Development of a laser wire beam profile monitor and measurement of vertical emittance in the KEK-ATF damping ring

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Abstract

We describe the development of the laser wire beam profile monitor, and the measurement of the vertical emittance in the KEK-ATF damping ring by utilizing laser wire monitor. This monitor is based on the Compton scattering process of electrons with a laser light target, which is produced by injecting a CW laser beam into a Fabry-Perot optical cavity. In order to measure low vertical emittance, thin and intense laser wire is required. We could reduce its laser wire beam size to $7.3 \pm 0.2\mu$m (its beam waist was $w_0 = 14.5 \pm 0.4\mu$m). With high reflectivity mirrors ($> 99\%$), we achieved a power enhancement factor of 220 ± 20. The effective laser power inside the cavity exceeded 11 W. After installing this monitor in the ATF damping ring. We could successfully identify the Compton photons and the measured vertical emittance was $\varepsilon_y = (1.17 \pm 0.08) \times 10^{-11}$ m·rad. The counting rate as well as its energy spectrum agreed well with the expected ones.

1 INTRODUCTION

Production of low emittance beam 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. 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-Perot 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 non-destructiveness and durability in an intense circulating beam. We also note that a CW laser, instead of a pulsed one [2, 3], is selected because it is suited for the quasi-continuous 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 ($\simeq 10\mu$m).

In this paper, we will report on the measurement of the vertical emittance with this laser wire beam profile monitor.

2 EXPERIMENTS

2.1 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,

$$k = \frac{k_0 E}{E + k_0 - \sqrt{E^2 - m_e^2}\cos\theta_c} \quad (1)$$

where m_e denotes the electron mass, and θ_c the scattering angle with respect to the initial electron beam.

The cross section of the Compton process is given by Klein-Nishina formula 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 barn as compared with 0.65 barn in total.

The actual setup was installed at one of the straight sections of the ring. The laser wire system was

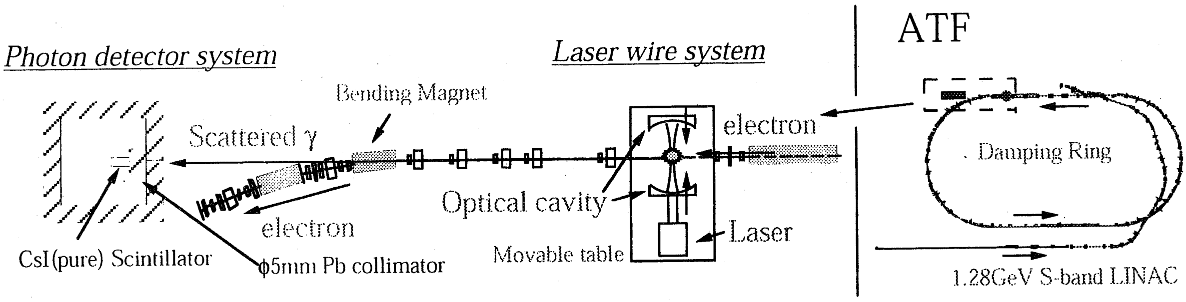

Figure 1: Experimental setup of the laser wire.

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 was monitored by a position sensor and its resolution 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 5mm 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, 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 4 discriminators after splitting. Their thresholds were set equivalent to the energy from 5 MeV to 45 MeV with a 10 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, and laser power intensity.

2.2 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 [4], 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. 1st and 2nd mirrors have curvatures of 20 mm. The power gain S_{res} of the cavity is given by

$$S_{res} = \frac{T_1(1+R_2)}{(1-\sqrt{R_1R_2})^2} \qquad (2)$$

where suffixes of T,R stand for those of 1st and 2nd mirror, and $R_{\rm m}$, $T_{\rm m}$, and $A_{\rm m}$ ($m = 1, 2$) denote, respectively, the reflectivity, transimissivity and absorption of the mirror ($R_{\rm m} + T_{\rm m} + A_{\rm m} = 1$). By using the 1st and 2nd mirror with measured reflectivity 98.9$\pm$0.03%, 99.4$\pm$0.04%, transmissivity 0.83$\pm$0.03%, 0.087$\pm$0.004%, $S_{res} = 220 \pm 20$ was obtained. A green laser (λ = 532nm) with an output power of 100 mW was used. These results correspond to the effective power 11 ± 1 W inside the optical cavity [1].

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 $w_0 = 14.5 \pm 0.4$ μm. We note that w_0 corresponds to 2σ in the gaussian distribution.

3 DATA AND ANALYSIS

We measured the vertical emittance two times (2000/12/05),(2000/12/14). The procedure of data taking was as follows. One run corresponded to one fill, during which the laser wire was turned on and off with 1kHz modulation. This procedure was found to work well to subtract backgrounds simultaneously. After one run, we changed the laser wire vertical position, and repeated the same procedure.

The data from the scalers were sorted according to the energy bin of 10 MeV interval and each electron beam current at 0.4 mA intervals. The count rates were calculated and normalized to the electron beam current (mA).

Fig.2 shows an example of the signal count ratio (Hz/mA) as a function of the laser wire vertical positions for 4 energy bins at interval between 1.0 - 1.4 mA on 2000/12/05. As expected, the genuine Compton signals are mainly seen in the energy interval of 15 to 25 MeV. The obtained beam size σ_{ob} results in $(11.3 \pm 0.5)\mu$m. Furthermore, its energy spectrum and

[1] Transmission ratio of the transport line and the matching efficiency was measured and included

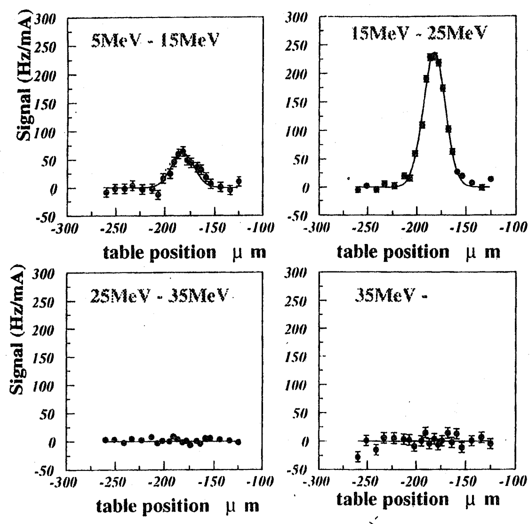

Figure 2: Results of the vertical beam size measurements (2000/12/05).

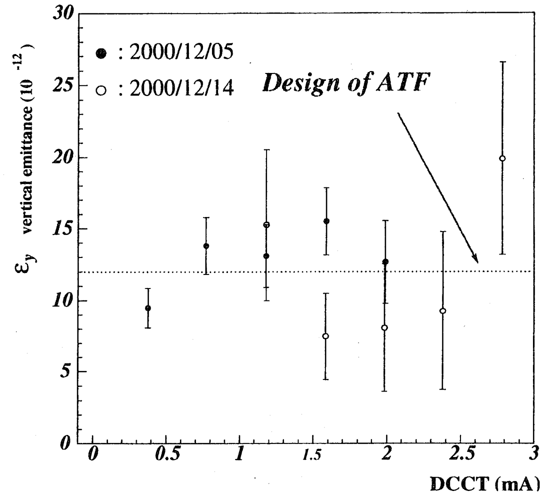

Figure 3: Results of the vertical emittance measurements.

counting rate are found to agree with the expectations. By contrast, the signal rates above the Compton energy (35-45 MeV) [2].

The obtained width $\sigma_{\rm ob}$ contains the effect of a finite laser beam waist. Assuming the gauss distribution, the vertical electron beam size $\sigma_{\rm y}$ was obtained by

$$\sigma_{\rm y} = \sqrt{\sigma_{\rm ob}^2 - \left(\frac{w_0}{2}\right)^2} \tag{3}$$

After subtracting the beam waist effect, we replace the genuine electron's beam size to the vertical emittance ε_y from the relations $\sigma_y = \sqrt{\beta_y \varepsilon_y}$, where β_y is the β function of the laser wire point. β_y were also measured at two measurements and resulted in (5.77 ± 0.07)m on 2000/12/05 and (3.97 ± 0.17)m on 2000/12/14, respectively.

We summarized the vertical emittance measurements in Fig.3 as a function of the beam current. Solid (open) circles show the measurements on 2000/12/05 (2000/12/14). Two measurements agree well with each other. It is expected that vertical emittance of the ATF damping ring may grow due to the intra-beam scattering effect as the beam current increases. To justify the current dependence of the vertical emittance we apply the constant fit in Fig.3 and obtained $\chi^2/\nu = 10.7/8$. Unfortunately, on these two measurements we have not seen clear current dependence of the vertical emittance growth. Then to quantify the measured vertical emittance, we averaged them aver the whole currents and resulted in $(1.17 \pm 0.08) \times 10^{-11} m \cdot rad$. This value is agree well with the calculation of the ATF damping ring design.

[2]The signal counts below 15 MeV is due to the detector response.

4 SUMMARY AND DISCUSSION

In this paper, first we have described the development of the laser wire system by utilizing optical cavity. The beam size of laser wire could reduce to $(7.3 \pm 0.2)\mu$m and the effective power increased to 11W successfully. Second we described the measurement of the vertical emittance in the ATF damping ring with a laser wire beam profile monitor. We have observed clear signals of the Compton scattered photons as can be seen in Fig.2. 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 vertical emittance ε_y to be $(1.17 \pm 0.08) \times 10^{-11} m \cdot rad$, This value is agree well with the calculation of the ATF damping ring and satisfies the emittance requirement set for linear collider. In order to study intra-beam scattering more systematically, it is essential to improve signal-to-noise ratio. We are now planning to increase the laser power and the finesse of the cavity.

5 REFERENCES

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