EXPERIMENTAL VERIFICATION OF ENERGY DEPENDENCE IN A CNT WIRE MONITOR FOR BEAM PROFILE MEASUREMENTS IN THE J-PARC LINAC*

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Abstract

The J-PARC linac accelerates a 50 mA H⁻ beam up to 400 MeV for user operation. To mitigate emittance growth caused by space-charge effects, transverse beam profiles are measured using wire scanner monitors (WSMs) for routine beam tuning. Tungsten is generally used as the wire material. However, the WSMs employ carbon nanotube (CNT) wires in the low-energy region between the RFQ and DTL, because the beam energy is low as 3 MeV and the thermal load is substantial. CNT wires were introduced in 2017 as a more heat-resistant alternative, and since then they have operated without replacement due to beam-induced damage, demonstrating excellent durability. In this study, we report beam profile measurements obtained with the CNT WSM at various beam energies.

INTRODUCTION

The J-PARC consists of three accelerators (Linac, 3-GeV Synchrotron (RCS), and 50-GeV Synchrotron (MR)) and three experimental facilities (MLF, NU, and HD) [1]. The beam accelerated up to 400 MeV by the J-PARC Linac is further accelerated to 3 GeV in the RCS and then delivered to the MLF and MR. Their design beam powers are 1 MW and 1.3 MW, respectively, and part of these goals has already been achieved.

The J-PARC Linac accelerates a negative hydrogen ion (H^-) beam up to 400 MeV. In user operation, a maximum of beam pulse width is 500 μs, and a peak beam current reaches 50 mA. Beam tuning is indispensable for realizing high-intensity beam operation with minimal beam loss. A wire scanner monitor (WSM) is one of the most important diagnostic devices because it is used to determine a current settings of quadrupole magnets (QMs) for optimizing a transverse beam profile. A WSM signal is obtained by measuring current induced when the wire intercepts the H^- beam, using a preamplifier that converts the current into a voltage signal. However, when a beam current increased to 50 mA, the carbon fiber wire previously used in the WSM could no longer withstand the thermal load induced by the 3 MeV H^- beam. Therefore, a carbon nanotube (CNT) wire manufactured by Hitachi Zosen Corporation [2] was adopted, and performance evaluations have been carried out since 2017 at the 3 MeV H^- beam test stand [3]. In this study, we report the beam-energy dependence of H^- beam measurements using the CNT wire in the J-PARC Linac.

WSMS FOR PERFORMANCE EVALUATION

In the J-PARC Linac, three beam dumps, shown in Figure 1, are used for high-intensity beam tuning. The 0-degree dump has a limited beam power capacity of 0.6 kW; however, because it is installed on the straight beamline section, it can accept beams with energies ranging from 3 MeV to 400 MeV. The 30-degree dump has a larger beam power capacity of 5.8 kW compared with the 0-degree dump, but because the beam must pass through a bending magnet, it is generally used only for 400 MeV beam operation. The 100-degree dump has a beam power capacity of 2.0 kW and is used to receive the 400 MeV beam immediately upstream of injection into the RCS. For beam monitor studies, we have installed one WSM in the 0-degree dump beamline and has been investigating its energy dependence. However, because the accelerator is primarily used for user operation, it is difficult to secure sufficient beam time for dedicated beam tests.

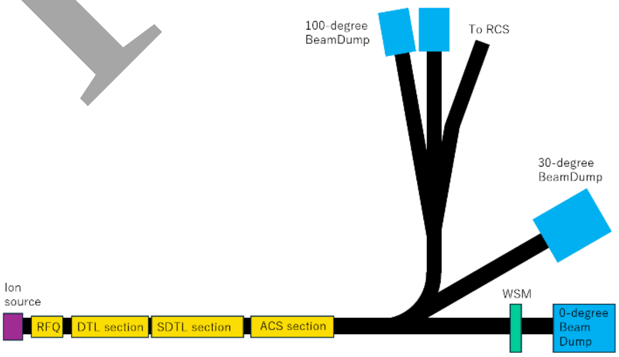

Figure 1: Layout of the J-PARC Linac.

For the development of beam diagnostic devices for high-intensity hadron beam facilities, we constructed a test stand consisting of an ion source and a radio-frequency quadrupole linac (RFQ) cavity [4]. The maximum beam parameters of a test stand (RFQ-TS) are a beam energy of 3 MeV, a peak beam current of 50 mA, a pulse width of 500 μs, and a repetition rate of 25 Hz. Figure 2 shows a layout of beamline connected to the RFQ. Three quadrupole magnets (QMs), a bending magnet, a test chamber, and a beam dump are installed. Between the

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RFQ and the chamber, a WSM, three beam position monitors, and a current transformer (SCT) are located.

Therefore, detailed measurements with the 3 MeV H$^-$ beam using the CNT wire were carried out with the WSM installed at the RFQ-TS, while the beam-energy-dependence measurements were performed with the WSM installed in the 0-degree dump beamline of the J-PARC Linac.

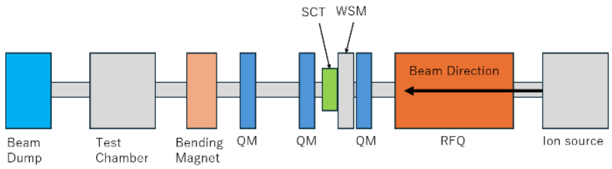

Figure 2: Beam line layout of test facility.

BEAM-TEST AT RFQ-TS

In the RFQ-TS, we investigated the dependence on macropulse width. A CNT wire was moved to a beam center, and measurements were carried out at a beam energy of 3 MeV, a peak beam current of 10 mA, and a repetition rate of 2.5 Hz, while the pulse width was varied from 50 μs to 500 μs in 50 μs increments. Figure 3 shows the WSM signals obtained for beam pulse widths from 50 to 500 μs.

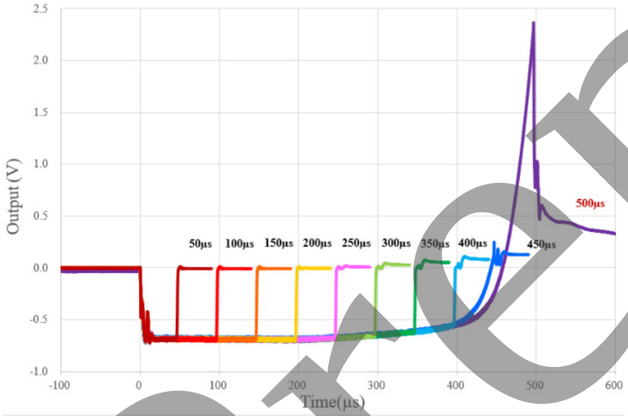

Figure 3: WSM signals at 10mA beam pulse 50-500μs.

Up to a macropulse width of 200 μs, the acquired waveform simply becomes longer. However, for pulse widths of 250 μs and above, the signal, which had previously been negative, increases in the positive direction. The region where the signal increases markedly (beam pulse widths of 450 and 500 μs) is considered to originate from thermionic electrons emitted from the heated CNT. This interpretation is supported by a SCT signal downstream of the WSM, which also rises during the latter part of the beam pulse in the 400–500 μs interval, as shown in Figure 4, indicating the detection of thermionic electrons.

Based on these results, beam tuning in the J-PARC Linac is carried out using beam pulse widths in the range of 50–100 μs. By scanning the wire position, the transverse beam profiles shown in Figure 5 were obtained. For the 3 MeV beam, the beam profile was measured as a negative signal.

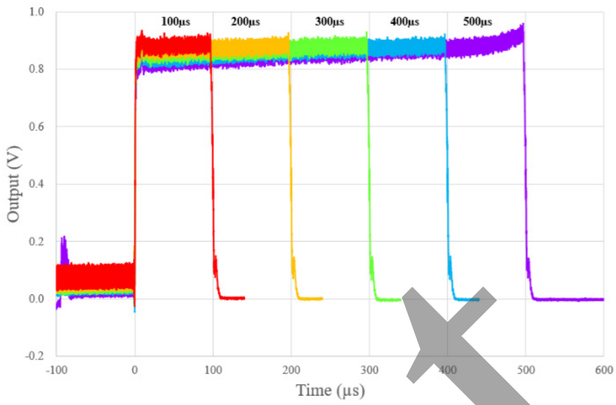

Figure 4: SCT signals at 10mA beam pulse 50-500μs.

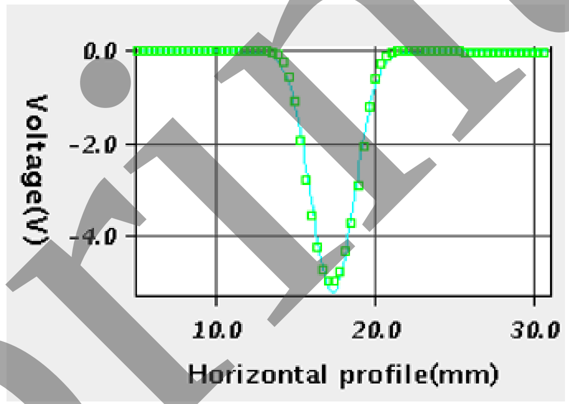

Figure 5: Beam profile measurement at the RFQ-TS.

BEAM-TEST AT 0-DEGREE BEAM DUMP OF J-PARC LINAC

Beam Profile

In the 0-degree beam dump of the J-PARC Linac, we measured beam profiles at a beam current of 10 mA. Beam energies are 20, 37, 50, 76, 84, 103, 122, 142, 162, 171, 181, 191, 200, 255, 305, 357, and 400 MeV. Figure 6 shows the measured beam profiles at the different beam energies. Whereas a negative signal was obtained at 76 MeV, a positive signal was observed at 400 MeV. As in the RFQ-TS study, a beam pulse width was limited to 50 μs; therefore, signal inversion due to thermionic emission did not occur. This suggests that the mechanism of current induced in the CNT differs between the low-energy and high-energy regions.

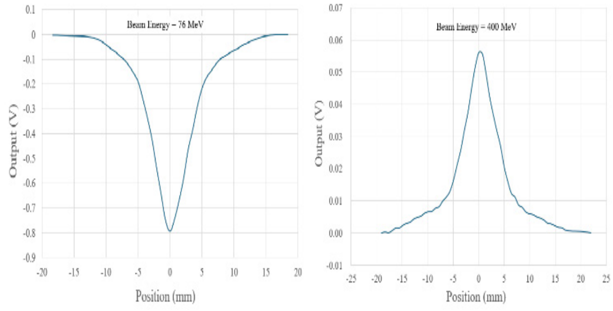

Figure 6: Beam profile measurement at 76 and 400 MeV.

Energy Dependence

Figure 7 shows integrated beam-profile signals at each beam energy. For comparison, integrated WSM signals obtained using a 50-µm-diameter tungsten wire are also presented. For a tungsten wire, a consistently negative signal was obtained regardless of beam energy. In contrast, for a CNT wire, a signal was negative at beam energies of 171 MeV and below, while a signal inversion was observed between 171 and 181 MeV, and a signal became positive at beam energies above 181 MeV. Therefore, a CNT-WSM cannot be reliably used in the energy range of 171–181 MeV.

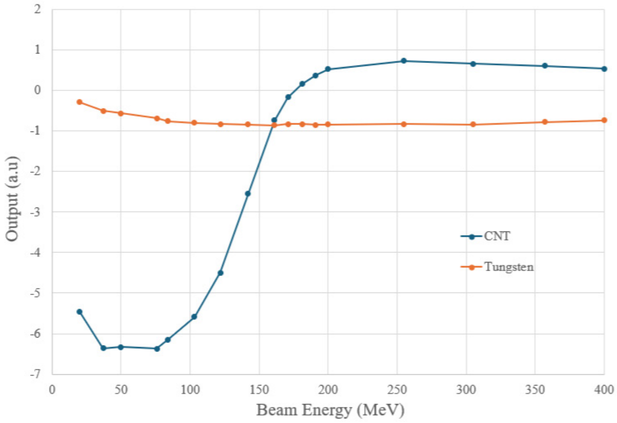

Figure 7: Integral signal of CNT and Tungsten.

DISCUSSION

Figure 8 shows WSM signal models of a CNT wire. In the low-energy region, a CNT wire has a characteristic of electron stripping easily, and the number of stripped electrons exceeds that of emitted secondary electrons [5]. Consequently, the WSM current signal becomes negative. In the energy range of 171–181 MeV, the numbers of stripped electrons and emitted secondary electrons are comparable. Above 181 MeV, the number of emitted secondary electrons is expected to exceed that of stripped electrons.

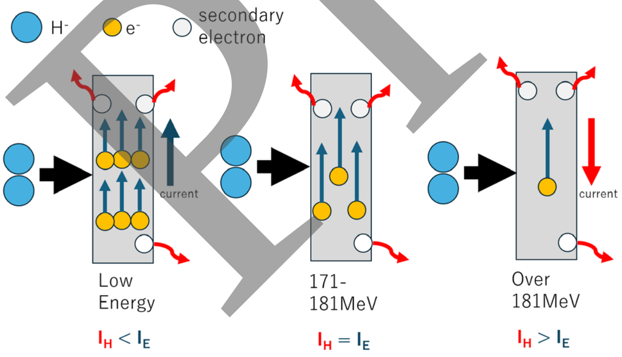

Figure 8: WSM Signal models of CNT wire .

SUMMARY

We measured beam profiles with a CNT wire and investigated beam-pulse-width dependence and beam-energy dependence for a low beam current. A beam-pulse-width study showed that increasing the pulse width induces thermionic emission from a CNT wire, resulting in a risk of wire breakage. In a beam-energy study, while a tungsten wire consistently produced a negative signal, the CNT wire exhibited a signal inversion around 171–181 MeV. Furthermore, because the signal becomes nearly zero in the 171–181 MeV region, it was found that a WSM using a CNT wire cannot be used for beam-profile measurements.

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