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TENSILE FRACTURE TEST OF METALLIC WIRE OF BEAM PROFILE MONITORS*

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Abstract

In order to mitigate the beam loss during a beam transportation in the high-brilliant accelerator facilities, wire-based profile monitors are used to measure by both transverse and longitudinal beam profiles using wire-scanner monitors and bunch-shape monitors for the tuning of quadrupole magnets and buncher cavities. Signals are generated due to the direct interaction between a metallic wire and beam. We have used the tungsten wire as a high melting-point material by estimation of heat loading during the impact of beam particles. In addition, a spring is applied for the relaxing a flexure under wire's own weight. A tensile fracture is tested by supplying an electrical current as a simulated beam loading. As the results, we obtained the relation between the thermal limit to fracture and tension loading to a tungsten wire.

INTRODUCTION

In the J-PARC linac, a negative hydrogen ion beam (H^-) is accelerated by RF cavities up to 400 MeV. The quadrupole magnets (QMs) are tuned by the transverse beam profiles taken by the wire scanner monitor (WSM). The linac has a bunch shape monitor (BSM) in a matching section in which acceleration frequency jumps from 324 MHz to 972 MHz to take the phase width. Amplitude setting of buncher cavity is tuned by the phase width at the downstream of buncher cavity [1, 2].

Signal source of BSM is the secondary electrons come from the direct interaction between a metallic wire and beam. We have used the tungsten wire as a high melting-point material. In addition, a spring is applied for the relaxing a flexure under wire's own weight. A high tensile fracture is required for the high beam loading, when the peak-beam current is increased, unless the tensile strength can be secured against the beam loading, temperature is a possible cause of the fracture. We produced a small vacuum chamber to conduct a tensile-fracture test using an electrical current as a simulated beam, and weights hanged on an end of wire to put a tension instead of a spring. In addition, a wire diameter is a parameter. In this paper, the relation between the tensions applied to the wire and the temperature leading to fracture is described.

SENSOR HEAD OF BEAM PROFILE MONITOR

Transverse Profile Monitor

The J-PARC linac has the eight matching sections to tune the QMs, in which four WSMs as a transverse profile monitors are installed. According to the dynamic aperture of the beam line at the installation point, several sizes of WSMs are designed. A diameter of wire on a sensor head is chosen, based on the maximum temperature can be discussed using a yield of H^- beam and wire material [1].

Figure 1 shows a sensor head installed in J-PARC linac. Two wires (red and blue lines) are fixed on the frame. One is for the profile in the horizontal and the other is in the vertical. Since the head is installed in a chamber inclined at 45° to take both profiles in a stroke. The frame is made of metal to prevent from electrons charge-up, and the wire is insulated by ceramic spacers. Each wire is connected to a metal plate to transmit a signal to the cable. The other end was connected to another metal plate through a spring in order to eliminate a flexure by its own weight and a stretch by temperature-increase.

Signal source of the beam profile measurement is the captured electrons by the direct interaction of the beam with the wire. A wide dynamic range of 10^4 to 10^5 can be realized in the measurement of negative hydrogen ion beam by this reason. In the design of the sensor head, selection of material with high melting point and tension control by a spring and diameter of wire are important.

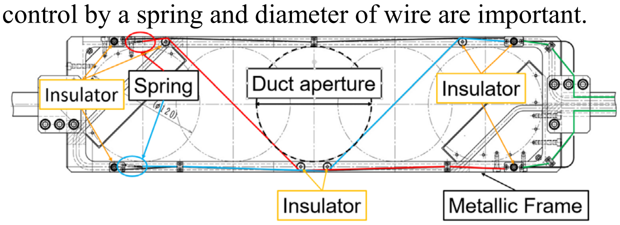

Figure 1: A WSM-sensor head and wires.

Longitudinal Profile Monitor

In the J-PARC linac, a bunch shape monitor (BSM) to measure a phase width (longitudinal beam profile) locates in a matching section in which acceleration frequency jumps from 324 MHz of separated-type drift tube linac cavities to 972 MHz of annular-ring coupled structure linac cavities for the tuning an amplitude of buncher cavity. Figure 2 shows a BSM sensor head used in J-PARC linac. A single tungsten wire is fixed to this sensor head and a bias of up to -10 kV is applied. One end of the wire is connected to a spring and the other end is connected to a metal support to fix.

Signal source of the longitudinal profile measures is the secondary electrons emitted by the collision between a wire and H^- beam. Secondary electrons generated at wire surface are accelerated by a negative bias which is typically -10 kV, and are transported it to the electron multiplier [2]. In the design of a wire holder, it is important to select the material with high melting point and which can endure a high temperature and tension control by a spring and diameter of wire. These are common requirements of

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the wire based profile monitor. In addition of the BSM design, it is important to endure a supplied negative bias.

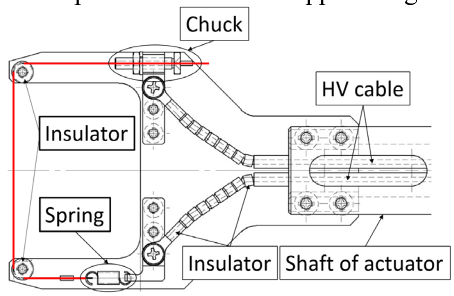

Figure 2: A wire holder of BSM to generate and accelerate secondary electrons.

Tension Requirement

To estimate a minimum tension by a spring, second moment of wire-cross section was calculated by following eq. (1).

$$I = \frac{\pi}{64} d^4 , \quad (1)$$

where d is a diameter of wire. Using this moment, a flexure by uniform distributed load can be obtained by,

$$\delta_{max} = \frac{5WL^3}{384EI} d^4 . \quad (2)$$

Where W is a total weight, L is a length, and E is a Young's modulus. When the largest head is assumed, the flexure is calculated to be 0.90 mm by eq. (2) without suppling tension. The spatial resolution is required to be less than 0.1 mm because the measured beam size is approximately 3.0 mm in rms. In order to suppress the flexure at which the wire is suspended by own weight within 0.1 mm, it is necessary to supply the tension with a spring to the wire. The tension is estimated to be at least 20 cN.

J. Herranz [3] estimated the breaking tension of 34 μmϕ-carbon wire to the vibration wire scanner monitor as a 0.3 – 0.5 N. Tensile strength of 7 μmϕ-carbon wire is twice to three times high as that of 80 μmϕ-tungsten wire [4-6]. The range of the tensile strength is thought to be from 20 to 100 cN.

TENSILE-FRACTURE TEST

Setup

A setup for the tensile-fracture test is shown in Fig. 3. The vacuum chamber has two viewports provided at the both sides of the chamber to observe the status of the wire during a test. Two ports are provided for vacuum gauges on the top of the chamber. A turbo molecular pump is directly attached to one side of the chamber, and the pressure can be achieved to less than 10^{-5} Pa in 10 minutes. The wire sample is fixed to the upper holder and hangs down a weight. The lower holder is made longer than the upper holder by 5 mm, so that the upper and lower holders make contacts with the wire and provide an electrical current to the wire. Because the lower holder is longer, the wire is inclined about 5.7° from the vertical.

Test Parameter

This test is carried out at a room temperature as 27 ± 1 °C and vacuum pressure 10^{-4} to 10^{-5} Pa. Tungsten with high melting point is used as the wire sample to be tested, and the diameters are 20 and 30 μm, the load weights are 5, 10, 25, 30, 50 g based on a tensile strength at room temperature of a wire in 80 μm diameter. Input current as a simulated beam loading is hold for a minute and shifted up from 0 to the current to fracture in steps of 10 mA. In this test, input voltage and wire resistivity versus an input current are measured.

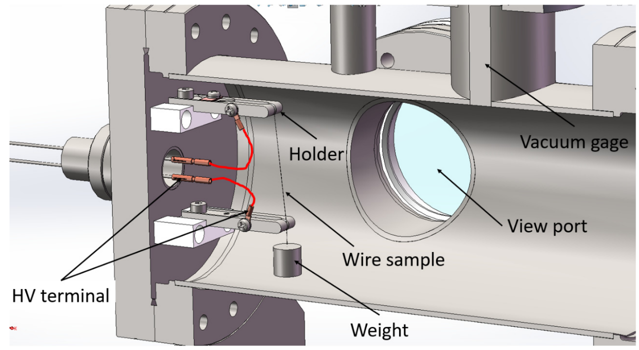

Figure 3: Inside view of test chamber.

RESULT

Temperature Estimation

After a wire set on a wire holder, a resistivity of wire is measured at room temperature (R_0). A wire temperature can be estimated by following equation (3) using R_0 as

$$T = \frac{R\frac{S}{\rho_0 l} - 1}{\beta} = \frac{\frac{R}{R_0} - 1}{\beta} , \quad (3)$$

where the β is a temperature-coefficient and this is referred as 5.3×10^{-3} (1/°C) in product sheet. The R is the resistance (Ω) which can be calculated by a measured voltage and input current, ρ_0 is the electrical resistivity (Ωm) at room temperature, and S is the cross section (m^2) of wire. In other words, the temperature can be estimated from R/R_0 and β using the input current and measured voltage. Input power can be also estimated using input current and estimated resistivity.

Tungsten Wire in a Diameter of 20 mm

A part of the acquired data is shown in Table 1. In this test of Table 1, a weight of 20 g was loaded to a wire with a diameter of 20 μm, the current was increased from 10 mA, and the wire broke down at an input current of 180 mA. Similarly, the weight loaded on the wire is changed from 5 g, 10 g to 100 g, and the current and voltage which is facing a fracture is measured. Figure 4 shows the relationship between the input current and the load weight to fracture and Fig. 5 shows it between the temperature and the tension.

In the present operation, WSM measures beam profiles of 40-mA of a peak beam current. The signal current can be estimated as about 0.2 mA for a wire in a diameter of 100 μm [1]. This is not sufficient high to increase a tem-

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perature to be infirmed. It is shown that the tensile strength decreases to fracture a wire even a small loading of 20 cN over 1,000 ºC in Fig. 5.

Table 1: Test Results at 20-g Weight for 20 μmϕ Wire

Current (mA)	Voltage (V)	Resistivity (Ω)	Input (mW)	Temperature (ºC)
10	0.065	6.5	0.65	15.7
60	1.16	19.3	69.6	419.3
120	3.72	31.0	446.4	786.2
180	7.40	41.1	1332	1104.1

Tungsten Wire with Different Diameter

Data between a tension and temperature at fracture of a wire in 30-μmϕ diameter are plotted in Fig. 5 with a wire in 20-μmϕ diameter. Fracture line of a 30-μmϕ wire is about 25 % higher than that of 20-μmϕ wire. This suggests that the wider wire has a priority at the point of tensile fracture.

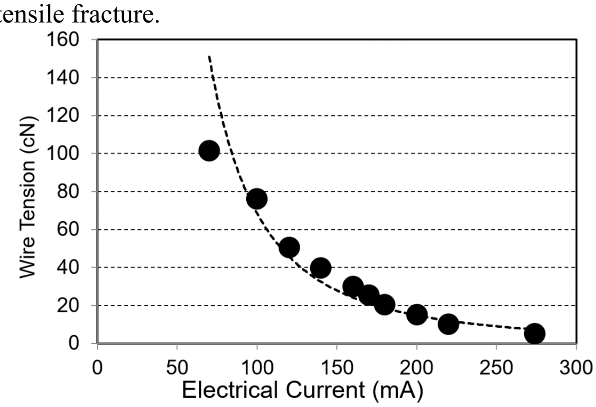

Figure 4: Tensile fracture strength of 20 μmϕ wire with electrical current.

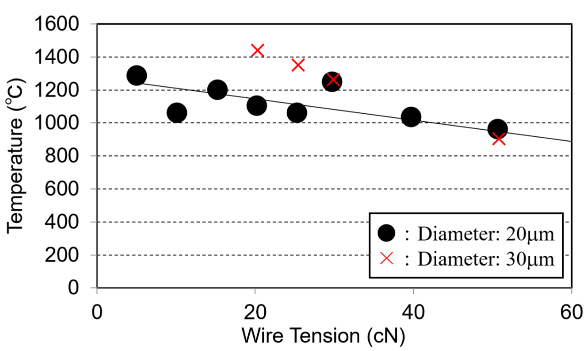

Figure 5: Tensile fracture strength of 20 and 30 μmϕ wire with estimated temperature.

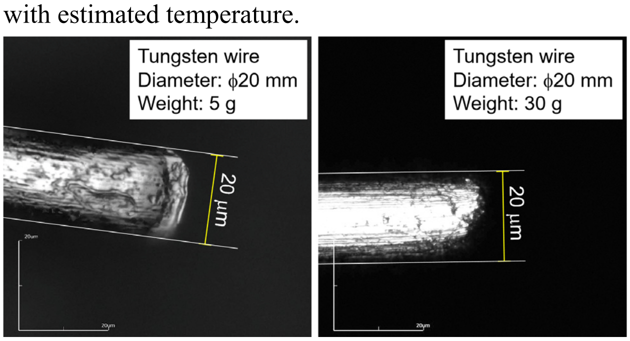

Figure 6: Microscopic observation of wire fracture. Loading weight of left is 5 g and right is 30g.

Microscopic Observation of Wire after Test

Wires fractured between the holders and fracture points are observed by microscope shown in Fig. 6. Left one is the one point of fracture wire tested with 5-g load weight, and right is the one with 30-g load weight. Smooth surface at 5 g and rough surface at 30 g can be seen in the figure. Left and right figures show the fracture by a weak force while the lower tensile strength, and the fracture by a strong force while maintaining a tensile strength. This suggests that excess weight causes a fracture of a wire.

CONCLUSION

The authors obtained the results of the relationship between the tension and temperature of tungsten wire with a diameter of 20 μm and 30 μm at the wire-fracture by the test with controlled tension and simulated beam loading for the future upgrade of beam power. The fracture was found at low tension while high beam loading. The result suggests a wire was soften and teared. The wire with wider radius should be employed and weaker tension should be supplied for the prevision from the fracture.

A required tension to minimize a flexure of the wire is estimated to be 20 cN, and this has been employed for all WSMs. As the point of the diameter, based on the thermal calculation of 50 mA of peak beam current, diameter should be under 30 μm an enough margin to the melting point [1]. Based on the above discussions and Fig. 5, we considered 30 μm of a diameter and 20 cN of an input tension. In Ref. [1], the wire temperature is conservatively estimated because a radiation cooling is only considered in a thermal calculation. When other cooling processes as a conductive and thermionic cooling are considered [7], an estimated temperature is lower and it leads to use a wire of larger diameter.

We used DC-current supplier, and total heat loading in this test is much higher than that of beam by pulse operation. However, the difference of estimated achieving temperatures between DC and 1 Hz operation is only 100 ºC to 50 mA, 30 μmϕ in diameter, 100 μs in pulse duration, and 3.0 mm RMS in beam radium. Characteristic frequency of the fixed wire is nearly 1 GHz, and it is not considered with the resonance heating with beam frequency and repetition. Further tests will be conducted with pulse current supplier, different diameters of wires, and other materials [6, 8] with more precise temperature-estimation.

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