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APPLICATION OF CARBON NANOTUBE WIRE FOR BEAM PROFILE MEASUREMENT OF NEGATIVE HYDROGEN ION BEAM*

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Abstract

A wire-scanner monitor (WSM) using metallic wire is reliably employed for the beam-profile measurement. Because the loading of negative hydrogen (H^-) ion beam on a wire increases under high-current beam operation, we focus on using a high-durability beam profile monitors by attaching another wire material. Carbon nanotube (CNT) has a tensile strength not less than 100 times that of steel. The electric conductivity has higher than that of metals, and hardness is endured thermally around 3000 °C in a vacuum circumstance. We applied the CNT wire to WSM and measured transverse profiles with a 3-MeV H^- beam. As a result, we obtained the equivalent signal levels taken by carbon fiber made of polyacrylonitrile without significant damage. The signal response, the beam profile and the surface observation were discussed in this paper.

INTRODUCTION

In the Japan proton accelerator research complex (J-PARC) linac, a wire-scanner monitor (WSM) is used to measure the transverse beam profile by scanning two wires mounted on a sensor head. Tungsten wire has been used for the sensor head in the present beam line excepting 3-MeV part in which a very thin carbon fiber in 7 μmϕ in a deameter made of polyacrylonitrile has been used. The fiber is thin enough to suppress the collision damage by accelerated beam particles, however, the manipulation is difficult. The present linac accelerates a 40-mA beam as the peak beam current, and the beam current will be upgraded to 50 mA to realize a 1.0 MW at the exit of downstream 3-GeV synchrotron. Thermal loading to the wire depends on the peak-beam current, and higher thermal durability is required for the wire material. A tungsten wire of 30 μmϕ installed in the beam line fractured at a temperature lower than the melting point. Tensile fracture strength of the tungsten wire drops down with a temperature increase, which leads to break a wire. Instead of the carbon fiber and tungsten wire, we referred some other materials to apply the sensor head [1] at the points of the high-durability, small change of tensile strength and high electrical conductivity at high temperature, and decided to test a wire made from carbon nanotube (CNT).

BEAM TEST

Test Facility (RFQ-TS in J-PARC)

The J-PARC linac accelerates a negative hydrogen (H^-) ion beam up to 400 MeV. For the instrumentation development for the high brilliant hadron beam facility, we have operated a test-stand consisting of an ion source and radio frequency quadrupole linac (RFQ) cavity. The beam parameters of the test-stand (RFQ-TS) is 3-MeV beam energy, 30-mA peak beam current, 500-μs pulse duration and 25-Hz repetition. A beam line layout connected to the RFQ is shown in Fig. 1.There are three quadrupole magnets (QMs), bending magnet, test chamber and a beam dump. A WSM, three beam position monitors, a chamber of current and phase monitor (SCT/FCT) are installed between RFQ and the chamber.

A WSM has a sensor head with 7-μmϕ carbon-fibers made of polyacrylonitrile (PAN). The carbon fiber is thin enough to pass the 3-MeV hydrogen ion beam because the beam stopping power at 3-MeV to carbon substance is high to break [2]. It is difficult to handle the fiber exchange and to warrant the any fiber diameter because the fiber is thin and low tensile strength. It may increase an operability, and maintain a reliability of the measurement by using a CNT wire due to high tensile-fracture strength.

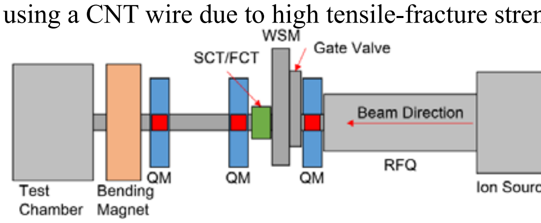

Figure 1: Beam line layout of test facility.

CNT-Wire

It is known that CNT have a variety of its electrical characteristics because of its microscopic chiral structure. A tensile strength and an electric conductivity are higher than those of metals, and hardness is endured thermally 3,000 °C in a vacuum circumstance [3]. In addition, a density is 1.3 g/cm^3 which is almost half of graphite.

Table 1: Physical Properties of Wire Material

Material	Tensile strength (N/mm^2)	Conductivity (Ωcm)
Tungsten	1,000	5.5x10^{-6}
Carbon	3,500	~ 1.0x10^{-4}
CNT [4]	2 ~ 5x10^6	~ 1.0x10^{-6}

CNT-wires are made by spinning from a mixture of single- and multi-wall CNT. Single-wall CNT, the simplest CNT, has an ideal physical properties [3, 5], and the structural chirality defines on the electrical conductivity. The commercial product is usually a mixture of the single- and multi-wall CNT which has multiple-different diameter concentric tubes. The wire product is 10-walls CNT and it shows half- metallic and half-semi conductivity. A tensile strength and an electrical conductivity of tungsten, carbon and CNT are listed in Table 1.

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Sensor Head

CNT wires with three different diameters such as 30, 50 and 100 μmϕ are adopted to evaluate the signal gain, beam profile and damage. CNT wires mounted on a sensor head is shown in fig. 2. Because the wires are connected on a sensor head 45° against the horizontal axis, both horizontal and vertical profiles can be measured in a stroke. The frame was constructed from stainless steel to prevent from charging by secondary electron capture.

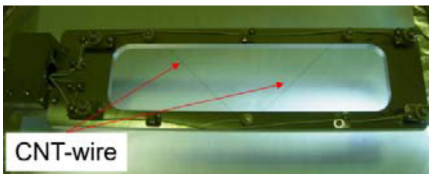

Figure 2: WSM sensor head with CNT wires of which is 100 μmϕ in a diameter.

Parameters of Test

Signal sources are electrons of H^- beam captured by the direct interactions between a wire and H^- beam, and neutral hydrogen particles (H^0) are passed through the wire. The signal current is amplified and converted to the voltage by a pre-amplifier. Usual profile measurement employs an operational peak-beam current with shorter pulses as 100 μs and low repetition as 1 - 2.5 Hz, however, the RFQ-TS can only sustain 30 mA which is 25% lower than present operational peak-beam current. In order to take equivalent loading power to 40-, 50- and 60-mA peak beam current, we use 135, 170 and 200 μs pulse duration. In addition, we compared the signal levels in different diameter as 30, 50 and 100 μmϕ, and finally we evaluated a durability by 4-minutes continual beam operation with 200-μs pulse-width and 5-Hz repetition.

RESULT

Beam Profile

In order to measure the profile, we scan the wire in steps of 0.5 mm and plot the signal height against the stroke. Figure 3 shows the profiles taken by CNT wire and carbon fiber. The intensity is normalized with the maximum output to evaluate the signal-to-noise ratio (S/N ratio). Calculated rms-beam size of CNT is 2.98 mm, and there is very small difference which corresponds within 1.0 %. The background signal level can be observed at the intensity of 10^{-2} to 10^{-3}, and it is lower than that in the carbon fiber. The cause is based on the signal value, and the biggest signal by CNT is 2.5 V and one by carbon fiber is 0.4 V. It is thought that CNT wire has more improved S/N ratio and can become a sufficient candidate material for the beam profile measurement.

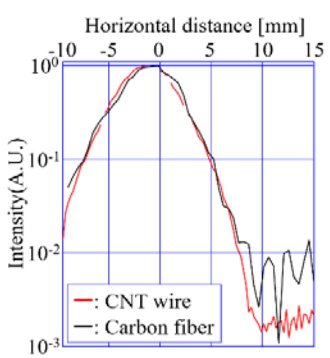

Figure 3: Beam profile taken by CNT wire and carbon fiber.

Signal Gain

The CNT wire with 100 μmϕ was inserted to the point of the maximum signal which is the center of Gaussian distribution, and the signal waveform was observed in fig. 4. The signal marked by green was received with the CNT wire, and beam-current waveform marked by pink was received with SCT installed downstream of WSM. Negative output of -2.5 V with 100-μs pulse width was induced, because the signal source is based on the electrons of H^- beam. The signal was attenuated to match the range of amplifier. If the signal without attenuation was beyond the range of amplifier, this means much bigger signal was induced from present carbon fiber.

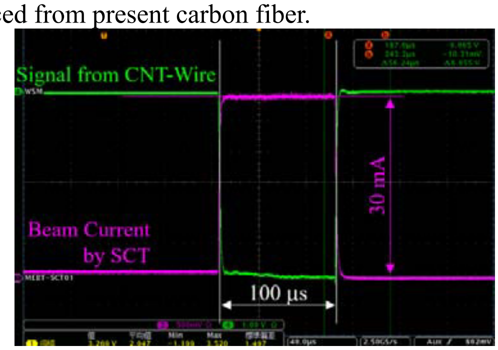

Figure 4: Signal wave form of 100 μs beam pulse taken by CNT wire of 100 μm in diameter.

Signal Current Estimation

Preamplifier is used for the signal-current amplification. Design relationship between signal current and output voltage is described by

$$V = 2.162I - 0.007. \quad (1)$$

Where V is output voltage (V) and I is signal current (mA). We can estimate a signal current using this equation. Because an output is obtained to be 2.5 V from fig. 4, an estimated signal current taken by 100 μmϕ is 1.17 mA.

Waveform with Different Pulse Duration

When the pulse duration was extended from 50 to 200 μs, waveforms taken by the CNT wire with 50 μmϕ diameter are obtained in fig 5.

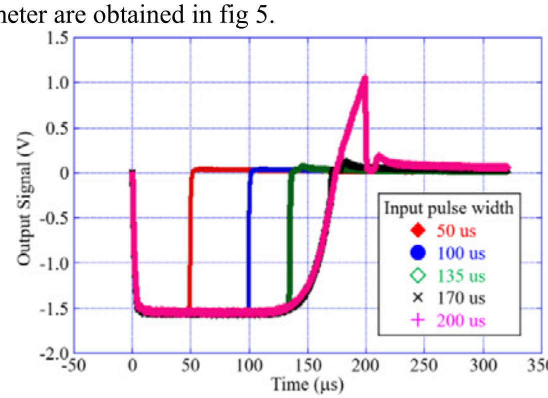

Figure 5: Output signals of different pulse widths.

Signal height of all waveforms are same, and pulse width is corresponding to an input pulse. The signal waveforms longer than 170 μs was turned from negative to positive after 145 μs. The last 30 μs of 200 μs pulse, a signal completely appears in positive. When a large posi-

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tive signal is generated, the rapid increase of a current monitor signal can be detected. This rapid signal should be generated by electrons, which is estimated to be ther-mal electrons emitted from carbon or CNT-wire.

Diameter Difference

We applied CNT-wire with 30, 50 and 100 μmϕ for the profile measurement. The maximum signal gain can be at the point of Gaussian center. Measured output signals are listed in the Table 2, and signal currents are estimated using equation (1). Signal should be proportional because a cross section between beam and wire depends on a cross-section of wire and beam diameter. Estimated cur-rent is increased with a diameter, however the diameter dependence is slightly weak. When the temperature is discussed with the wire diameter, the thinner wire reaches lower maximum temperature [6]. The signal gain is not proportional to the diameter because the maximum tem-perature is inverse proportional to the cooling surface.

Table 2: Diameter Difference on Signal Gain

Diameter	Output	Signal current
30 μmϕ	1.1 V	0.51 mA
50 μmϕ	1.5 V	0.70 mA
100 μmϕ	2.5 V	1.17 mA

Damage Observation & Resistivity

In order to evaluate a durability, we inserted a CNT wire of 100 μmϕ to the point of the maximum signal, and supplied beam with 200-μs pulse-width (60-mA equiva-lent beam) and 5-Hz repetition for 4 minutes. This beam condition is much higher than measurement parameter which is 100 μs, 1 Hz for several minutes for profile measurement. Figure 6 shows the surface observation using a microscope. The center of the image is the point for beam irradiation. Damage can be seen at the surface, however this wire can be operated after durability test. This is thought that the damage is not significant under this beam loading.

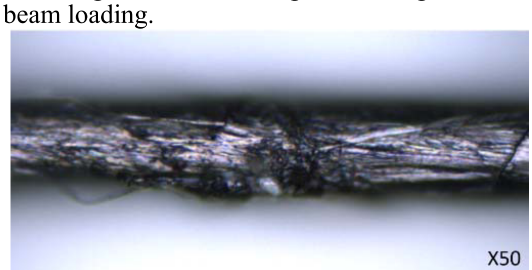

Figure 6: Microscope image of CNT wire after test.

Because the small damage was observed, we compared with a resistivity before and after beam test. This is sum-marized into Table 3. An "X" in the Table is a wire for horizontal wire and "Y" is for vertical and three different diameters are compared. Beam loading conditions are same as durability test (30 mA, 200 μs and 25 Hz for 4 minutes at the point of the maximum signal). Several percent of resistivity of all wires are increased upward. This is because small damage on wires might happen as seen in fig. 6, however the reproducibility of signal gain was maintained of all profile measurement. This should be discussed more in the observation of detail CNT struc-ture using scanning electron microscope.

Table 3: Resistivity of CNT Wire before and after Test

Diameter	Wire	Resistivity (before)	Resistivity (after)	Increase rate (%)
100 μs	X:	318.9 Ω	332.4 Ω	+4.23%
	Y:	285.4 Ω	298.1 Ω	+4.45%
50 μs	X:	1.212 kΩ	1.278 kΩ	+5.45%
	Y:	1.009 kΩ	1.037 kΩ	+2.78%
30 μs	X:	2.866 kΩ	3.073 kΩ	+7.22%
	Y:	2.543 kΩ	2.650 kΩ	+4.21%

DISCUSSION

An H^- radius can be estimated to be 0.20 nm because an orbit of a 1s' electron of H^- atom is 3.8 times larger than Bohr radius which is described in fig. 7. A CNT is almost transparent for H^- beam because the lattice constant (0.142 nm) is slightly smaller than H^- radius. This is a reason of high duration of CNT.

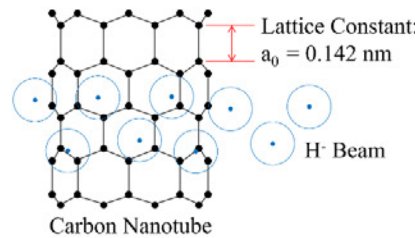

Figure 7: Lattice constant of CNT and diameter of H^-.

CONCLUSION

We tested the CNT wire to confirm the signal gain and the durability by using 3-MeV H^- beam. As a result, al-most the same profiles can be obtained by both CNT wire and carbon fiber. The signal gain is enough high and the background became smaller, which led to improve the S/N ratio. Furthermore, about the durability of the CNT wire, no damage can be seen by the surface observation after beam test in the excess high beam loading. The frac-ture strength of the wire is stronger as the wire diameter is larger, but the larger diameter brings higher temperature in general. However, the CNT wire in large diameter takes a higher signal gain and the change of the resistivity which is associated with damage of wire is not depending on the diameter. The CNT has an advantage to use a beam profile measurement in 3-MeV beam line. We are con-tinuing a beam test of CNT wire at the high energy sec-tion of linac to confirm the signal gain and to investigate a mechanism of the physical processes of signal and ther-mal electron generation.

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