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Design studies on compact four mirror laser resonator with mode-locked pulsed laser for 5 μm laser wire

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ABSTRACT

A compact prototype four-mirror optical cavity is being constructed at KEK-ATF to measure low-emittance electron beams in the damping ring. Four-mirror-resonators reduce the sensitivity to the misalignment of mirrors in comparison to two mirror-resonators. The aspect ratio is important when constructing a compact resonator with a very small beam waist of less than 5 μm. The total cavity length of a four-mirror resonator is matched according to the pulse repetition of mode-locked laser oscillator. Minimum beam waist is obtained in the sagittal plane using an IR pulsed laser. The advantage of such types of compact four-mirror-resonators is the total scanning time for measurement of the beam profile is much shorter in comparison to a CW laser wire system. By using a pulsed green laser that has been converted to the second harmonics from an IR pulsed laser, a minimum beam waist that has half the beam waist when using an IR laser oscillator can be obtained. Therefore, it is possible to obtain the beam waist of less than 5 μm (σ value) that is required for effective photon–electron collision. We report on the development and performance studies for such types of compact four-mirror laser wire systems.

1. Introduction

Laser-Compton scattering has become an important technique for beam diagnostics in the latest accelerators. In order to develop technologies for low-emittance beams, an Accelerator Test facility (ATF) was built at KEK [1]. It consists of an electron linac, a damping ring in which beam emittance is reduced and an extraction line. For emittance measurement we are developing a new type of beam profile monitor that works on the principle of Compton scattering between electron and laser light. In order to achieve effective collision of photons and electrons, a very thin size laser is required. Such an optical resonator system is called a laser wire. The laser wire is one technique for measuring small beam size. Using a pulsed compact laser wire, we can measure a 5 μm electron beam in the vertical direction. If we keep the distance ratio of concave–concave and plane–plane mirrors constant, a compact four-mirror cavity with thin waist size can be made. A four-mirror resonator consists of two plane mirrors and two concave mirrors. The boundary condition is introduced by forming a rectangular structure in which two concave mirrors and two plane mirrors face each other [2] as shown in Fig. 1.

The aspect ratio of the resonator is the ratio of the length of resonator, i.e. distance between concave–concave mirror to the distance between the adjacent plane and concave mirror. The aspect ratio is a geometrical property of the resonator. It depends on the position vector of each mirror. Therefore we can also define this ratio as being the cavity angle α of the resonator or

$$\alpha = \tan^{-1}(d/L) \tag{1}$$

The beam waist inside a four-mirror resonator is dependent on many parameters. Selection of the aspect ratio is quite important as it is a function of the two parameters L and d. The repetition rate of the electron bunch inside the ATF damping ring is 357 MHz. For an effective collision between an electron and photon, the four-mirror optical cavity's dimensions must be chosen according to the electron bunch repetition rate [3]. Table 1 shows the variation of the minimum beam waist for the same aspect ratio in the case of an infrared (1064 nm) laser oscillator ω_s and ω_T are the minimum beam waists in the sagittal plane and tangential plane.

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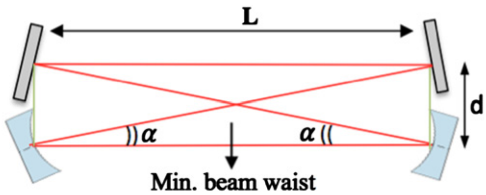

Fig. 1. Four-mirror resonator model.

Table 1
Four-mirror resonator's beam waist variation for constant value of aspect ratio.

Length L (mm)	412	206	103
Distance d (mm)	116	58	29
Curvature ρ (mm)	408	204	102
Total path length (L_{cav}) (mm)	1680	840	420
Aspect ratio (α) (radians)	0.2745	0.2745	0.2745
Min. beam waist in 2σ, (ω_S, ω_T) (μm)	(29.3, 80)	(21, 57)	(14, 40)

From Table 1 it is clear that if we keep the aspect ratio constant and keep reducing the length of the cavity, we can achieve a very small beam waist. The round-trip time in the cavity has to match the pulse repetition of the laser source. Hence, precise control of the absolute cavity length is important. In this case, the curvature of the cavity mirrors is the only parameter for controlling waist size. In order to realize a small waist size, mirrors of a specially designed curvature are needed. The beam waist is calculated by solving the one round trip ray transfer matrix for the beam inside the resonator. The resonator model can be visualized with an equivalent lens diagram, where the concave mirror functions as a convex lens and the plane mirror acts as the identity matrix as shown in Fig. 2.

The round trip ray transfer matrix [4] for a planar four-mirror resonator is given by

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & L/2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -2/\rho & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & L_2 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & L_3 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -2/\rho & 1 \end{pmatrix} \begin{pmatrix} 1 & L/2 \\ 0 & 1 \end{pmatrix} \quad (2)$$

where, the radius of curvature ρ is different for the sagittal and tangential plane [5,6].

$$\rho_s = \rho/\cos(\alpha/2) \quad (3a)$$

$$\rho_T = \rho\cos(\alpha/2) \quad (3b)$$

The distance between the mirrors and the curvature of the mirrors are the parameters for designing the waist size (ω_0) of the laser.

The minimum beam waist is given by [4]

$$\omega = \left(\frac{\lambda}{\pi}\right)^{1/2} \frac{(|B|)^{1/2}}{\left[1-[(D+A)/2]^2\right]^{1/4}} \quad (4)$$

where A, B and D are elements of the round trip ray transfer matrix (ABCD matrix) from the waist point.

In order to realize the small waist size, the cavity has to be designed to be close to the marginally stable configuration [4,6]. i.e.

$$4-(D+A)^2 > 0.$$

Note that the rms size (σ) of the photon distribution is related to ω_0 as $2\sigma = \omega_0$.

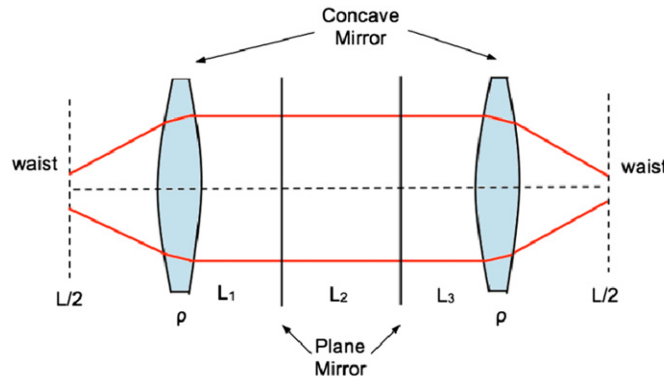

Fig. 2. Lens equivalent diagram.

2. Selection of resonator design values

2.1. Selection of L and d

Assuming a laser oscillation cavity length of L_{cav} and four-mirror optical cavity length to be L_{cav}, the pulsed repetition is the same as the repetition frequency of the laser. All of the frequencies in the mode-locked laser can be resonant in the optical cavity when the following condition [3] is satisfied:

$$L_{cav} = n\frac{\lambda}{2} \quad (5)$$

where λ is the wavelength of the laser and n is a positive integer. For a mode-locked pulsed laser, the spectrum has discrete Fourier components with the separation $\approx \lambda^2/2L_{laser}$ around λ. Therefore, an additional condition for the optical resonant cavity length is required in order for all Fourier components of the laser pulse to be in resonance. The condition is expressed as

$$\mathrm{m}L_{cav} = L_{laser} \quad (\mathrm{m}: \text{ integer}) \quad (6)$$

To achieve minimum beam size we have to choose the length of resonator "L" to be close to the cavity mirror curvature. In order to match the resonating frequency of the optical cavity, we need to keep the total path length of the cavity in accordance with the length of oscillation cavity. The pulse repetition rate of our laser system is f_{laser}=714 MHz. We keep the total length of the four-mirror resonator=420 mm. A mode-locked pulse laser consists of an array of superposed waves with a broad frequency spectrum that provides short- pulse lasers. Therefore, when we stack the pulsed laser inside the optical cavity the proper selection of the side by side mirror distance "d" is very important. We keep L=103 mm. Fig. 3 below shows the variation in beam size with the side by side distance "d".

The sagittal beam size tends to reduce with d, but the tangential beam size is almost constant. The distance d is measured from the center of both sides by side mirrors. Mirrors used in this setup are of 1 in. diameter. The minimum beam size is obtained for d=29 mm, which leaves a very small gap between the edges of the mirrors. A special type of mirror alignment scheme is needed to fix this parameter.

2.2. Fixing curvature of mirror

Fig. 4 shows the beam waist variation with the radius of curvature of the concave mirror. The horizontal axis indicates the radius of curvature of the concave mirror in millimeters. The vertical axis shows the beam size in millimeters. To get the minimum beam size in one plane, i.e. sagittal plane in this case,