Measurement of an electron beam size with a laser wire beam profile monitor

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We describe the first measurement of an electron beam size in the accelerator test facility damping ring at KEK with a laser wire beam profile monitor. This monitor is based upon the Compton scattering process of electrons with a laser light target, which is produced by injecting a cw laser beam into a Fabry-Pérot optical cavity. We have observed clear signals of the Compton scattered photons and confirmed that the observed energy spectrum as well as the count rate agree with the expected ones. From the measurement, we have deduced the vertical beam size σ_b to be 9.8 $\pm$ 1.1 $\pm$ 0.4 μm, where the first (second) error represents statistical (systematic) uncertainty. Various improvements are in progress to enhance the signal-to-noise ratio, which is essential for the detailed study of the beam dynamics.

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I. INTRODUCTION

Production of low emittance beams is one of the important techniques of an electron accelerator and storage ring. An example of the application is third-generation synchrotron light sources where a natural emittance of a few nm is already achieved. In high energy physics, TeV-range electron linear colliders require an extremely low emittance beam to achieve necessary luminosity. In order to develop technologies for such a low emittance beam, an accelerator test facility (ATF) was built at KEK [1]. It consists of an electron linac, a damping ring in which the beam emittance is reduced, and an extraction line. Results of the horizontal emittance measurement, done successfully at the extraction line with a tungsten wire scanner, have already been published [2].

Of crucial importance is a vertical emittance measurement in the damping ring itself. For this purpose, we have been developing a new type of beam profile monitor, which is based on the Compton scattering process of electrons with laser light. In order to achieve both good spatial resolution and fast response for the monitor, the target light must be very thin and intense. These requirements are realized by injecting a cw laser beam into a Fabry-Pérot optical cavity. We call this system a laser wire beam profile monitor. The salient features of this monitor, when compared with a solid wire scanner, are nondestructiveness and durability in an intense circulating beam [3]. We also note that a cw laser, instead of a pulsed one [4–6], is selected because it is suited for the quasicontinuous beam of the ATF damping ring. In principle, the monitor can measure beam width in the range of a few to a few hundred μm by adjusting its wire radius; however, in this particular application, we set it to match with the expected electron beam width ($\simeq$10 μm).

In this paper, we will report on the first measurement of the electron's vertical beam size with this laser wire beam profile monitor. This paper is organized as follows. In Sec. II we describe our experimental setup. Then the data taking procedure and analysis method are presented in the Sec. III. Section IV is devoted to the summary and discussions.

II. EXPERIMENTS

A. Setup

The experimental setup, shown in Fig. 1, consists of two main components: a laser wire system and a photon detector system. The measurement principle is as follows. An electron interacts with the laser light by the Compton scattering process and emits energetic photons into the forward direction. A count rate of scattered photons is measured as a function of the laser wire position. Then a beam profile is obtained by unfolding the count rate shape with a known laser intensity distribution. Before we describe our actual setup, we briefly summarize the Compton process for the present configuration. Circulating electrons of energy $E = 1.28$ GeV elastically scatter off the laser light of wavelength $\lambda = 532$ nm ($k_0 = 2.33$ eV). The energy of the emitted photon is expressed by

$$k = \frac{k_0 E}{E + k_0 - \sqrt{E^2 - m_e^2}\cos\theta_c}, \tag{1}$$

where m_e denotes the electron mass and θ_c denotes the

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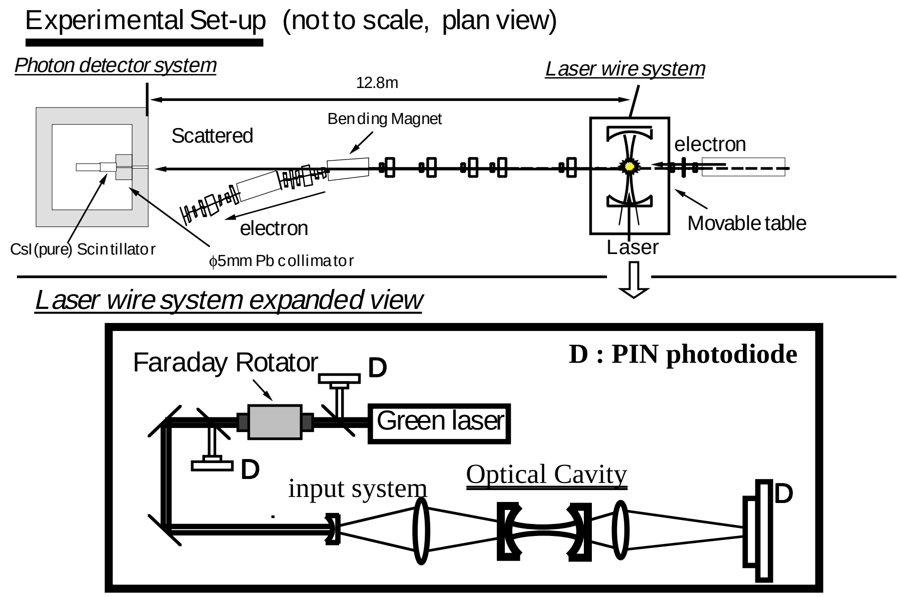

FIG. 1. Schematic diagram of the experimental setup. The lower part is an expanded view of the laser wire system.

scattering angle with respect to the initial electron beam.[1]

The cross section of the Compton process is given by the Klein-Nishina formula [7] with an appropriate Lorentz transformation. In order to identify the Compton signals unambiguously, it is best to detect energetic photons emitted in the forward direction. This is because the cross section is sharply peaked at $\theta_c = 0$, where the photon energy takes its maximum value (28.6 MeV). For example, within $\theta_c < 0.2$ mrad, which corresponds to our actual collimator bore (see below), photons with 20 MeV or larger are emitted with a partial cross section of 0.16 b as compared with 0.65 b in total.

The actual setup was installed at one of the straight sections of the ring. The laser wire system was mounted on a movable table, directing the wire perpendicular to the electron beam. The table was moved vertically to measure the vertical emittance in the present experiment. Its position resolution was checked by a position sensor [8] and was found to be better than 1 μm.

Scattered photons were detected by a rectangular ($50 \times 50 \times 100$ mm^3) scintillator made of a pure CsI crystal. The location of the detector was 12.8 m downstream from the cavity. A photon collimator, a 100 mm thick lead block with a 5 mm diameter bore at the center, was placed in front of the detector to reduce backgrounds. The scintillator was viewed by a photomultiplier attached at the rear end. Prior to the experiment, the energy scale was calibrated with standard gamma sources of ^{22}Na and ^{137}Cs. The output signal from the photomultiplier was sent to a counting room and was fed into five discriminators after splitting. Their thresholds were set equivalent to the energy from 10 to 30 MeV with a 5 MeV step. Then they were counted by scalers, and finally were read by a computer every second via a CAMAC system, together with other relevant information such as the beam current, the vacuum pressure, and various laser power monitors.

During the experiment, a single bunch of electrons was accelerated up to 1.28 GeV and was stored in the damping ring. Figure 2 shows an example of an intensity history for one fill from injection to abortion. The electron's beam shape is expected to be flat in the damping ring; in particular, at the location of this monitor, the designed dimensions are 8.8 μm vertically, 61 μm horizontally, and 5 mm longitudinally.[2]

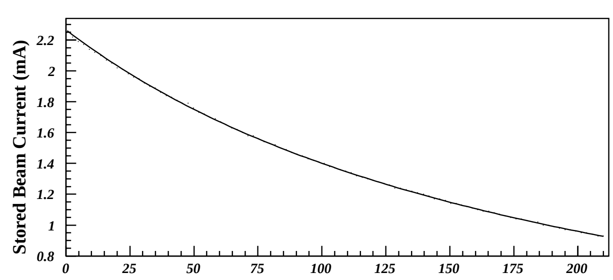

FIG. 2. A typical history of the electron current. The solid line is a fit by a lifetime function to the data.

[1]In principle, k also depends upon the azimuthal angle measured with respect to the laser incident direction. However, since E is much larger than k_0 its dependence can be neglected.

[2]Influence of the electron beam divergence is negligibly small; the beam divergence is expected to be 6 μrad vertically and 40 μrad horizontally at the location of the laser wire, which should be compared with the detector acceptance of 0.2 mrad.

B. Optical cavity

The heart of the laser wire system is an optical cavity; it must stably produce a thin enough beam waist and realize sufficient intensity amplification. Since we have already described their properties in detail [9,10], we briefly reproduce here some basic characters relevant to the present study. A Gaussian beam of the fundamental TEM_{00} mode is excited inside an optical cavity, which is made of a pair of spherical mirrors in a nearly concentric configuration. The mirrors are identical and have curvatures of 20 mm with reflectivity of 99%. The reflectivity, transmissivity, and power gain of the cavity are given by [11,12]

$$\begin{aligned} \frac{P_{\mathrm{refl}}}{P_{\mathrm{in}}} &= \left(\frac{T_{\mathrm{m}}}{T_{\mathrm{m}} + A_{\mathrm{m}}}\right)^2 = (1 - a_{\mathrm{eff}})^2, \\ \frac{P_{\mathrm{trs}}}{P_{\mathrm{in}}} &= R_{\mathrm{m}}\left(\frac{A_{\mathrm{m}}}{T_{\mathrm{m}} + A_{\mathrm{m}}}\right)^2 = R_{\mathrm{m}} a_{\mathrm{eff}}^2, \\ \frac{P_{\mathrm{cav}}}{P_{\mathrm{in}}} &= \left(\frac{T_{\mathrm{m}}}{T_{\mathrm{m}} + A_{\mathrm{m}}}\right)\left(\frac{1 + R_{\mathrm{m}}}{1 - R_{\mathrm{m}}}\right) \simeq (1 - a_{\mathrm{eff}})\,\frac{2F}{\pi}, \end{aligned} \tag{2}$$

where P, with obvious subscripts, stands for the laser power and R_{m}, T_{m}, and A_{m} denote, respectively, the reflectivity, transimissivity, and absorption of the mirror ($R_{\mathrm{m}} + T_{\mathrm{m}} + A_{\mathrm{m}} = 1$). In the above equations, we have also introduced the finesse $F = \pi\sqrt{R_{\mathrm{m}}}/(1 - R_{\mathrm{m}})$ and an effective absorption coefficient $a_{\mathrm{eff}} = A_{\mathrm{m}}/(1 - R_{\mathrm{m}})$ to simplify the expressions.

The beam waist w_0 is controlled by the cavity length. It was measured before and after the experiment with two different methods. One was to measure laser beam waist $w(z)$ at far field: It is related to the waist w_0 by $w(z) \simeq \lambda z/(\pi w_0)$, where z is the distance from the cavity center. The other was to excite a higher mode by displacing one of the cavity mirrors laterally; the difference in the cavity length at resonance between the higher and fundamental modes gives the waist w_0. The result of these measurements was found to be $w_0 = 14.8 \pm 0.5\ \mu\mathrm{m}$.

We note that w_0 corresponds to 2σ in the Gaussian distribution. A green laser ($\lambda = 532$ nm) with an output power of 50 mW was used [13]. We measured the input power to the cavity (P_{cav}) to be $P_{\mathrm{cav}} = 25$ mW.[3] We also measured the finesse and found $F = 321 \pm 16$; this is consistent with the value of 313 evaluated with the nominal reflectivity of $R_{\mathrm{m}} = 99\%$.

In this measurement, it is essential to keep stable the stored power inside the cavity. Its stability was assured by the stability of the laser's output power and the transmitted (P_{trs}) or reflected (P_{refl}) power of the cavity. They were monitored continuously by *p-i-n* photodiodes during the experiment. It is necessary to know a_{eff} to determine P_{cav}, and there are two ways to determine it: by transmissivity measurement or reflectivity measurement. We measured both and found that a_{eff} was 0.37 from the former and 0.67 from the latter. Accordingly, the stored power had some uncertainty and it was estimated to be in the range of 1.6 W and 3.3 W.[4]

III. DATA TAKING AND ANALYSIS

The procedure of data taking was as follows. One run corresponded to one fill, during which the laser wire was turned on and off several times. This procedure was found to work well to subtract backgrounds, which were determined by the laser-off data (see below). After one run, we changed the laser wire vertical position and repeated the same procedure. The entire measurement lasted about 3 h.

The data from the scalers were sorted according to the energy bin of a 5 MeV interval. The count rates were calculated and normalized to the electron beam current (mA). The upper plots in Fig. 3 show examples of the raw count rates as a function of the beam current.[5] Then laser-off data points were fitted to a polynomial function to determine background rates (see the solid lines in Fig. 3). We then subtracted the background from each data point. The residuals, which were normalized by electron beam current, are shown in the lower part of Fig. 3, where the solid circles (cross points) represent the laser-on (off) data. Figures 3(a) and 3(b) are the data for which the laser wire was positioned on and off the electron beam, respectively. The Compton signal is seen clearly only in Fig. 3(a). We averaged the subtracted count rates over the laser-on data[6]; the resultant value is refereed to as a signal rate.

Figure 4 shows such signal rates as a function of the laser wire vertical positions for five energy bins. As expected, the genuine Compton signals are seen mainly in the energy interval of 15 to 25 MeV. Furthermore, its energy spectrum and counting rate are found to agree with the expectations (see below for the detail). By contrast, the signal rates above the Compton energy (30–35 MeV)[7] and those outside the electron beam region (two outer points in each plot) are consistent with zero. The chi square (χ^2) per degree of freedom (ν) are, respectively, $\chi^2/\nu = 5.6/9$ and $\chi^2/\nu = 18/10$. The latter value gives a somewhat small

[3] This value took into account a mismatching effect between the input laser and cavity modes.

[4] After the experiment, we found that this discrepancy was related to aberration in the mode matching system, and that its adjustment improved consistency of the a_{eff} measurements as well as transmissivity itself.

[5] Since we took data with a time interval of 1 s, the data points are not equally spaced when plotted as a function of the current.

[6] The electron beam width may be dependent on the beam current, and investigation of such an effect is one of our future plan. However, it is obvious that we need much higher counting rate for this purpose.

[7] The signal counts below 20 MeV are due to the detector response.

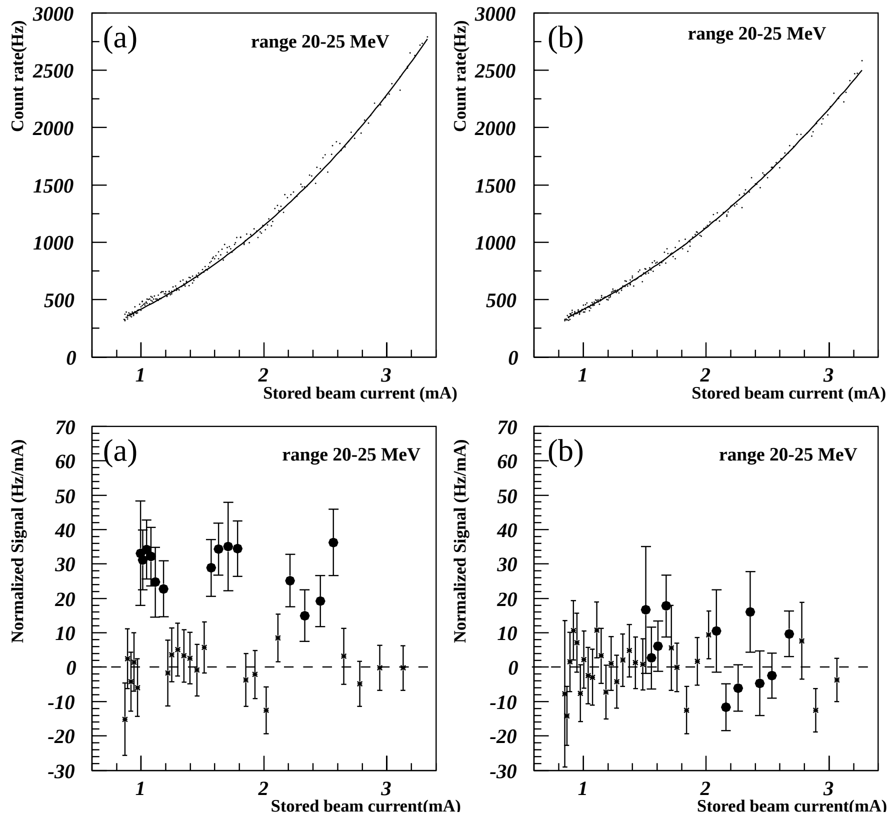

FIG. 3. Examples of the raw count rates as a function of the beam current (the upper plots). The solid lines are fits to the laser-off data by a polynomial function. The background subtracted count rates are shown in the lower plots. The solid circles (cross points) represent the laser-on (off) data. Note that approximately six data points in the upper plots are combined into one to reduce statistical fluctuation. The laser wire was positioned (a) on and (b) off the electron beam.

value of confidence level (5%); we believe that it is just a statistical fluctuation (see below).

In order to deduce the electron beam size from the data, we combined the data for 15–25 MeV and fitted them by a Gauss function with center, width, and peak height being left as free parameters. Note that we employed a simple Gauss function based on the fact that no substantial background exists outside the electron beam region. Figure 5 shows the results ($\chi^2/\nu = 7.7/6$). In particular, the width σ_y is found to be 12.3 $\pm$ 0.9 μm. As an additional check, we tried several other fitting procedures. Fitting by a Gauss function plus a constant term yields $\sigma_y = 12.2 \pm 1.0$ μm, while fitting by a Gauss function plus a linear term gives $\sigma_y = 12.4 \pm 1.1$ μm. If we artificially enlarge all error bars in Fig. 4 in such a way that the data points outside the beam region yield $\chi^2/\nu = 1$ instead of 1.8, then the fit results in $\sigma_y = 12.3 \pm 1.2$ μm. These results indicate good stability in the fitting procedure. To be conservative, however, we assign, somewhat arbitrarily, 0.3 μm (=1.2 − 0.9) as a systematic error on σ_y in the fitting procedure. Thus our final value is $\sigma_y = 12.3 \pm 0.9 \pm 0.3$ μm.

The obtained width contains the effect of a finite laser beam waist. Assuming the Gauss distribution, the vertical electron beam size σ_b was obtained by

$$\sigma_b = \sqrt{\sigma_y^2 - \left(\frac{w_0}{2}\right)^2}, \qquad (3)$$

where the factor 2 stems from the definition for the beam waist w_0. The final result is $\sigma_b = 9.8 \pm 1.1 \pm 0.4$ μm, where the first (second) error represents statistical (systematic) uncertainty. This width does not represent the pure vertical beam size, but rather a combination of other possible effects such as a beam position jitter/drift during the measurements.

Each solid line in Fig. 4 is a fitted Gauss function; in this case, only the peak height was made free with the center and width given by the values obtained in Fig. 5. We consider that the peak values obtained in this fit suffer less from statistical fluctuation, and that they represent the signal count rates for that energy interval. Figure 6 shows the peak values as a function of energy. The histogram in Fig. 6 shows the range of the expected count rates; uncertainty was originated mainly from uncertainty in the stored energy inside the cavity and possible misalignment of the lead collimator. The actual count rates were affected by the detector response, and we took this into account using the EGS4 [14] simulation. As can be seen from Fig. 6, the agreement is reasonable if we consider the uncertainty in $P_{\rm cav}$.

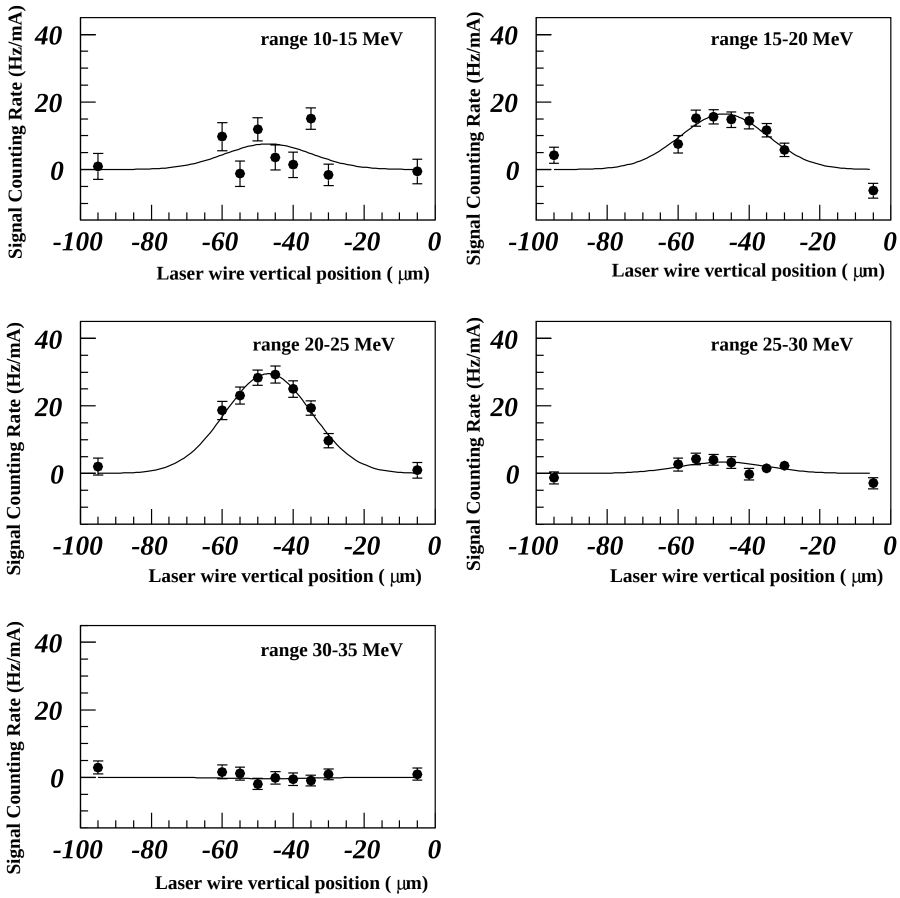

FIG. 4. The signal count rates for five energy intervals as a function of the laser wire vertical position. The solid lines are the Gaussian fits to the data (see the text for detail).

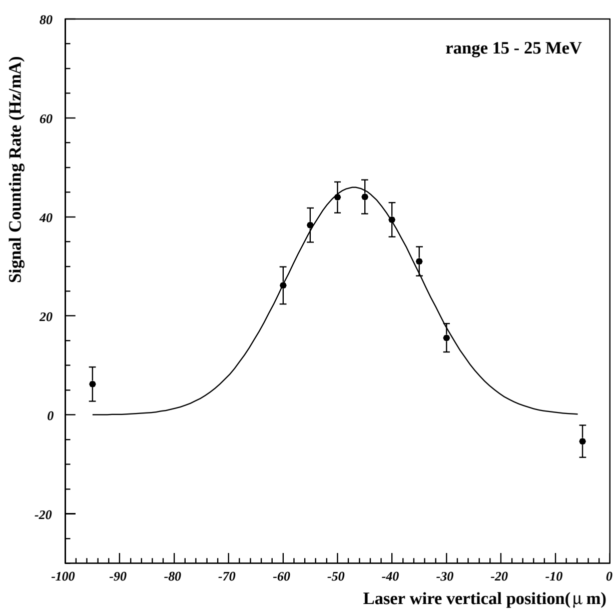

FIG. 5. The signal count rates for energies of 15–25 MeV as a function of the laser wire vertical position. The solid line is the simple Gausssian fit to the data (see the text for detail).

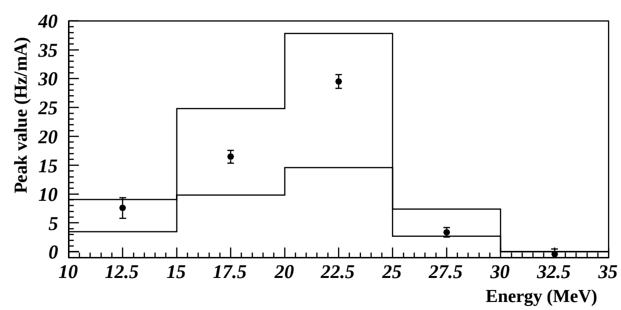

FIG. 6. The peak signal rates as a function of energy. The histogram shows the range of the expected count rates.

IV. SUMMARY AND DISCUSSION

In this paper, we have described the first measurement of the electron's beam size in the damping ring at ATF with a laser wire beam profile monitor. We have observed clear signals of the Compton scattered photons, as can be seen in Fig. 4. We have confirmed that the observed energy spectrum as well as the count rates agree with the expected ones. From the measurement, we have deduced the beam size σ_b to be $9.8 \pm 1.1 \pm 0.4$ μm, where the first (second) error represents statistical (systematic) uncertainty. This value corresponds to the vertical emittance of $(1.8 \pm 0.4 \pm 0.1) \times 10^{-11}$ m. This value might include some systematic effects such as jitter/drift in the beam position. In order to study beam dynamics more systematically, it is essential to improve the signal-to-noise ratio. We are now planning to increase the laser power and the finesse of the cavity by changing the mirrors with higher reflectivity and lower absorption.

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