PERFORMANCE STUDY OF FOUR MIRROR LASER RESONATOR FOR 6 μm MINIMUM BEAM SIZE USING GREEN LASER OSCILLATOR

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Abstract

The Accelerator Test Facility (ATF) was constructed at KEK to study low emittance beam physics and to develop the technologies associated with it. In ATF damping ring, electron beam size is measured with laser wire system based on Compton scattering. A new four mirror laser wire system is developed for this purpose. This system has many advantages over two mirror laser wire system. Four mirror resonator reduces the sensitivity towards misalignment as compare to two mirror resonator. Measured Finesse of resonator is more than 4000. Optical cavity has enhancement factor of 1900. Inside ATF damping ring, electron beam has very small size of 10 μm in vertical direction. To measure electron beam profile, very thin laser beam size is needed. Laser waist size, around 6 μm in sagittal plane is achieved in between two concave mirrors. Special type of mirror alignment scheme is used to make a compact four mirror optical cavity. Laser resonator is designed to work in vacuum environment with a complex mirror holder design .We report the performance studies of such four mirror resonator using 532 nm CW laser oscillator in this research.

1. Introduction

Production and handling of low emittance beam is important technology for linear colliders. For this damping ring generates low emittance beam by radiation damping process. The Accelerator Test Facility (ATF) in KEK is a test accelerator to examine the technical possibility in generating the low-emittance beam required for linear colliders. The damping ring has two arc sections and two straight sections [1]. In the damping ring at ATF, vertical beam size is less than 10 μm. For emittance measurement, we are developing a new type of beam profile monitor which works on the principle of Compton scattering between electron and laser light. A thin and intense laser beam is produced by exciting a Fabry-Perot optical cavity and it is scanned across the electron beam in perpendicular direction as shown in Figure 1.

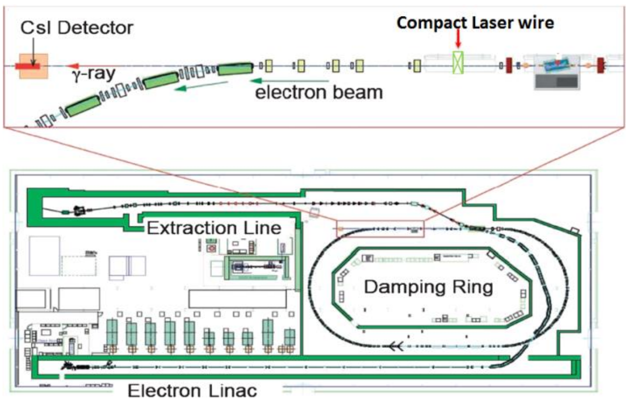

Figure 1: KEK-ATF Damping Ring

When electron beam crosses the laser, some of the electrons interact with laser light and emit energetic photons in the forward direction via the Compton scattering process. A detector placed downstream of the collision point measures the flux of the scattered photons. By scanning the position of laser beam and counting the number of scattered photons, a projected beam size is obtained. Such type of optical resonator system is called laser wire. Laser wire is one of such a technique to measure a small electron beam size. In particular, if both electron and laser beam are assumed to have Gaussian profiles with width σ_e and σ_{lw} , the observed profile is also gaussian with width σ_{obs} expressed by

$$\sigma_{\mathrm{obs}}^2 = \sigma_{\mathrm{lw}}^2 + \sigma_{\mathrm{e}}^2 \qquad (1)$$

We used a four mirror Fabry-Perot optical cavity to produce laser wire. It enhances the effective laser power and improves the intensity of the signal. The geometrical properties of laser beam are completely defined by boundary conditions formed with two concave mirrors and two plane mirrors [2, 3]. The minimum beam waist is obtained in between two concave mirrors. The two concave mirrors of same curvature are used in compact resonator. Electron beam interacts with laser pulse at minimum beam waist position, which is called interaction point (IP).

Aspect ratio of resonator is important parameter to achieve small beam waist. Aspect ratio of resonator is defined as ratio of side by side plane and concave mirror distance (d) to distance between two concave mirrors (L). The Aspect ratio α for four mirror optical resonator is given as [2]

$$\alpha = \tan^{-1} d/L. \qquad (2)$$

To achieve very small minimum beam waist, aspect ratio of cavity is kept constant and cavity length is reduced.

2. Design of compact resonator

2.1 Design values and mirror alignment scheme

The optical cavity assembly consists of four mirrors, mirror holder system and cyilindrical spacers which define length of cavity. In order to have precision control over cavity length , both plane mirror holders were supported by a piezo actuator through a disk type plate spring. Hollow piezo actuators are used for laser beam to pass through them [4]. Four mirror optical cavity is designed for 532 nm wavlength. Distance between concave-concave mirror is kept at 102.8 mm and distance between plane-plane mirror is kept at 103.2 mm. A complex mirror alignment scheme as hown in Figure 2 is used to keep side by side distance between plane and concave mirror to 29.2 mm. All mirrors used in cavity design are of 1 inch diameter. The radius of curvature for two concave mirror is 101.81 mm.

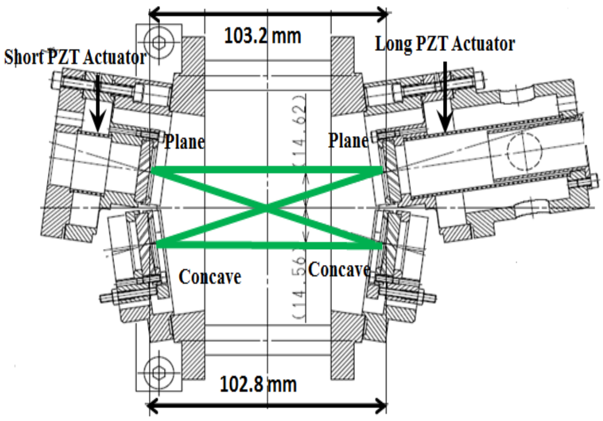

Figure 2. Cavity assemply and its mounting.

Figure 3 shows beam waist variation with radius of curvature of concave mirror. Horizontal axis indicates radius of curvature of concave mirror in mm and vertical axis shows beam size in mm. To get the minimum beam size in one plane i.e. sagittal plane in this case, we choose values of curvature of cavity mirrors close to the length of resonator. In order to obtain minium beam waist in this configuration we keep optical cavity at marginally stable condition and choose value of mirror curvature very close to distance between two concave mirrors. We choose the mirror curvature value as 101.81 mm.

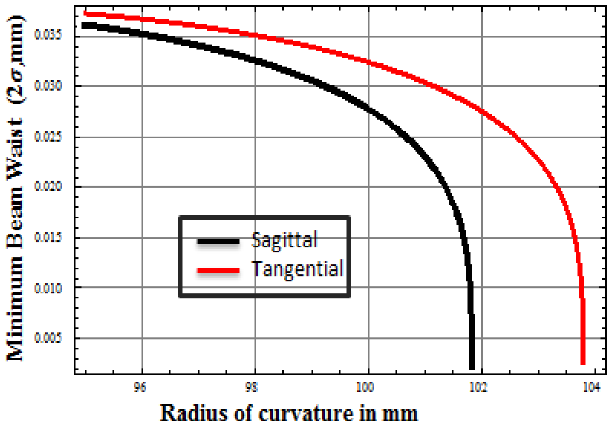

Figure 3: Beam waist variation with mirror curvature

2.2 Beam Evolution inside resonator

Figure 4 shows the evolution of beam size in both sagittal and tangential plane along longitudinal distance inside four mirror resonator. The beam size is squeezed in between concave mirrors. Large value of beam waist is obtained at the interface of concave mirrors. Smaller beam size in between two concave mirrors depends on the divergence of beam inside resonator. If beam waist at the interface of concave mirror is large then we get smaller value of beam waist in between two concave mirrors. The beam size is almost constant in both planes while prapogating through free space region formed among concave-plane-plane-concave mirrors. Beam size at the surface of concave mirrors and plane mirrors are greater than 1.2 mm in sagittal plane , and greater than 0.3 mm in tangential plane.

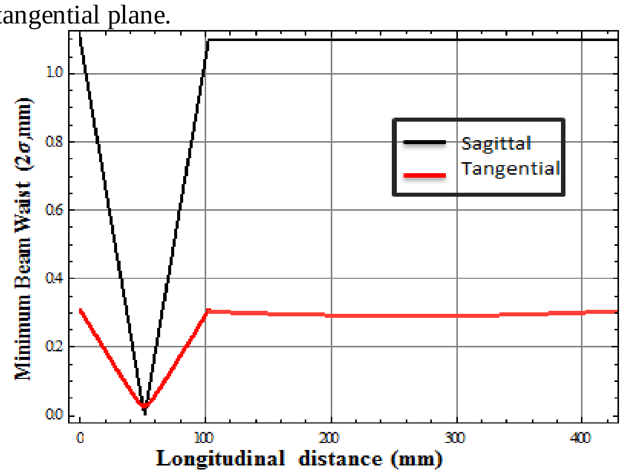

Figure 4: Beam evolution inside four mirror optical cavity

2.3 System Setup

We utilized a diode-pumped solid state laser with wavelength of λ=532 nm (Light-Wave Series 142). This laser employs the Non-Planer Ring–Oscillator (NPRO) technique to realize ultra-low line width (10kHz/msec). Its output power is 300mW. Two type of lens system is used to make the laser beam match to the TEM_{00} mode of the cavity. Spherical lens system consists of two spherical lenses is used to make laser beam divergence free and well collimated. Another lens system consists of cylindrical lenses is placed to make ratio of sagittal beam size to tangential beam size equal to 3.Thus we can obtain good coupling efficiency from laser output and matching section. The measured coupling efficiency for this setup is measured as 35 %. Photo-diodes are used to monitor transmitted light intensity. To observe the excitation of various modes of the cavity, the cavity length was swept repeatedly by the piezo actuator. The piezo actuator is driven by a sinusoidal wave through a high voltage amplifier. In order to reduce some higher order modes, matching lens section is tuned. Figure 5 shows diagram of system setup.

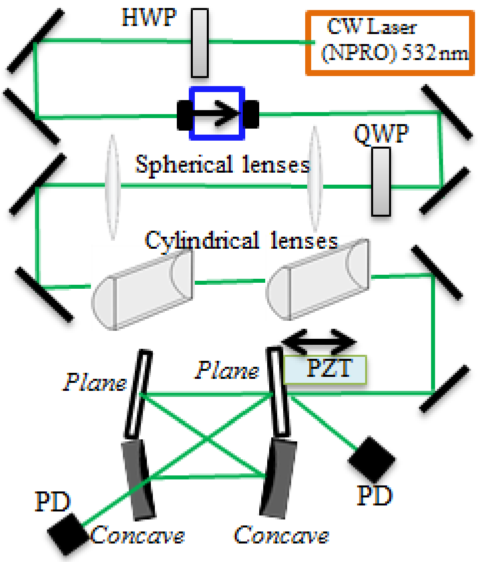

Figure 5: Total system setup

3. Parameters of Four Mirror Resonator

3.1 Finesse

Sharpness of the resonance width is represented by the cavity finesse (*F*), it is defined from the reflectance of the four mirrors of optical cavity as [5, 8]

$$F = \frac{\pi R_{eff}}{1-R_{eff}^2} \qquad (3)$$

, where R_{eff} is effective reflectivity of resonator defined by

$$R_{eff} = \sqrt[4]{R_1 R_2 R_3 R_4} \qquad (4).$$

Design reflectivity (R_1 and R_2) of plane mirrors are 99.9% and 99.99%. Reflectivities of both concave mirrors (R3 and R4) are 99.99 %. Total Finesse (F) of compact resonator is given by [2]

$$F = \pi \frac{\sqrt[4]{R_1 R_2 R_3 R_4}}{1-\sqrt{R_1 R_2 R_3 R_4}} \qquad (5)$$

Theoretical finesse of resonator is 4831.3

Finesse is measured experimentally by finding the ratio of Free Spectral range (FSR) to width of resonance at half maximum ($\delta\theta$) of Airy function. FSR is distance between peaks of two consecutive 0^{th} order modes

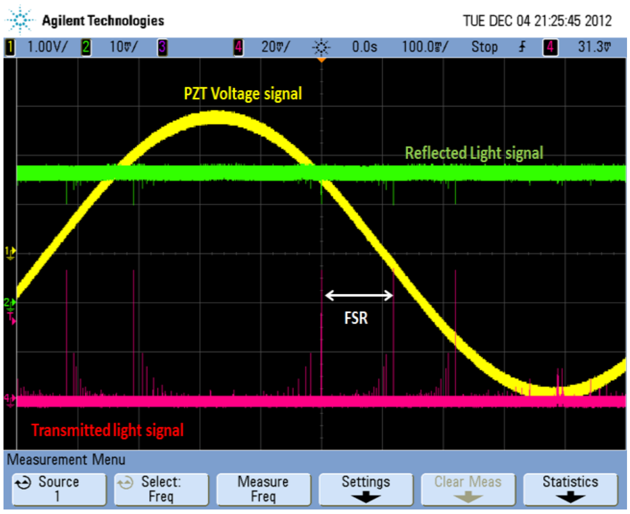

Figure 6: Transmitted laser signal

In Figure 6, the yellow waveform shows the voltage of piezo actuator, which means cavity length expansion. The red wave form shows the signal from photo diode detecting the cavity transmitted laser power.

$$\text{Experimental Finesse} = FSR/\delta\theta \qquad (6)$$

Experimental Finesse is obtained as 4126.6 ± 230 and Enhancement Factor (S_{cav}) is calculated as 1900

3.2 Waist Measurement by Transverse Mode Difference

The Guoy phase is defined by the order of the transverse mode (m+n) and the beam waist (ω_0) [10, 11]. The distance between two modes of one-order difference is defined by beam waist. When cavity length was swept while monitoring the resonation by the cavity transmission intensity, some peaks of the resonances were observed. Each resonance peak corresponds to some order of modes. There are two 1^{st} order modes representing two values of Guoy phase corresponding to sagittal and tangential plane. In order to calculate minimum beam waist of resonator based on mode difference method, distance between plane–plane and concave–concave mirrors are changed while keeping the total length of pulsed resonator constant.
Guoy phase can also be represented by ray transfer matrix of resonator for one round trip. Eigen values of a non-degenerate matrix are complex [12] and are given by

$$m_1 = m_2^* = e^{i\varphi} \qquad (7)$$

$$e^{\pm i\varphi} = \frac{A+D\pm\sqrt{(A+D)^2-4}}{2} \qquad (8)$$

Where phase angle φ is round trip Guoy phase of resonator. Figure 7 shows the theoretical variation of Guoy phase in sagittal and tangential plane with mirror separation. Since the dimensions of laser resonator are fixed, we measured the Guoy phase value at minimum beam waist position and calculated the corresponding waist size.

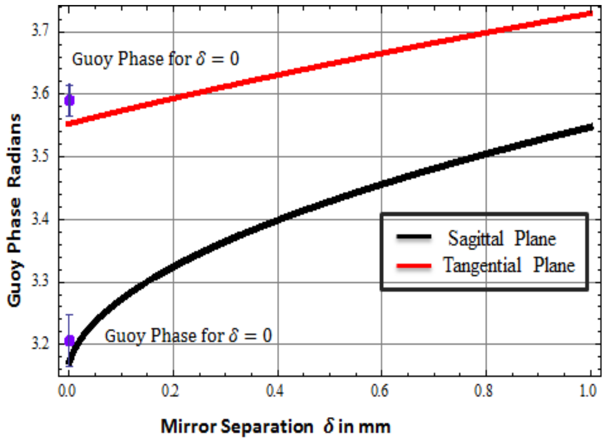

Figure 7: Variation of Guoy phase with mirror sepration

Minimum beam waist measured using transverse mode difference method in sagittal plane (σ_s) is 5.9± 1.5 μm and in tangential plane (σ_T) is 16.02 ± 2.5μm.

3.2 Waist Measurement by Divergence Method:

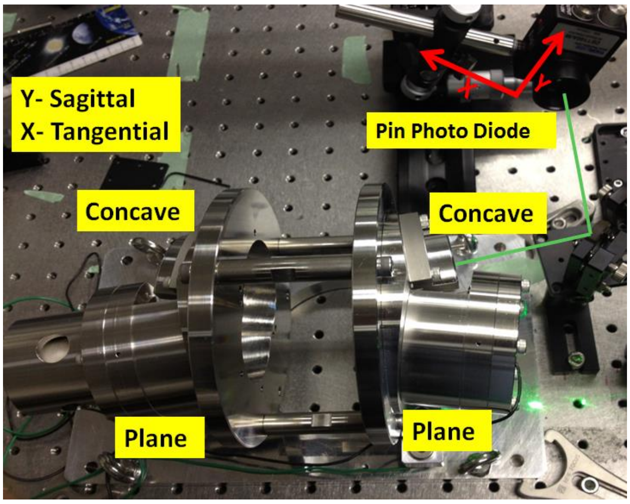

Figure 8: Minimum beam waist measurement using divergence method

The output laser profile is measured as an extension of the cavity resonating mode, so the waist size of laser beam inside optical cavity can be determined by measuring the output profile by scanning the pin hole photo diode, both in horizontal plane and vertical plane as shown in Figure 8. The output laser size at the distance z from the focal point is represented by $\omega(z) = \omega_0\sqrt{1+(z/z_0)^2}$, where z_0 is the Rayleigh length. In the case of $z \gg z_0$, the divergence angle θ_0 can be approximated as [7]:

$$\theta_0 = \omega(z)/z = \lambda/\pi\omega_0 \qquad (9)$$

The minimum beam waist measured using divergence method in sagittal plane (σ_s) is 6.9 ± 1 μm and in tangential plane (σ_T) is 20.14 ± 2 μm.

4. Analysis

Following Table 1 describes various parameters for compact four mirror laser resonator.

Table 1: Parameters for four mirror resonator

Parameter	Value
Length	103.2 mm
Side by side distance	29.2 mm
Finesse	4126.6±230
Enhancement Factor	1900
Min. beam waist (σ_s , σ_T)	6.9± 1 μm , 20.14 ± 2 μm.

We test the optical cavity using CW green laser and find that very high finesse can be achieved with very small beam waist in vertical direction. The results of beam waist measurement using Guoy phase difference method and divergence method are comparable. It is found that minimum beam waist of compact resonator has very high sensitivity towards any change in cavity length. Four mirror resonator has less sensitivity for misalignment compared to two mirror resonator. We carefully select length and mirror curvature parameters, so that beam waist around 6 μm can be achieved.

5. Conclusion

Compact four mirror laser wire system will make use of pulsed green laser to scan electron beam profile inside damping ring. Electron beam can be measured in vertical, horizontal and longitudinal direction in very short time as compare to CW laser wire system [13]. The laser cavity already is tested with 714 MHz IR mode locked laser oscillator. With IR pulsed laser oscillator, minimum beam waist of 12 μm is measured [2]. Thus same optical cavity design gives around 6 μm minimum beam waist using CW green laser oscillator. We developed a system, which amplifies laser pulse of 714 MHz IR laser oscillator with Yb doped photonic crystal fiber to high value. After amplification of pulsed IR laser, a non-linear crystal is used for 2^{nd} harmonics generation. Thus we can obtain pulsed green laser which has 714 M Hz repetition rate. This pulsed green laser can provide effective photon and electron collision. High Finesse and small beam size are most important characteristics of compact four mirror resonator.

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