DEVELOPMENT OF FOUR MIRROR PULSED LASER WIRE SYSTEM

Arpit Rawankar[1], Hirotaka Shimizu[2], Junji Urakawa[2], Yosuke Honda[2], Masafumi Fukuda[2], Alexander Aryshev[2], Yan You[3], Tomoya Akagi[4] , Kazuyuki Sakaue[5], Sakae Araki[2], Nobuhiro Terunuma[2]

[1]The Graduate University for Advanced Studies, Hayama, Japan
[2]KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[3]Tsinghua University, Beijing, China
[4]Hiroshima University, Hiroshima, Japan, [5]Waseda University, Tokyo, Japan

Abstract

We are developing a four mirror Laser Wire beam profile monitor at KEK-ATF to measure a low-emittance electron beam in the damping ring. At present, CW Laser Wire has been used to measure the small emittance beam. If we replace it to pulsed laser wire, more efficient laser-beam collision can be realized. Four mirror resonator reduces the sensitivity to the misalignment of mirrors comparing to two mirror resonator. The aim of this project is to make a compact and stable pulsed laser wire system which achieves beam size less than σ =5μ m in tangential plane. We report the development and performance studies of such type of compact four mirror laser wire system in this paper.

1. Introduction

Laser-Compton scattering has become an important technique for beam diagnostics of the latest accelerators. Laser wire is one of such a technique to measure a small beam size. Using a pulsed compact laser wire, we can measure 5μ m electron beam in vertical direction. If we keep the distance ratio of concave-concave and plane-plane mirrors constant, the compact four mirror cavity with thin waist size can be made.

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 are facing each other as shown in Figure 1(a). The round-trip time of the cavity has to match with 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 to control waist size. In order to realize a small spot size, mirrors of specially designed curvature are needed [1] .

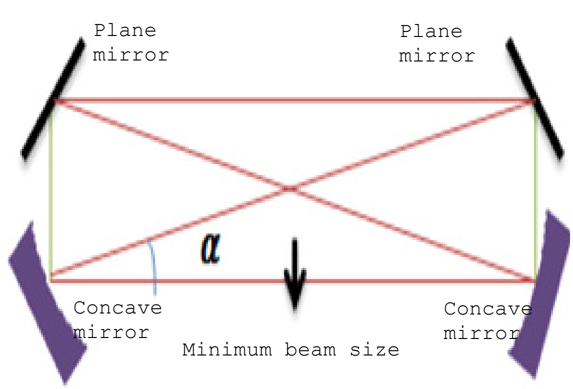

Figure 1(a): Four mirror resonator model

Beam waist is calculated by solving the one round trip ray transfer matrix for beam inside resonator. The Resonator model can be visualized with equivalent lens diagram, where concave mirror functions as a convex lens and plane mirror acts as identity matrix as shown in Figure 1(b). The round trip ray transfer matrix for a planar four mirror resonator is given by

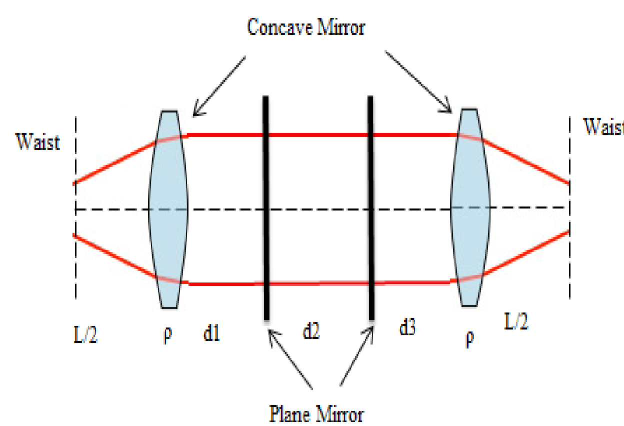

Figure 1(b): Lens equivalent diagram

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & \frac{L}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{\rho} & 1 \end{pmatrix} \begin{pmatrix} 1 & d1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & d2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & d3 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{\rho} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{L}{2} \\ 0 & 1 \end{pmatrix}$$

Where, radius of curvature ρ is different for sagittal and tangential plane.

$$\rho_s = \rho / \cos(\tfrac{\alpha}{2}) \quad (1).$$

$$\rho_T = \rho \ \cos(\tfrac{\alpha}{2}) \quad (2).$$

arpit@post.kek.jp

Distance between the mirrors and curvature of the mirrors are the parameters to design the waist size (w_0) of laser.

The minimum beam waist is given by

$$\omega = \left(\frac{\lambda}{\pi}\right)^{1/2} \frac{(|B|)^{1/2}}{[1-[(D+A)/2]^2]^{1/4}} \qquad (3).$$

In order to realize the small waist size, the cavity has to be designed close to the unstable configuration .i.e.

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

Or $$-2<(D+A)<2$$

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

2. Selection of Resonator design Values

2.1 Fixing curvature of mirror

The Figure 2.1 (a) below shows beam size variation with radius of curvature of concave mirror.The horizontal axis indicates radius of curvature of concave mirror in mm. The vertical axis shows beam size in mm.The beam size on tangential plane is shown with blue line and beam size on sagittal plane is shown with red line. There are two regions of obtaining beam size. The region which shows very large beam size at higher values of radius of curvature is neglected [2].

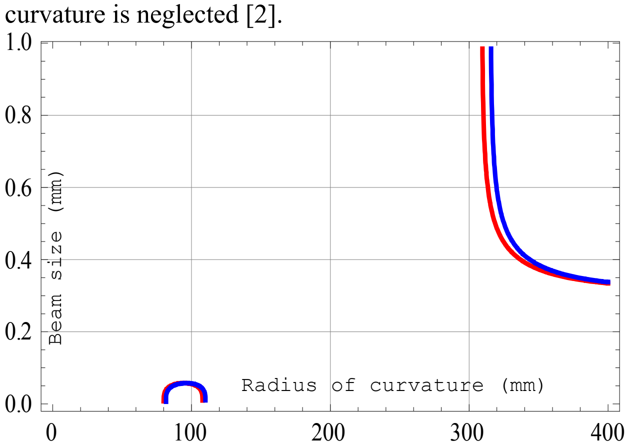

Figure 2.1(a): Variation of beam size with curvature of concave mirror

Figure 2.1(b) is magnification of Figure 2.1(a) for beam size on tangential plane. It shows the squeezed beam waist on tangential plane at radius of curvature>105mm. The minimum beam size obtained is **44.2 μm** at **105.4 mm.**

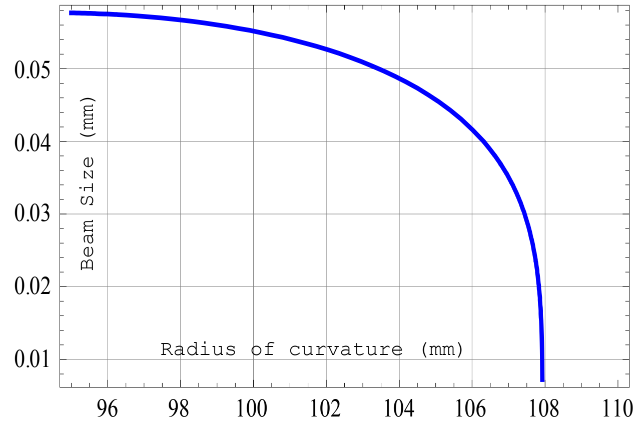

Figure 2.1(b): Magnified beam waist in tangential plane

2.2 Beam Evolution inside resonator

The Figure 2.2 shows the relationship between longitudinal distance and beam size variation inside the four mirror resonator. The horizontal axis shows longitudinal distance in mm inside four mirror resonator.The vertical axis shows beam size in mm.The beam size is squeezed in between concave mirrors. The beam size is expanded at the surface of concave mirrors and beam evolution is almost flat and parallel while passing through plane mirrors. Beam sizes at the surface of concave mirrors and plane mirrors are greater than 400μm, but chances of any diffraction around the edges of mirror is not possible as mirrors of diameter 1inch are used. Minimum beam size in tangential plane is calculated as **44.2μm** and in sagittal plane is calculated as **50.2μm**.

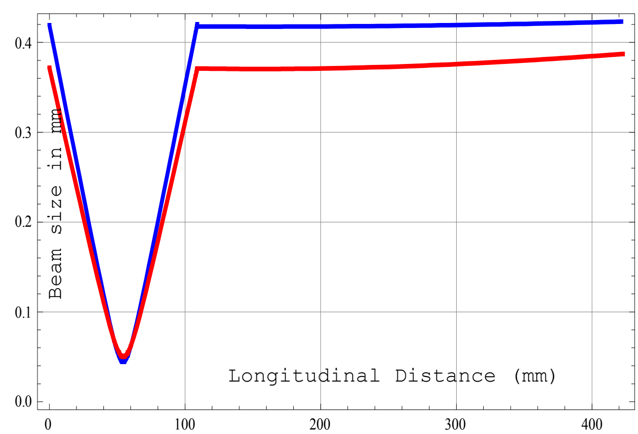

Figure 2.2: Beam evolution of compact resonator

3. Experimental setup

3.1 Optical components of system

The experimental setup is shown in Figure 3.1. Pulsed Laser output from laser oscillator passes through half wave plate which retards one polarization by half a wavelength or 180 degrees. This type of wave plate changes the polarization direction of linear polarized light. Optical isolator protects the laser oscillator from any back reflection from the mirrors. The laser beam passes through the lens system which consists of a pair of concave and convex lens. Thus, it reduces the spread of laser beam and also provides the parallel beam .A parallel beam must be obtained for injection into one of the plane mirror of four mirror resonator. A piezo actuator is attached to concave mirror for length scanning.

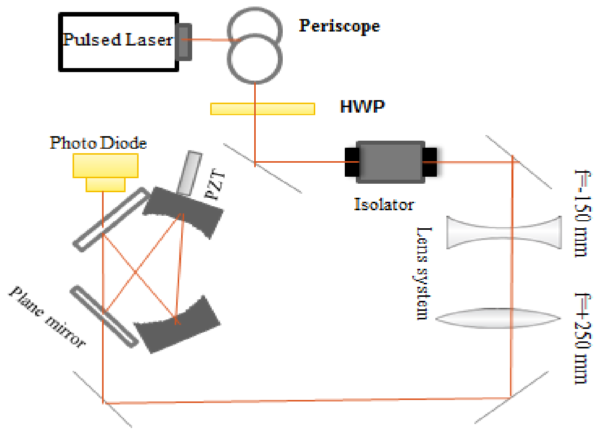

Figure 3.1: Resonator setup

The distance between adjacent concave mirror and plane mirror is reduced by using aluminum spacers. These spacers provide the facility to keep all the mirrors and 45 degree angle, thus reducing the gap between plane and concave mirror to much extent. Such type of structure is shown in Figure 3.2

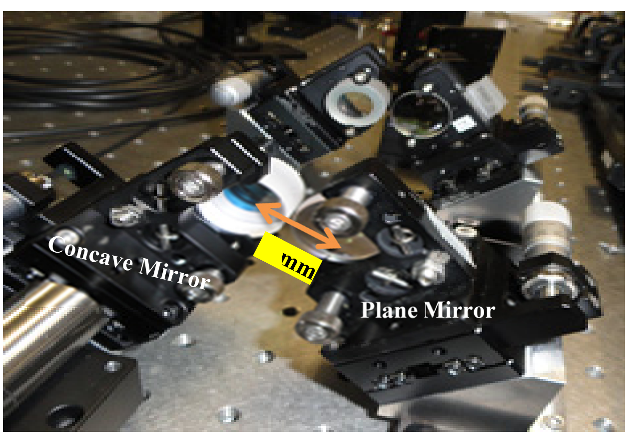

Figure 3.2: Mirror holders on aluminum spacers

The Mode locked laser oscillator used for the experimental setup shown in Figure 3.3 has repetition rate of 714 MHz. The wavelength of IR laser diode is 1064 nm. The Parameters of such oscillator is shown in Table1.

Table 1: Mode Locked Laser Oscillator Parameters

Parameter	Value
Operating Current	2.28 A
Output Power	559 mW
Wavelength	1064 nm (IR Laser)
Repetition rate (f_p)	714.084 MHz

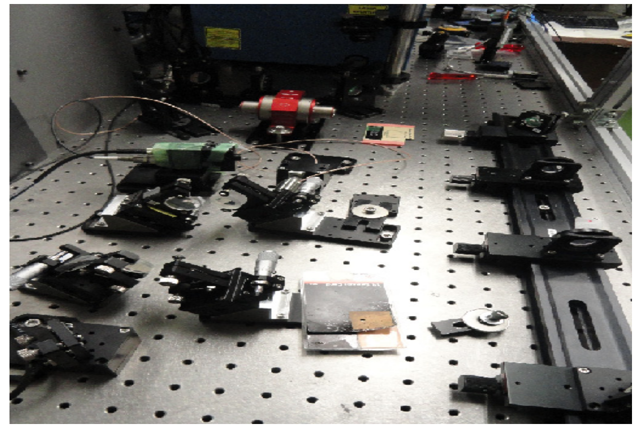

Figure 3.3: Mode Locked Laser and system setup.

The repetition rate of mode locked laser must match to total path length inside resonator. The total path length of 109 mm resonator in our setup is 420 mm. Table 2 shows the values of resonator parameter used in our present setup. The distance between adjacent plane and concave mirror is 32 mm as shown in Figure 3.2.

Table 2: Test Compact Resonator Parameters

Length (L)	109 mm
d	32 mm
Aspect Ratio($\alpha/2$)	0.1464 rad
Radius of Curvature	105.416 mm
Beam size(2σ)	(44.2, 50.2) μm
Finesse	240
wavelength	1064 nm (IR Laser)

4. Measurement of Finesse and Gouy Phase of Resonator

4.1 Finesse

Another important role of the cavity is to enhance the effective laser power. Laser beam from a laser oscillator is injected to the cavity through one of the plane mirrors. The laser wave inside the cavity reflects back and forth and builds up the effective power. The power enhancement realizes only when the cavity satisfies the resonance condition of a standing wave. Sharpness of the resonance width is represented by the cavity finesse (F), it is defined from the reflectance of the four cavity mirrors as

$$F = \frac{\pi R}{1-R^2} \quad (4).$$

Where R is reflectivity of each mirror. In our compact resonator design reflectivity (R1) of plane mirrors is 99% and reflectivity (R2) of concave mirrors is 99.7 %. So total Finesse of compact resonator is calculated by replacing R by $\sqrt{R1R2}$ in equation (4) total finesse of compact resonator is given by [2]

$$F = \pi \frac{\sqrt{R1.R2}}{1-R1.R2} \quad (5).$$

Calculated Finesse= **240.6**

Finesse is measured experimentally by finding the ratio of Free Spectral range (FSR) to full width half maximum bandwidth of Airy function. FSR is distance between peaks of two consecutive 0^{th} mode as shown in Figure 4.1.

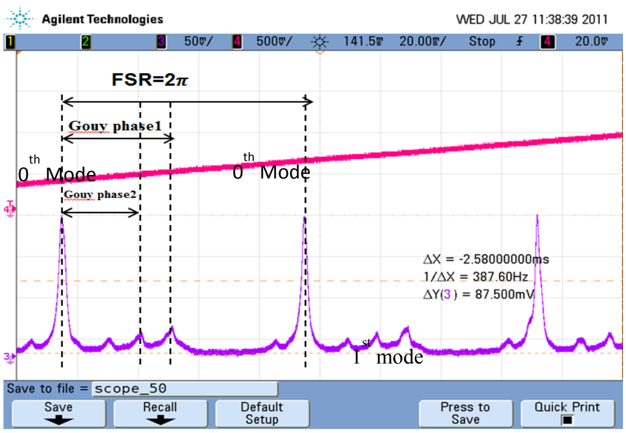

Figure 4.1: FSR and Gouy Phase observation

$$\text{Experimental Finesse} = \frac{FSR}{BW(FWHM)} = \mathbf{240 \mp 10}$$

4.2 Gouy Phase and Evaluated Beam waist

Along its propagation direction, a Gaussian beam acquires a phase shift which differs from that of a plane wave with same optical frequency. This difference is called Gouy phase shift. Overall Gouy phase shift of Gaussian beam going through a focus is π.

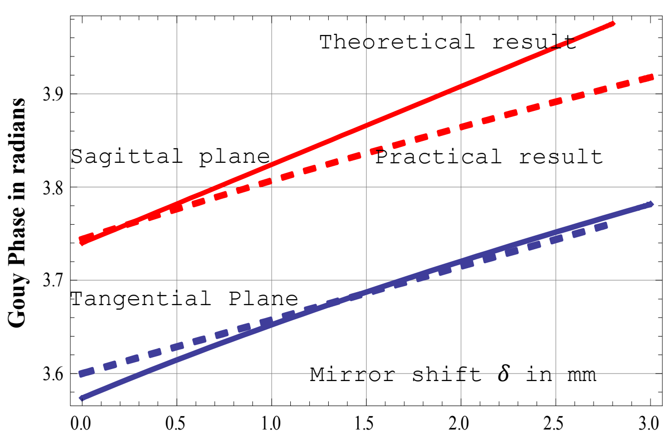

Figure 4.2: Gouy phase variation with mirror shift

The FSR of transmitted light corresponds to total phase shift of 2π. FSR is the time interval between consecutive 0^{th} order mode. The 1^{st} order mode has two peaks which gives 1^{st} Gouy phase and 2^{nd} Gouy phase as shown in Figure 4.1. Gouy phase can be helpful in determining beam size of resonator. If the mirrors of resonator are shifted by distance δ mm, such that distance between concave-concave mirrors increased by δ and distance between plane-plane mirrors are reduced by δ. Then Gouy phase corresponding to δ=0 value gives minimum beam size of four mirror resonator in sagittal and tangential plane [2] Gouy phase in sagittal and tangential plane as a function of mirror shift δ is shown in Figure 4.2. The horizontal axis shows mirror shift δ in mm and vertical axis shows Gouy phase 1 and Gouy phase 2 in radians. By Observing Gouy phase values we obtained minimum beam sizes in tangential plane and sagittal plane are **44.2∓1.1 μm** and **50.2∓3 μm.**

5. Scheme for obtaining 5μm beam size

In four mirror resonator, angle α as shown in Figure 1(a) is defined as angle between line joining the center of concave mirrors to diagonally opposite plane mirror.

$$\alpha = \tan^{-1}\frac{d}{L}. \quad (6).$$

Angle $\alpha/2$ points the position vector of concave mirror to mid-point of diagonally opposite plane and concave mirror. Keeping value of Aspect ratio $\alpha/2$ fixed to theoretical design values, we can obtain minimum beam waist less than 5μm for such a compact four mirror resonator. In order to obtain beam size less than 5μm, green laser oscillator of wavelength 532nm to be used. If we reduce the distance between adjacent plane mirror and concave mirror to 26.54 mm and by selecting suitable mirror curvature of 104.2 mm, we can reduce the beam size in tangential plane. Table 3 shows the parameter values need to be designed to achieve minimum beam size of 5μm in one of the plane.

Table 3: Ideal parameters for achieving 5 μm beam size

Length(L)	105 mm
d	26.54 mm
Aspect Ratio(α/2)	0.12378 rad (Fixed)
Radius of Curvature	104.2 mm
Beam size(2σ)	(9.94, 27.2) μm
Wavelength	532 nm (Green Laser)

6. Summary

Experimental results show that a compact four mirror pulsed laser wire system can be made with **5μm** desired beam size. Using green laser oscillator (λ=532nm), If we can select proper combination of length L and distance d then beam size can be reduced in one of the plane. Our purpose is to design a compact pulsed laser wire system with minimum beam size. To make pulsed laser wire system with minimum beam size, design of pulsed green laser oscillator (λ=532nm) is necessary. The mirror holders used in our present setup are not designed for the component in vacuum, so special mirror holder designed for the component in vacuum is necessary for ATF Laser wire system.

References

[1] Y.Honda *et al*, "Upgraded laser wire beam profile monitor", Nucl.Instr.Meth. A. 538 100-115 (2005)
[2] S.Nagata, Master thesis submitted to Hiroshima University, (2010), in Japanese