibly smaller than other two major charge state cross sections. It thus has no significant role on the production yields.

Based on the present cross sections, the stripping efficiency for a 200 $\mu g/cm^2$ carbon foil for 181 MeV $H^-$ ion energy in the RCS is calculated to be 99.75%. In order to obtain an expected stripping efficiency of 99.7% for the design 400 MeV injection energy, a required foil thickness is estimated to be 333 $\mu g/cm^2$.

An energy scaled cross sections based on the present measured values are also given in the later half of the Table 2 for some nearby energies and up to 400 MeV, which can be applicable to many of the very recently designed and upgrading similar accelerators. The injected $H^-$ energy for the newly designed CSNS (Chinese Spallation Neutron Source) project is 80 MeV and will be upgraded to 250 MeV in the 2nd phase [6]. As an intensity upgrade program at CERN, present 50 MeV $H^+$ injector Linac2 is to be replaced by a 160 MeV $H^-$ ion injector called Linac4 [7]. The intensity upgrade plans in the ISIS of RAL (Rutherford Appleton Laboratory) is also highly focusing on an upgrading injection energy for the synchrotron by replacing presently 70 MeV $H^-$ ion Linac to a 180 MeV one [8]. The $H^-$ stripping cross sections obtained in the present experiments can thus be directly used to determine an appropriate foil thickness for a desired stripping efficiency. A proper understanding of the required foil thickness strongly related for designing the waste beam dump as well as keep un-controlled foil scattering beam loss to an acceptable limit.

## 6. Conclusion

The stripping cross section of 181 MeV $H^-$ beam by the carbon stripper foil has been measured with good accuracy. All three charge stage cross sections, $\sigma_{-11}$, $\sigma_{-10}$ and $\sigma_{01}$ are uniquely determined by fitting $H^0$ and $H^-$ charge fractions measured by two independent monitor systems very accurately. The present cross sections are found to be consistent with energy ($\frac{1}{\beta^2}$) scaled cross sections of the previously measured ones at 200 and 800 MeV. It is thus well verified with good accuracy in the present experiment. The presently given cross sections are very important for determining an appropriate foil thickness for the recently upgraded RCS injection energy to 400 MeV. In the same way, it can also play an important role for the same purpose for many newly constructing and upgrading as well as proposed accelerators, where $H^-$ ion energies for most cases are below 200 MeV.

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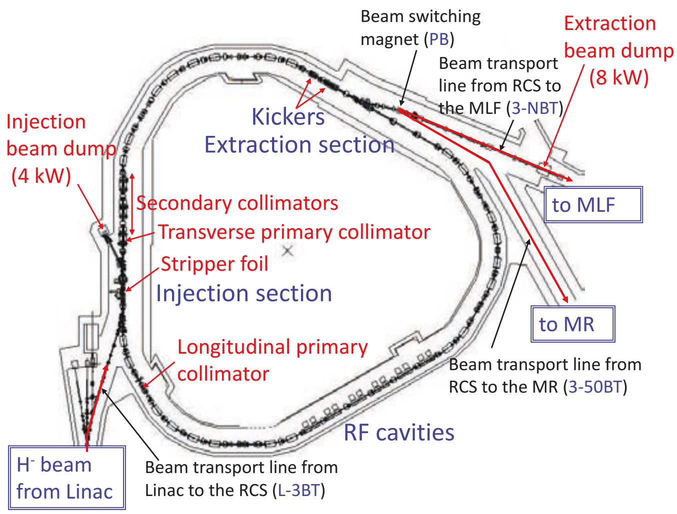


Figure 1: A schematic view of the 3-GeV RCS of J-PARC. The RCS has a three-fold symmetric lattice with three long straight and three arc sections having a circumference of 348.333 m. The $H^-$ charge-exchange devices are located at the 1st half of the injection section.

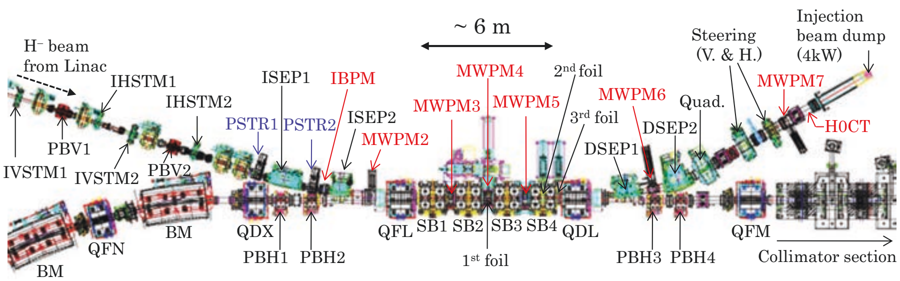


Figure 2: Layout of the RCS injection area and successive injection beam dump. The injected $H^-$ and the circulating $H^+$ beams are merged at the $1^{st}$ foil by 4 chicane magnets called Shift bump magnets (SB1 $\sim$4) for multi-turn injection. A more than 99.7% of the incoming $H^-$ are stripped to $H^+$ by the $1^{st}$ foil and injected into the ring. The remaining are mostly with one electron stripping and called $H^0$ beam. The $H^0$ and un-stripped $H^-$ (if any) are further stripped to $H^+$ by the $2^{nd}$ and $3^{rd}$ foil, respectively, but they are transported to the injection beam dump. In this experiment, 5 carbon foils with different thicknesses in the range of 48 to 193 $\mu g/cm^2$ are used as the $1^{st}$ foil in order to measure the stripping cross sections of 181 MeV $H^-$ ion beam.

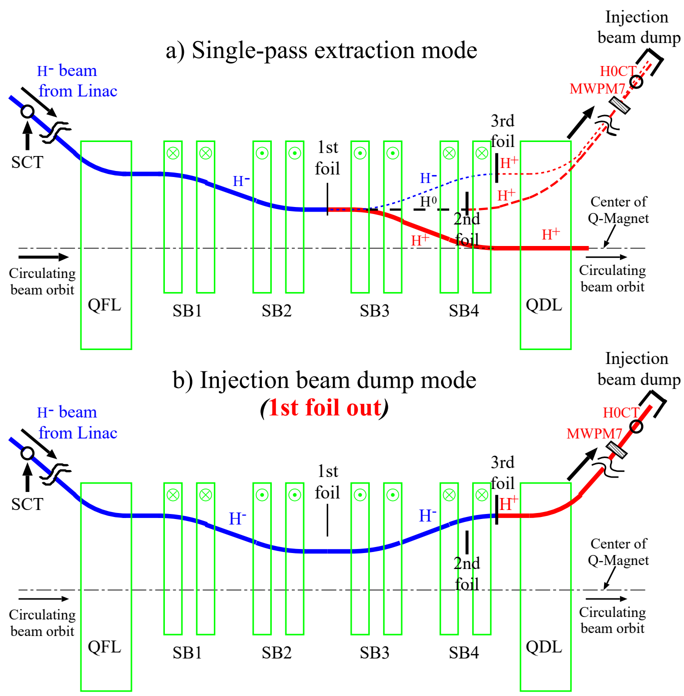


Figure 3: A schematic view of the RCS injection along with the beam orbits are shown for describing the present measurement principle. In the single pass extraction mode (top), all foils are set in place and thus $H^-$ beam stripping to $H^+$ by the $1^{st}$ stripper foil is injected into the ring. The partially stripped $H^0$ and un-stripped $H^-$ (if any) are further stripped by the $2^{nd}$ and $3^{rd}$ foils, respectively. They are transported to the injection beam dump and measured by the H0CT and MWPM7 separately. However, in the injection beam dump mode (bottom), the $1^{st}$ foil is removed from the beam line and thus incoming $H^-$ is stripped to $H^+$ by the $3^{rd}$ foil and transported to the dump. A ratio of the signal measured by the MWPM7 or H0CT in the former mode to the later mode gives $H^0$ and $H^-$ charge fractions for a corresponding $1^{st}$ stripper foil. The $H^+$ charge fraction which is injected into the ring can thus be automatically calculated as 1- ($H^0$+$H^-$). In order to take into account any fluctuation of the injected beam intensities (usually negligible) during the measurement, the injected beam intensity is also always measured by an SCT (Slow Current Transformer) placed a few meter upstream of the $1^{st}$ foil. A no beam data is also always taken in order to subtract the background from the measurement.

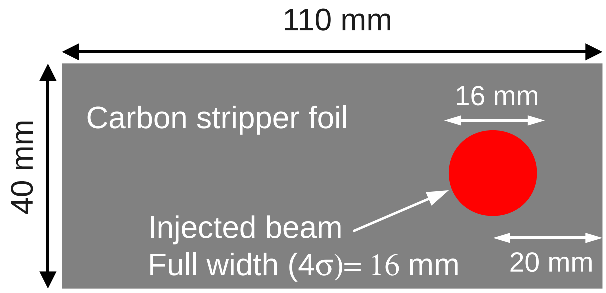


Figure 4: A typical dimension of a carbon stripper foil used for the present experiment is sketched with a typical size of the injected $H^-$ beam. The foil size, especially in the vertical direction was twice bigger than it is used in the usual operation. The injected beam positioning on the foil was also carefully done in order to make sure for no any missing $H^-$ at $1^{st}$ the foil.

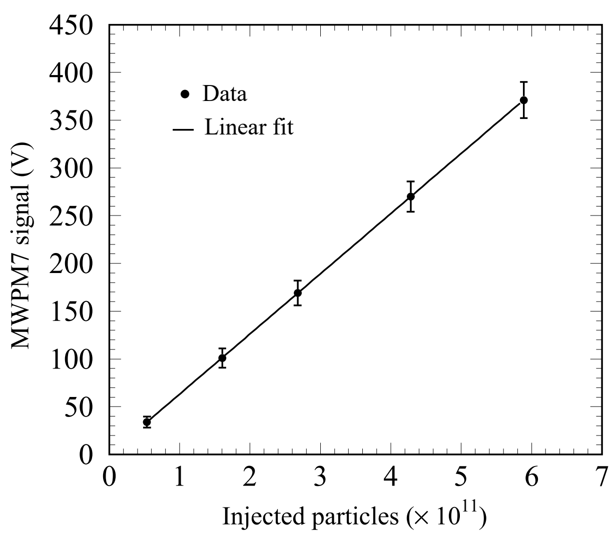


Figure 5: Linearly of the MWPM7 obtained for a beam intensity range used in the present experiment was measured in the injection beam dump mode. The horizontal axis is the injected $H^-$ beam intensity measured by the SCT in the injection beam transport line (see Fig. 3), while the vertical axis is the corresponding integrated yield obtained from the measured beam profile by the MWPM7. The error bars are one standard deviation errors obtained by multiple measurements for each intensity. The solid line is a linear fitting of the data. The linearity of the MWPM7 was found to be good enough within the intensity range used in the present experiment

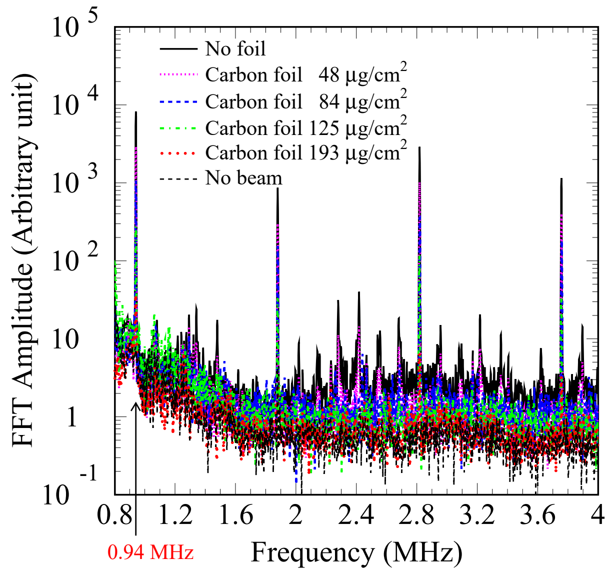


Figure 6: FFT spectra of the H0CT time domain signals measured for 4 carbon foils in the single-pass extraction mode are shown along with that no foil measured in the injection beam dump mode. A background data measured with no beam data is also shown. The signal at the expected fundamental frequency of 0.94 MHz and successive higher order harmonics at rf multiples are clearly seen even for the thickest foil of nearly 200 $\mu g/cm^2$.

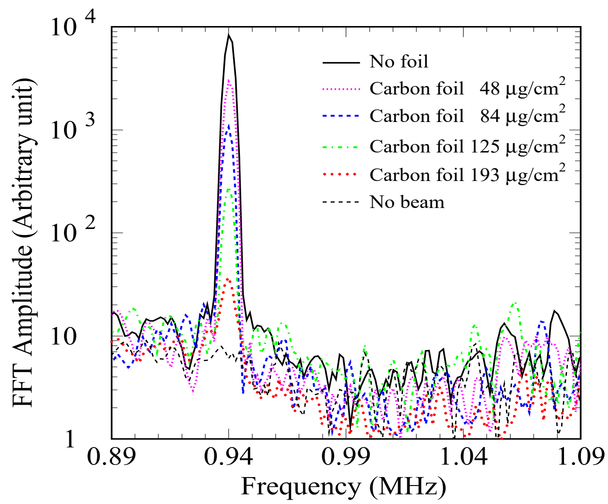


Figure 7: Expanded view of the FFT spectra (Fig. 6) near the fundamental frequency region of 0.94 MHz shows a clear view of the signals for the partially stripped $H^0$ and un-stripped $H^-$ for each foil. The peak position with all foils coincided to that with no foil (solid line) confirm the expected signal. The differences in signal heights among foils reflect a difference in their thickness.

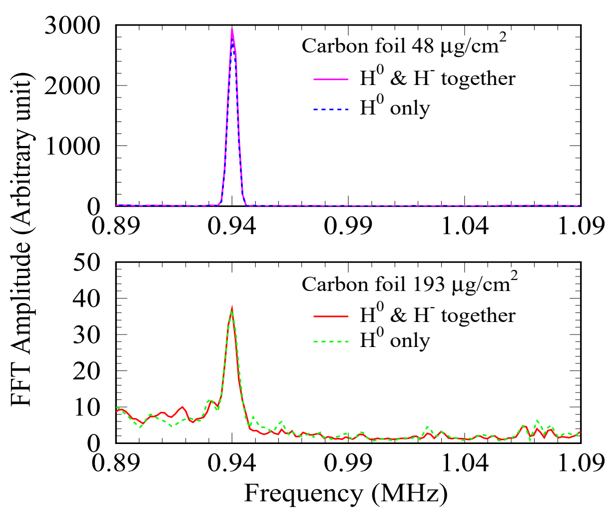


Figure 8: The FFT spectrum for only the partially stripped $H^0$ yield (broken line) measured by removing the $3^{rd}$ foil (see Fig. 3) is plotted with that for the $H^0$ and $H^-$ yields together (solid line). The upper and lower figures correspond for the thinnest and thickest foils of 48 and 193 $\mu g/cm^2$, respectively. The difference of the peak heights gives the un-stripped $H^-$ yield for the corresponding foil.

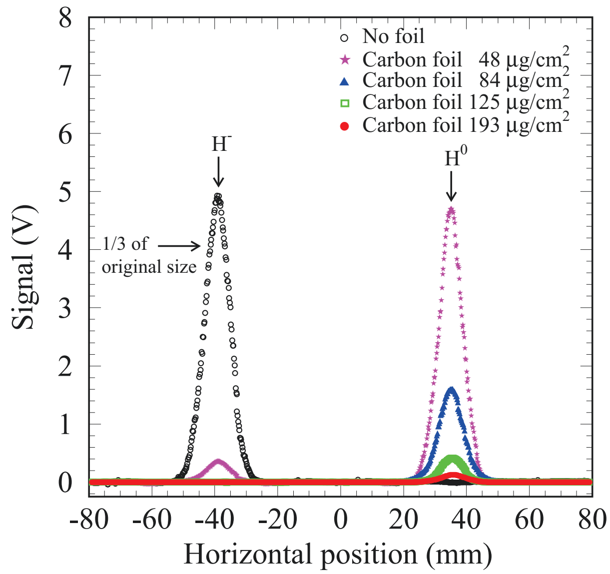


Figure 9: Beam profiles of the partially stripped $H^0$ (right) and un-stripped $H^-$ (left) measured by the MWPM7 are plotted together for 4 carbon foils. The injected $H^-$ beam profile itself measured with no foil in the injection beam dump mode (empty circles) is also shown with a reduced scale. A ratio of the integrated yields for the $H^0$ and $H^-$ beam profiles measured in the former mode to that with $H^-$ yield measured in the later mode gives the $H^0$ and $H^-$ charge fractions.

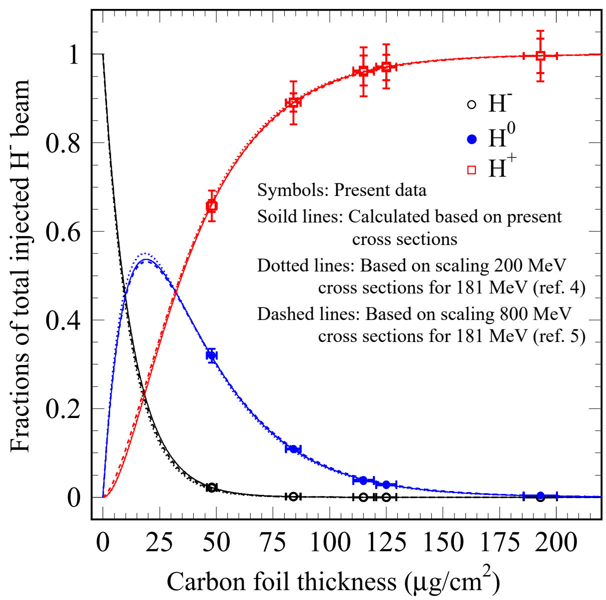


Figure 10: Measured charge fractions of 181 MeV $H^-$ ions incident on the carbon foils are plotted as symbols. In this experiment, the $H^0$ (filled circles) and $H^-$ (empty circles) fractions are directly measured and the $H^+$ fractions (empty squares) are obtained as 1-($H^0$+$H^-$). The absolute values of the measured charge fractions by both H0CT and MWPM7 are found to consistent with each other as they can be seen as completely overlapped. In most cases the measurement errors are even smaller than the size of symbols. The difference between two monitor systems can only be seen in the size of the error bars, especially for the $H^+$ fraction, where the smaller ones (inner) are obtained from the H0CT and the bigger ones (outer) are from the MWPM7. The calculated $H^-$, $H^0$ and $H^+$ charge fractions based on the present cross sections and using in Eqs. 1∼ 3 are shown by black, blue and red solid lines, respectively. The dotted and dashed lines are also the calculated ones for 181 MeV obtained by using energy ($\frac{1}{\beta^2}$) scaled cross sections of the previously measured data at 200 MeV [4] and 800 MeV [5], respectively.

Table 1: Numerical results of the measured charge fractions of all foils in the present experiment. The $H^-$ and $H^0$ were measured together with both $2^{nd}$ and $3^{rd}$ foils setting in place. The $H^-$ and $H^0$ with H0CT were also separately measured by removing the $2^{nd}$ and $3^{rd}$ foil, respectively. The $H^+$ was obtained as 1 - ($H^0$ + $H^-$). The errors are one standard deviation errors obtained from multiple measurements for each data set. The data in the upper part are the H0CT results, while MWPM7 results are given in the lower part.

| **Foil thickness** ($\mu g/cm^2$) | **($H^-$+$H^0$)** | **$H^-$** | **$H^0$** | **$H^+$** |
|---|---|---|---|---|
| 48±2.1 | 0.3425±0.0070 | 0.0209±0.0002 | 0.3206±0.0070 | 0.6575±0.0134 |
| 84±3.2 | 0.1089±0.0020 | 0.0013±0.0001 | 0.1094±0.0020 | 0.8911±0.0205 |
| 115±4.5 | 0.0370±0.0013 | 0.0002±0.0001 | 0.0364±0.0010 | 0.9630±0.0338 |
| 125±4.5 | 0.0300±0.0009 | 0.0002±0.0001 | 0.0296±0.0010 | 0.9700±0.0291 |
| 193±7.3 | 0.0038±0.0002 | 0.0001±0.0001 | 0.0038±0.0002 | 0.9962±0.0393 |
| 48±2.1 | 0.3423±0.0180 | 0.0229±0.0004 | 0.3194±0.0160 | 0.6577±0.0346 |
| 84±3.2 | 0.1099±0.0060 | 0.0016±0.0002 | 0.1083±0.0060 | 0.8901±0.0486 |
| 115±4.5 | 0.0399±0.0023 | 0.0002±0.0001 | 0.0397±0.0023 | 0.9601±0.0553 |
| 125±4.5 | 0.0274±0.0014 | 0.0002±0.0001 | 0.0272±0.0014 | 0.9726±0.0497 |
| 193±7.3 | 0.0042±0.0002 | 0.0001±0.0001 | 0.0041±0.0002 | 0.9958±0.0569 |

Table 2: Summary of the stripping cross sections of $H^-$ ions incident on carbon stripper foil at different energies. The present 181 MeV measured cross sections are given in the top, while previously measured ones at 200 and 800 MeV including energy ($\frac{1}{\beta^2}$) scaling of those cross sections for the 181 MeV are also given for comparison. The present values are found to be consistent with past measurement results, especially with the later one measured at 800 MeV. An energy scaled cross sections of the present measured values for the J-PARC design $H^-$ energy of 400 MeV and some lower energies around 200 MeV are also given, which can be applicable for many newly constructing and upgrading similar accelerators.

| **Energy** (GeV) | $\sigma_{-11}$ ($\times 10^{-18} cm^2$) | $\sigma_{-10}$ ($\times 10^{-18} cm^2$) | $\sigma_{01}$ ($\times 10^{-18} cm^2$) | **Remarks** |
|---|---|---|---|---|
| 0.181 | 0.002±0.001 | 1.580±0.034 | 0.648±0.014 | Measured (this experiment) |
| 0.200 | -0.08±0.13 | 1.56±0.14 | 0.60±0.10 | Measured (ref. [4]) |
| 0.181 | – | 1.682 | 0.647 | Scaling ref. [4] data |
| 0.800 | 0.012±0.006 | 0.676±0.009 | 0.264±0.005 | Measured (ref. [5]) |
| 0.181 | 0.029 | 1.611 | 0.629 | Scaling ref. [5] data |
| 0.080 | 0.004 | 3.111 | 1.276 | Scaling present data |
| 0.160 | 0.002 | 1.739 | 0.713 | Scaling present data |
| 0.250 | 0.002 | 1.248 | 0.512 | Scaling present data |
| 0.400 | 0.001 | 0.924 | 0.379 | Scaling present data |