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Development of Laser wire beam profile monitor for measurement of low emittance beam

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Abstract

We have designed a beam profile monitor to measure the size of a low emittance electron beam down to the order of $\sim 10\mu$m. In the monitor, very thin and high intensity laser beam is created inside an optical cavity. The shape of the electron beam can be measured by crossing the laser and electron beams and detecting Compton scattered photons. We constructed a test cavity to create a laser beam with high intensity and size of the order of 10μm. We established methods to measure the beam intensity and the beam size.

1 Introduction

A beam profile monitor has been designed for measuring the beam size in the damping ring of the Accelerator Test Facility (ATF) at KEK. In this ring the beam size will be reduced to $\sim 10\mu$m vertically and $\sim 130\mu$m horizontally within 80 msec or less from injection. Thus the monitor must be able to measure the beam size of $\sim 10\mu$m. Typically wire (carbon or tungsten) scanners are used for the beam size measurement. However, they are destructive to the circulating beam in the ring. The monitor of ref.[1] might be used; however, we would like to develop a more handy and simple one that matches up with the quasi-continuous beam of $\sim 10\mu$m in size. Our monitor is based on a nearly concentric optical cavity in which a Gaussian beam with a $\sim 10\mu$m beam waist is realized. Electrons interact with the laser light inside the optical cavity and emit energetic photons to the original electron beam direction (Compton scattering). The rate of these energetic photons is measured as a function of the electron beam position relative to the the laser beam position. From the rate the beam profile in one direction can be calculated.

The monitor will not disturb the beam and allows us to measure its spatial and/or temporal structure. The optical cavity enhances the effective laser power inside the cavity. This moderates the requirement for the laser, which is important from the cost viewpoint.

In this paper we describe the design of the monitor and some experimental results of basic studies on the test cavity.

2 Design of the Monitor

For the calculations performed in this section, we assume the following parameters [2]. The 1.54 GeV beam consists of bunch trains. Each bunch contains 1×10^{10} electrons, and its length is about 5 mm. The separation between adjacent bunches is 2.8 nsec, and the separation between two trains is 60 nsec.

2.1 Compton scattering

We estimated the photon counting rate based on the following assumptions. The laser beam interacts perpendicularly with the electron beam. The light source is a 10 mW He-Ne laser and the power enhancement factor of the optical cavity is assumed to be 100. Gamma rays whose energy is above 10 MeV are detected. With these parameters the average counting rate is estimated to be 7.8 kHz. This may not be enough to trace the damping of the beam since the damping time is typically about 10 msec (ref [2]).

2.2 Optical cavity

It is known that a resonant mode called Gaussian beam [3] can exist in a resonator cavity. The electric field of the [TEM$_{00}$] mode is given by

$$\begin{aligned} E_0(x,y,z) &= A\frac{w_0}{w(z)}\exp\left(-\frac{x^2+y^2}{w^2(z)}\right) \\ &\quad \times \exp\left(ik\frac{x^2+y^2}{2R(z)}\right)\exp\left(i\Phi(z)\right) \end{aligned}$$

where λ represents the wave length, $w(z)$ the beam spot size at the location z, $R(z)$ the curvature of the wave front, and $\Phi(z)$ the Guoy phase factor. The parameter w_0 is called the beam waist, and represents the smallest spot size at the middle of the cavity ($z = 0$). Suppose two spherical mirrors (optical cavity) with curvatures R are placed at $\pm z_R$. With a stable laser beam in this cavity whose length is $D(D = 2z_R)$, the beam waist is represented by

$$w_0^2 = \frac{\lambda}{\pi}\frac{\sqrt{D(2R-D)}}{2} \qquad (1)$$

From this equation it can be calculated that a beam waist of, say, 10 μm is obtained for $\lambda = 640$ nm and $R = 20$ mm when $D = 40\text{mm} - 24\mu\text{m}$. It should be also noted that the requirement for the positioning accuracy in D is very strict.

A fraction of the beam incident on the other side of the cavity is transmitted to the other side. [Fig.1] The transmission ratio T is given by the Airy function:

$$T = 1/\left[1+\frac{4F^2}{\pi^2}\cos^2\left(\frac{2\pi D}{\lambda}\right)\right] \qquad (2)$$

The quantity F is called 'finesse'and is given by $F = \pi\sqrt{R_m}/(1-R_m)$ where R_m is the reflectivity of the mirrors. From the eq.(2) above, the finesse F can be expressed by $F = (\Delta D(peak-to-peak))/(\delta D(fwhm))$ where ΔD is the difference in D between the two adjacent peaks (equal to $\lambda/2$), and δD the full width at half maximum of the peaks. The average power enhancement factor $\bar{P}$ inside of the cavity is: $\bar{P} = \frac{1+R_m}{1-R_m}T \simeq \frac{2}{3}FT$. When $T = 1$, for example, we need mirrors of reflectivity $R_m = 98\%$ in order to obtain the power enhancement of 100.

3 Experiments

In this section, we describe some results of studies on the test cavity. We want to measure the beam waist w_0 and the average power enhancement factor $\bar{P}$. To our application, the beam waist is the most important parameter. Thus we tried several independent methods to measure w_0.

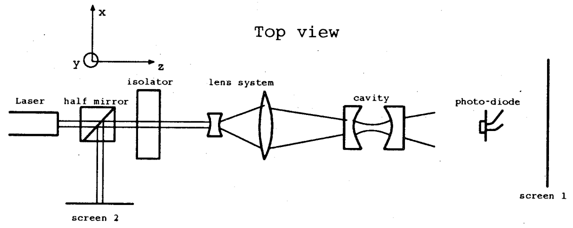

Fig. 1 Schematics of the test setup.

3.1 Setup of the experiment

Figure 1 shows a schematic diagram of our test setup. It consists of a He-Ne laser, an optical isolator, input lens system, the cavity and a detector.

These optical elements are installed on adjustable positioners. In particular, the downstream cavity mirror is equipped with a piezo translator so that the mirror can be scanned along the beam direction z. The piezo translator can be controlled remotely and its position is monitored with a strain gauge sensor with a 10 nm position resolution. We can position the piezo translator manually or scan it by applying a voltage signal to the controller.

The transmitted light intensity is monitored with a PIN photodiode at the exit of the cavity. Output signal of the diode is amplified with a simple current-to-voltage amplifier and monitored with an oscilloscope.

3.2 Measurement of the power enhancement factor

We measured the finesse to get the power enhancement factor. A function generator was used to produce a ~100 Hz sawtooth signal. The signal was fed into the piezo controller. The amplitude of the signal was set so that the cavity length D was scanned over several ΔD. A typical example of the detector output is shown in Fig.2.

The finesse F was found to be 70 (22) for the mirrors with $R_m = 96\%(85\%)$ (enhancement factor is 47 (15)). This value is consistent with the expected value of 77 (19).

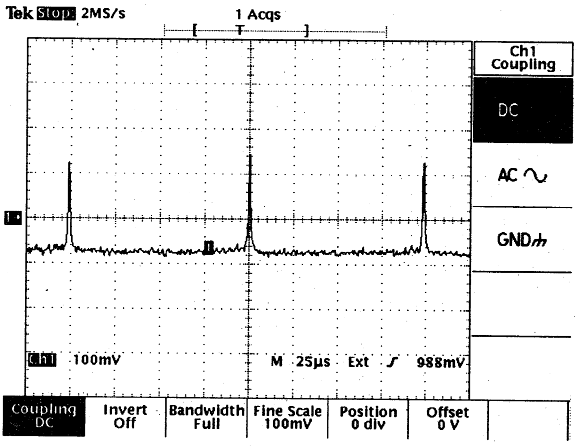

Fig. 2 A typical example of the detector output.

3.3 Three methods to measure the beam waist

Shift-rotation method We employed the following method [5]. Suppose that the cavity axis is aligned with that of the laser beam. One of the mirrors is shifted laterally. Since the mirrors are both spherical, the cavity can be realigned by rotating it. A simple calculation shows that the displacement x and rotation angle θ is related by

$$2R - D = \frac{x}{\tan\{\arcsin(\sin\theta/n)\}} \simeq \frac{nx}{\theta}$$

(The approximate formula is valid for small θ) By measuring x and θ, we can determine $2R-D$ by the eq.(1), which in turn determines the beam waist w_0. Fig.3 shows the results of the measurements.

Measurement of a beam divergence angle In the far field ($z \gg z_0$), the beam width $w(z)$ is proportional to z, i.e. $w(z) \simeq (w_0/z_0) \times z$. Thus one can determine w_0 by measuring the beam divergence. For convenience, we define a half-cone angle $a_{1/\sqrt{e}}$ at which the beam power is reduced to $1/\sqrt{e}$ of its maximum value. This quantity is related to the beam waist by $a_{1/\sqrt{e}} \simeq n\lambda/(2\pi w_0)$ where the effect due to the concave mirror (with a refractive index n) is taken into account.

We inserted a 200μm slit in front of the diode. The diode was scanned horizontally to measure the beam profile, from which $1/\sqrt{e}$-widths were be reduced. The profile measurements were repeated at several different z positions. Fig.4 shows $1/\sqrt{e}$-widths at several different z positions. The straight line is a linear fit to the data; a half-cone angle $a_{1/\sqrt{e}}$ is given as a slope of the fit.

Higher order transverse modes A phase of the higher transverse mode TEM$_{mn}$ shifts $(m+n)\Phi(z)$ at

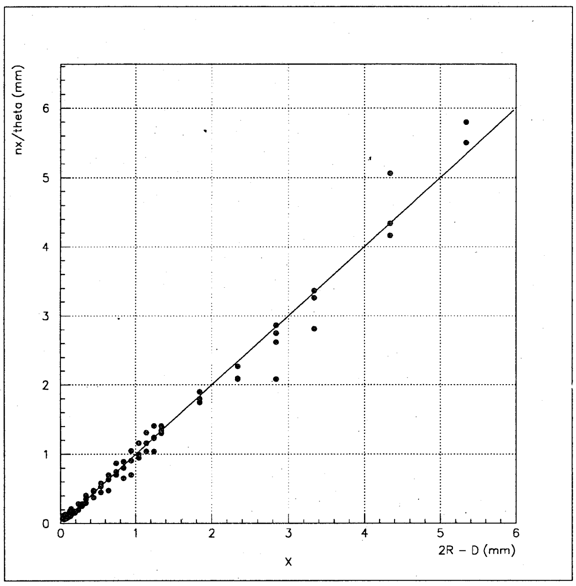

Fig. 3 Measurements of $2R-D$ by the shift-rotation method.

z on the beam axis from TEM_{00}. A straightforward calculation shows that the condition above is equivalent to

$$D_p = \frac{\lambda}{2}\left\{p + \frac{m+n+1}{\pi}\arccos\left(\frac{D_p}{R}-1\right)\right\}$$

where p is integer. The quantity D_p in the right hand side may be replaced by some representative value since its dependence is weak. Therefore, the spacing between the adjacent peaks due to the higher mode excitation (whose $m+n$ differs by 1) is $\left[\frac{1}{\pi}\arccos\left(\frac{D}{R}-1\right)\right]$ times the spacing of the corresponding($\lambda/2$) [4]. Thus we can calculate D by measuring the spacing of these peaks. The results of the three methods are summarized in Table1.

nominal w_0	shift -rotation method	$a_1/\sqrt{e}$ measure ment	transverse mode
20 μ m	20.0 ± 1.0	20.4 ± 1.7	20.1
25 μ m	25.0 ± 1.3	24.8 ± 1.2	24.9
30 μ m	30.0 ± 1.5	31.0 ± 1.6	30.0
35 μ m	35.0 ± 1.8	37.5 ± 1.4	36.4

Table 1
Comparison of beam waist measurements

4 Conclusions

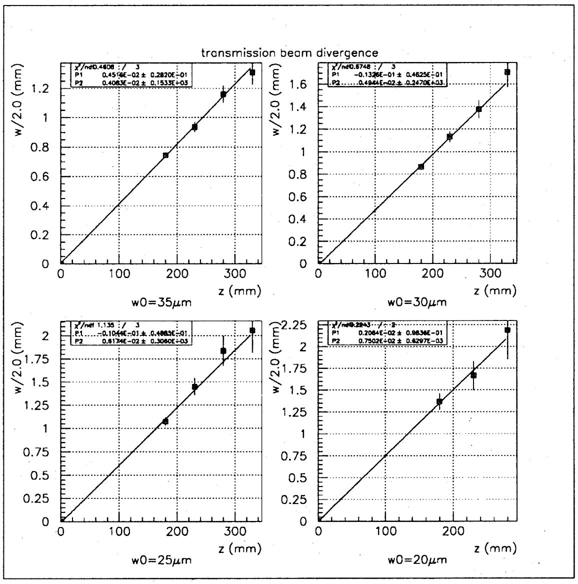

Fig. 4 Measurement of a beam divergence.

In this paper we described a conceptual design of a beam profile monitor for an electron beam with a size of ~ 10μm. Assuming a laser beam with a beam waist of 10μm and an effective power of 1 W, the expected counting rate is ~ 10 kHz when scattered photons with energies>10 MeV are detected. We measured the finesse F to obtain the power enhancement factor of the test cavity. Using mirrors with reflectivity of $R_m = 96\%$, we obtained an enhancement of 50, which is consistent with the expected value. We confirmed three methods of measuring beam waist in the test cavity. As seen in Table 1, the beam waist was measured with 10% accuracy.

Next, we plan to use mirrors with reflectivity of 98 ~ 99% for an optical cavity of a prototype monitor. We also plan to replace the He-Ne laser with a higher intensity output laser like a diode laser for example. A further design work is now underway.

Acknowledgments

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