MULTI-LASER-WIRE DIAGNOSTIC FOR THE BEAM PROFILE MEASUREMENT OF A NEGATIVE HYDROGEN ION BEAM IN THE J-PARC LINAC *

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Abstract

One of the major missions of Japan Proton Accelerator Research Complex (J-PARC) is the establishment of high-brilliance beam operation. For this purpose, transverse profile monitors play crucial roles in obtaining information concerning beam-mismatching factors and emittance evolution for the linac beam tuning. A wire scanner monitor using metallic wire is currently reliably operated in the J-PARC linac. Because the beam loading on a wire increases under high-current beam operation, we focus on using a laser-wire system as a nondestructive monitor. Additionally, we propose the use of a new multi-laser-wire system. In this study, we propose the multi-laser-wire system and its application. Finally we discuss its advantages over the present profile monitoring system.

INTRODUCTION

In the J-PARC linac, the negative hydrogen ion beam is accelerated to 400 MeV. The repetition rate is increased to be from 25 to 50 Hz. Half of the 400-MeV beams are injected into the downstream synchrotron (rapid cycling synchrotron (RCS)), whereas the other half are transported to the planned experimental laboratory of the accelerator-driven transmutation facility.

One of the important issues for high-current, high-brilliance accelerators is the understanding of beam dynamics. A wire scanner monitor (WSM) that employs a thin metallic wire is reliably operated in multiple accelerator facilities around the world to suppress excess beam loss and mitigate beam halo evolution. Because the heat loading on a metallic wire is increased under high-current beam tuning, we focus on using a laser-wire system as the nondestructive beam diagnostic device. In addition, we propose a new multi-laser-wire system [1,2] that uses a pair of concave mirrors with different focal lengths to form multiple laser beam paths, and the beam waists of the laser paths are aligned in principle. In this study, we propose the multi-laser-wire system and its application to beam-profile monitoring.

BEAM SPECIFICATION OF THE J-PARC LINAC

The linac comprises a 50-keV negative hydrogen ion source (IS), a 3-MeV radio frequency quadrupole cavity (RFQ), a 50-MeV drift tube linac (DTL) a 191-MeV separated-type DTL (SDTL), and a 400-MeV annular ring-coupled structure (ACS) [3] as shown in Fig. 1. The ACS-type bunchers are placed between the SDTL and the ACS cavities for longitudinal matching because the operating frequency is 972 MHz for the ACS, which is a threefold frequency jump over that for the SDTL. The ACS downstream is the beam transport line to the RCS.

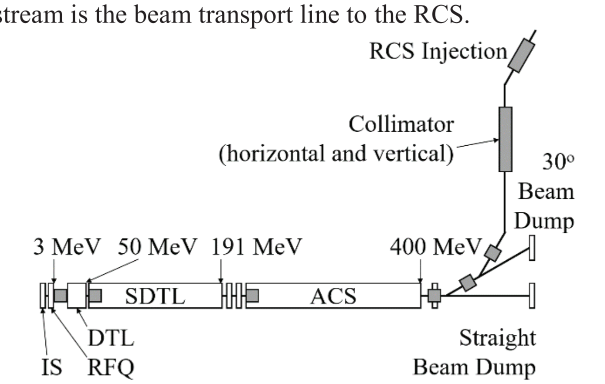

Fig. 1. Beam-line layout of Japan Proton Accelerator Research Complex (J-PARC) linac.

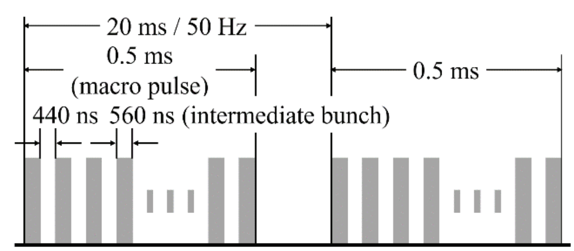

Fig. 2. Time structure of pulsed beam in linac.

The time structure of the pulsed beam in the linac, which is shaped by an RF chopper cavity for RCS injection, is shown in Fig. 2. The beam pulse comprises a 324-MHz micro-bunch, a 560-ns intermediate bunch length, and a 0.5-ms macro-pulse length with 25-Hz repetitions. The shortest pulse duration we can observe occurs during the 3.01-ns micro-pulse.

The metallic wire in a WSM collides with the accelerated beam and destroys a part of it as beam loss. Because it has a high dynamic range in principle [4], we have used it to tune the quadrupole magnets. Tungsten wire has been used due to its high melting point, and its diameter was decided based on the thermal balance and signal gain [4]. However, high beam-current resistance will be required in a device for beam profile measurement. In addition, because the radiation during a high peak current operation should be mitigated, it is important to realize a nondestructive profile monitor based on the laser-wire system.

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ISBN 978-3-95450-177-9

MULTI-LASER-WIRE DESIGN

Let us consider an optical system, as shown in Fig. 3, which comprises two concave mirrors with different focal lengths of curvature arranged such that both axes and focal points coincide [5]. The focal length of mirror 1 (or 2) is f_1 (or f_2). We refer to confocal point as "*a*," the points at which the laser beams passes through the plane containing the confocal point and is perpendicular to the axis c_n and the points on mirrors 1 and 2 at which laser beams are reflected at d_n and b_n, respectively.

A laser beam is injected in parallel with the axis of the cavity from the back, and it passes through c_0 just outside of the mirror 2, forming a waist. Then, it is reflected at d_0 on the mirror 1. Since the injected laser beam is in parallel with the axis, the laser beam reflected at d_0 passes through the focal point "*a*" of mirror 1 and reaches b_1.

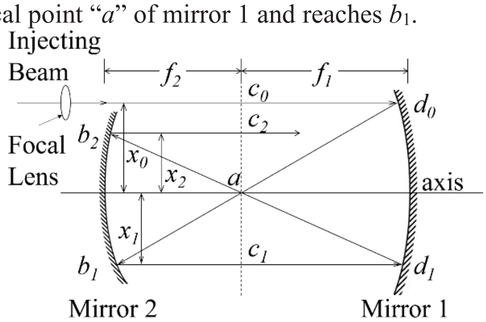

Fig. 3. Asymmetrical confocal cavity and the paths of multiple laser beam.

When the quality of the laser beam is sufficiently high, the intensity distribution is considered to be Gaussian. A Gaussian laser beam is characterized by two parameters; its half-waist size (w), which is defined as the radius where the laser beam intensity is $1/e^2$ of the peak value, and its Rayleigh range (z).

Because "*a*" is the confocal point of mirrors 1 and 2, the laser beam reflected at b_1 is in parallel with the cavity axis and forms a waist at c_1. Then, the laser beam reflected at d_1 returns to "*a*" again, forming a waist. Thus, the laser beam repeats triangular paths, and reaches "*a*" as a waist every time, reducing the separation of the path from the cavity axis with an increase of n.

Here, let us consider the distance between the parallel laser paths. The definition of the distance of the injected laser beam from the axis is x_0, and the first path is formed from b_1 to d_1. The distance of the first path from the axis is assumed to be x_1, and this can be described as follows:

$$x_1 = (f_2/f_1)\, x_0.$$

Then, we estimate the laser-wire position of the nth path using the following equation:

$$x_n = (f_2/f_1)^n\, x_0. \quad (1)$$

When x_0 is negligibly smaller than the distance between mirrors 1 and 2 ($f_1 + f_2$), the distance between c_0 and mirror 1 nearly corresponds to the length f_1. When the Gaussian laser beam is irradiated to the mirror 1 from the back of mirror 2 and the focal lens is set to form a waist at c_0, the waist is also formed at c_1. The beam waist at c_0 is w_0 and that at c_1 is w_1. These are related through the wave length of the laser beam (λ) expressed as follows:

$$w_0 w_1 = \lambda f_1/\pi\,. \quad (2)$$

This relation describes the waist of each laser path. Therefore, the waist radius (w_1) can be expressed as follows:

$$w_1 = (\lambda f_1/\pi)/w_0, \quad (3)$$

Then, we can estimate the waist of the nth laser path (w_n) at c_n using w_0:

$$w_n = (f_2/f_1)^n\, w_0. \quad (4)$$

DEMONSTRATION OF MULTI-LASER-WIRE FORMATION

To examine the formation of the multi-laser wire in a confocal cavity, we assembled the optical setup shown in Fig. 4 using a He–Ne laser with a wavelength of 515 nm. A laser oscillator and a pair of confocal mirrors are set on a guide rail. Because we choose a pair of mirrors with focal lengths of f_1 (435 mm) and f_2 (417 mm), the mirrors are set at a distance of 852 mm. The diameters of the mirrors are the same at 50 mm. We cut an edge of 2.0 mm of mirror 2 for the laser axis to have an offset of 25 mm from the center axis because the beam should be injected from the backside of mirror 2.

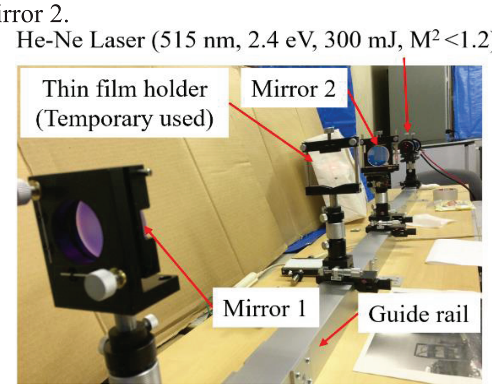

Fig. 4. Optical setup of an asymmetrical confocal cavity.

We set the thin-film target to observe the waist of the multiple laser spots on the guide rail between mirrors 1 and 2, where the film position is adjusted to the line of c_0, c_1, c_2, …, c_n that is perpendicular to the center axis. The aligned multi-laser spots on the target are clearly observed in Fig. 5.

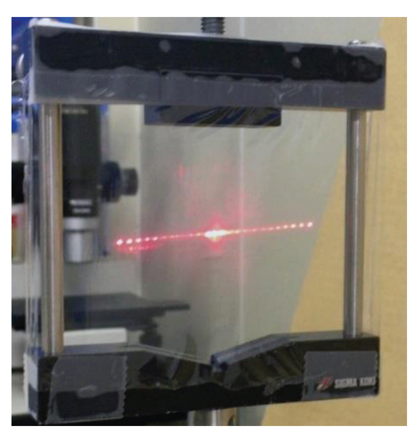

Fig. 5. Laser beam spots of multi-laser wire on a thin-film plane including the confocal point and vertical to the cavity axis.

ISBN 978-3-95450-177-9

The laser beam spots at c_n approach "a" as n increases, and all laser beams reflected by mirror 1 gather at "a" and are stacked up. Eq. (4) suggests the spot size, suggesting that the waist of the laser beam decreases if $f_2 > f_1$.

As a next step, the quantitative measurement of the laser beam intensity distributions on the upper or lower sides of the confocal point are prepared to clarify the extent to which the turns stack up. To compensate the light intensity of each laser wire, we measure the intensity using a photodiode and a micro-mirror, which comprises a golden wire with a ϕ30-mm diameter. The mirror surface is produced via a compression with the optical flat surface (Fig. 6). When the micro-mirror is mechanically scanned with small steps (−0.01 mm), each laser path can be independently reflected.

The intensity measurement result is shown in Fig. 7. A horizontal axis shows the position of the micro-mirror from c_0 to the center of confocal cavity "a." The vertical axis shows the signal gain from the photodiode. Because the diameters of the laser spots decrease from c_0 to "a" in principle, the signal gain relatively increases. We can count over 24 laser spots at the top half of the center axis. As the distance between the spots decreases, spots are overlapped around the center axis.

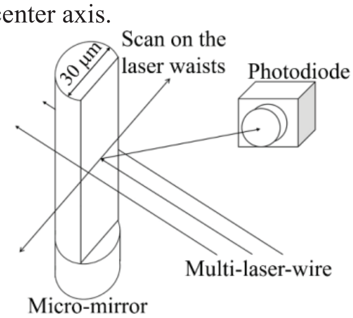

Fig. 6. Image of laser intensity measurement using a micro-mirror.

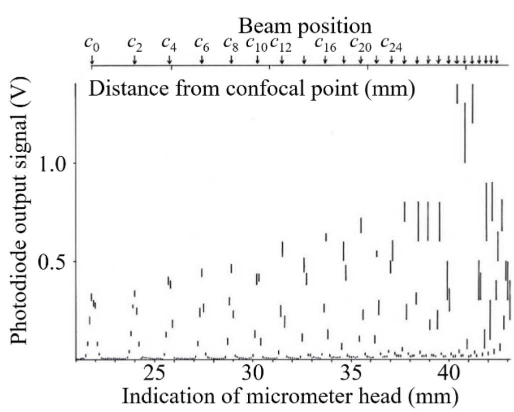

Fig. 7. Position dependence of the multi-laser-wire intensity.

DESIGN OF THE BEAM PROFILE MONITOR USING MULTI-LASER WIRE

When we design the beam profile monitor using the multi-laser wire, we should consider the system configuration in terms of collisions between the laser wires and the accelerated beam bunches to the greatest extent possible. Because the destination of the laser beam is the center axis of the mirrors and the laser wires gather to the center axis, we can use the top half or bottom half of the face aligned on the laser wires shown in Fig. 3. In Fig. 3, the direction of the accelerated beam is perpendicular to the face.

Wavelength of the Laser Beam

When the wavelength of the laser beam matches the ionization cross-section in Fig. 8, we can obtain an electron and a neutral hydrogen atom (H^0) from a negative hydrogen ion. This process is known as photodetachment. When the laser beam with wavelength λ_{LF} collides with the accelerated beam with an energy of βc (where c denotes light velocity) and an incident angle (α), its wavelength (λ_{PRF}) is shifted by the Doppler effect expressed as follows:

$$\lambda_{PRF} = \lambda_{LF}/\gamma(1+\beta\cos\alpha). \quad (5)$$

The photodetachment cross-section of a negative hydrogen ion on the wavelength of the irradiated laser beam is shown in Fig. 8 [6]. A considerably broad peak is observed to be centered at approximately 800 nm, and the cross-section is approximately 4×10^{-17} cm^2 over a range of ±100 nm around the center. Using visible laser light (λ_{LF} = 380–800 nm), we can obtain a large cross-section with an injection angle α at a beam energy β using Eq. (5).

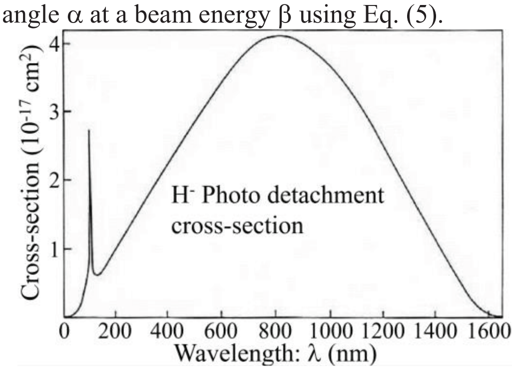

Fig. 8. Photodetachment cross-section of a negative hydrogen ion [6].

Optical Design

When we choose the curvature radius and the focal length of a pair of confocal mirrors, the system configuration of the total length as well as the laser radius and the distances of multiple laser paths are defined by Eqs. (1) and (4). In the J-PARC linac, the smallest transverse beam size is designed upward of the ACS section and the one measured by the WSMs has a root-mean-square (RMS) value of approximately 2.0 mm (Fig. 9). The beam halo is observed in the beam profile measurement under 1/10 of the magnitude of the beam center [7]. The specifications of the beam profile monitor are required to observe the beam halo such that the dynamic range of the laser beam profile monitor should be over two orders of magnitude. Transverse resolution is required to be approximately 0.1–0.5 mm as in the case of the WSM. The top half of the confocal cavity in Fig. 3 is chosen to be used to avoid the focal point "a" which is the laser beam destination. The even-numbered laser path formed by c_0, c_2, c_4, …, c_{2n} is employed for the

ISBN 978-3-95450-177-9

profile monitor, and the laser wire is aligned with a distance of 0.1–0.5 mm. To form a proper span in each laser wire, we should choose appropriate focal lengths as f_1 and f_2 to set the x_0, x_2, x_4, …, x_{2n} values around 0.1 mm. If the ratio of f_2 and f_1 increases ($f_2 > f_1$), we can obtain closer spans.

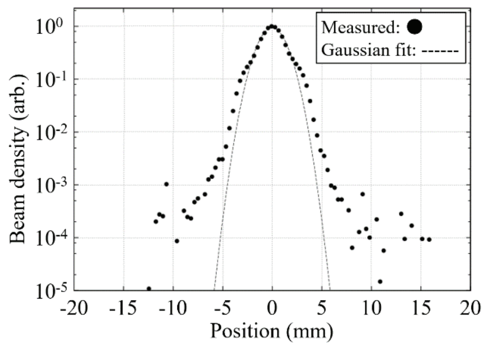

Fig. 9. Minimum transverse profile of linac beam with 191 MeV used by wire scanner monitor.

A pair of mirrors is arranged with a distance L, which is the sum of the focal lengths expressed as follows:

$$L = f_1 + f_2. \quad (6)$$

The laser beam is reflected at mirror 1 and reflected again at mirror 2 with the light velocity in the confocal cavity. The laser path length from c_n to c_{n+2} is approximately $4L$, travel time of the laser beam from c_n to c_{n+2} is $4L/c$. We need to adjust the timing of the laser beam to a frequency of 324 MHz (3.01 ns). In fact, the timing of the laser beam should be "n" times of 324 MHz. Further, we consider the following equation:

$$4L/c = n/(324 \times 10^6). \quad (7)$$

When we define "n" in Eq. (7), the laser path length can be adjusted to the $(n + 1)^{th}$ beam bunch and the distance L by Eq. (6). When we chose 3, 4, or 5 as "n," L becomes 69.4, 92.5, or 115.7 cm, respectively. The laser wire interacts with the accelerated beam bunch with intervals of 9.03, 12.04, and 15.05 ns. The signals generated by photodetachment electrons can be obtained by the electron multiplier in each time interval, and the signal height corresponds to the number of detached electrons. Because the time interval corresponds to the path length (L), it can be converted into the transverse position in the geometry. Therefore, the plots of the signal peaks versus time can yield the accelerated beam intensity versus the transverse geometry. When we consider the easy access of the confocal mirrors, we should choose a distance (L), which corresponds to the sum of the focal lengths ($f_1 + f_2$) of approximately 1.0 m.

Detection of Detached Electrons

We can use the detached electrons in the beam profile measurement by employing an electron multiplier. As Yamane reported [8], when a laser beam with a 515-nm wavelength, a full width at half maximum of 1.0 ns, and pulse power of 100 μJ is assumed to be irradiated to the accelerated beam, a number of 10^8 electrons can be estimated. Because this number is sufficiently high for obtaining the signal from the electron multiplier, it is brought to a profile monitor. Because an electron can be bent by a weak magnetic field, electrons are easily separated from the particles with electrons H^0 and H^-. Time structure of electrons is still maintained from the original beam time structure. When the signals have beem highly sampled, the signal waveform can be converted to the beam profile by plotting the peaks of the signals.

CONCLUSION

We proposed a multi-laser-wire profile monitor using the confocal laser cavity proposed by Yamane [2]. Based on the beam profile measurement by the WSM, we set the reqired specifications for the profile measurement system.

When testing the performance of a multi-laser-wire formation, we counted over 20 laser wires in the cavity. Currently, it requires a few minutes to obtain one transverse profile by a WSM; however, this multi-laser-profile monitor only requires one intermediate bunch with several hundres ns. In addition, because we can measure several profiles for each macro-pulse to observe the trend of the accelerated beam profile, it facilitates the evaluation of the RF power stability in a macro-pulse. The system does not require motor-scanning devices; therefore, it uses only a small space and poses low mechanical difficulty compared to a present WSM or a single laser-wire profile monitor. This system offers multiple advantages over the present methods.

We have a 3-MeV linac beam line in the J-PARC as the demonstration beamline. We design and fabricate a multi-laser-wire profile monitor to verify its performance in the beamline. Furthermore, we will apply the system to the 400-MeV linac in the future.

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