Development of a 4-mirror optical cavity for an inverse Compton scattering experiment in the STF

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1. Introduction

An optical cavity is frequently used in ICS experiments to increase the laser intensity [1–6]. The optical cavity fully utilizes the laser property of coherency. If we can precisely control the position of the mirrors that form the cavity, the total length of the optical cavity can be adjusted to superpose the injected laser additively inside the cavity with the same phase. As a result, we can obtain a laser intensity gain of two or three orders of magnitude depending on the mirror reflectivity. This is known as laser accumulation technology.

A new concept for easing mirror alignment tolerance while maintaining a thin waist size is introduced into the design of the optical cavity. Instead of using a simple 2-mirror concentric-type cavity, two plane mirrors are added to construct a 4-mirror optical cavity, and the cavity shape is transformed from a straight-line shape to the so-called bow-tie-type ring cavity with crossing in the center. This property of the cavity structure allows us to construct a confocal-type cavity, and it improves the stability of the optical cavity by over 1000 times that of the concentric type cavity. This new type of optical cavity structure provides valuable flexibility in the design of an optical cavity, and it enables the achievement of head-on collisions, which is the most efficient collision style for ICS.

The “Development of the Next-Generation Compact High Brightness Photon Beam Source by Superconducting Acceleration” research sub-program of the Quantum Beam Technology Program (STF-QB) has been carried out at the Superconducting RF Test Facility (STF) accelerator at KEK. In this research, using the superconducting RF cavity acceleration system and mode-locked pulse laser accumulation technology, a compact high-brightness X-ray generator was developed. Infrared (IR) laser pulses emitted from a commercial laser oscillator (GE-100, Time-Bandwidth Products AG) were stacked into a newly designed 4-mirror optical cavity to amplify the laser intensity. Using those lasers and the 40 MeV electron beam provided by the accelerator, via the ICS process, we could obtain a quasi-monochromatic X-ray flux with approximately 30 keV in energy [7].

Increasing the signal X-ray, another new idea was introduced to the 4-mirror optical cavity. Instead of using the usual plane mirrors, slightly bent cylindrical mirrors were used to keep the laser profile at the focal point round. By using handmade cylindrical mirrors, it was possible to exclude the astigmatism effect, and obtain 3.5 times higher luminosity.

In this paper, we describe the details of the 4-mirror optical cavity design and construction for this ICS experiment.

2. Design of the 4-mirror optical cavity

In this section, the basic design of the 4-mirror optical cavity is described. Optical cavities used for ICS are normally installed in accelerators, so the designs of each are mutually intertwined. The available space for the ICS region is typically determined by the
design of the accelerator beam optics. For example, in the case of the STF-QB, the necessity of beam injection into, and its extraction from, the ICS region required two bending magnets spaced 441 mm apart. This size was determined by the sizes of the two bending magnets, and a beam monitor system (wire and screen monitors) for the electron beam focal point, which was located at the center between the two bending magnets. As a result, the distance between the two mirrors in the ICS region needed to be approximately 1000 mm.

Let us assume a target performance of the optical cavity that achieves a 20-μm laser size in 1-σ at the waist position. According to these requirements, we evaluate the tolerance of the mechanical alignment, comparing a 2-mirror optical cavity of this waist size with the 4-mirror optical cavity using the extended ABCD-matrix model [8]. If a mode-locked laser is used with a 162.5-MHz repetition rate, which corresponds to the eighth division of L-band RF frequency (1.3 GHz), the total length of the 2-mirror optical cavity would be fixed at 922.44 mm (round trip: 1844.88 mm) with two concave mirrors each having a 461.28-mm radius of curvature. 1.3 GHz is the accelerator frequency. If only one side of these mirrors has a 100-μm position misalignment, the position of the laser spot of the stationary stacked laser trajectory on another mirror surface will move more than 300 mm. To keep the orbit of the stacked laser close, the cavity mirrors must be larger than the displacements of the laser spots. This does not appear feasible to realize. In comparison, for the 4-mirror cavity case, if the concave mirrors are misaligned by the same amount as the 2-mirror cavity case, the matrix calculation shows that it is possible to achieve a displacement of the laser spot position within 200 μm. Using 1.5-in. mirrors is sufficient to cover the displacement of stationary laser trajectory. In conclusion, the mechanical alignment tolerance of the 4-mirror optical cavity has a stability of over a 1000-times. Owing to this good stability, the 4-mirror optical cavity was adopted for the STF-QB experiment.

To construct the 4-mirror optical cavity, there is a choice of two geometrical schemes to align the mirrors. One is the 3-D optical cavity, and another is the 2-D optical cavity. It is well known that the twisted-type 3-D optical cavity has the advantage of making it possible to adjust the laser profile at the waist point by using each degree of freedom to arrange the mirrors [9,10]. However, for our case, in the construction of a 1-m-long large optical cavity, the ease of mirror disposition is quite important. Therefore, the standard 2-D mirror geometry is employed.

In Fig. 1, a schematic view of the 4-mirror optical cavity is shown. The figure shows two flat mirrors, M1 and M2, and two concave mirrors, M3 and M4 aligned in a trapezoidal shape. For STF-QB, the upper base was set at 753 mm and the bottom base at 1060 mm, which corresponds to twice the required fundamental repetition rate of 162.5 MHz. This means that there are two laser pulses in the cavity. The laser injection was from M1 to M2. The laser circulates with a “bow-tie” trajectory inside the 4-mirror cavity. The waist point was formed at the center between the two concave mirrors (M3 and M4).

In this configuration, the enhancement factor “I” at the laser waist point can be calculated. It is represented as follows:

$$I = \frac{T_1 R_3 R_4}{(1 - \sqrt{R_1 R_3 R_4})^2}$$  \hspace{1cm} (1)

where $T_1$ is the intensity transmittance of injection mirror M1 and $R_1$, $R_3$, and $R_4$ are the intensity reflectivities of each mirror. The design value of $I$ was chosen to be 3000. In order to easily match the injection to the cavity, the transmittance of M1 was set to a relatively large value. Therefore, the reflection coefficient of mirror M1, represented as $R_1$, was set to 99.9%. The intensity reflectivities of the remaining mirrors were set to the same value, 99.995% or more. The intensity of reflected light from injection mirror M1, $I_0$, is as follows:

$$I_0 = \frac{(\sqrt{R_1} - \sqrt{R_2 R_3 R_4})^2}{(1 - \sqrt{R_1 R_2 R_3 R_4})^2}$$  \hspace{1cm} (2)

In this case, the design value of $I_0$ is approximately 0.5. To evaluate the quality of the optical cavity, finesse is frequently used. The finesse of the optical cavity $F$ is represented using the cavity’s round-trip optical amplitude loss “a”, as follows:

$$F = \frac{\pi \sqrt{a}}{1 - a}$$  \hspace{1cm} (3)

If all the optical loss results from mirror reflectivity, then the optical amplitude loss could be written as

$$a = \sqrt{R_1 R_2 R_3 R_4}$$  \hspace{1cm} (4)

for a 4-mirror optical cavity case. The final representation of the cavity finesse becomes

$$F = \frac{\pi \sqrt{R_1 R_2 R_3 R_4}}{1 - \sqrt{R_1 R_2 R_3 R_4}}$$  \hspace{1cm} (5)

Substituting in the above numbers, $F$ was estimated to be approximately 5500 for this case.

3. Application of the 4-mirror optical cavity in the STF accelerator

As described above, a 2-D 4-mirror optical cavity configuration was adopted for the ICS experimental device in the STF accelerator. In this configuration, it is well known that the laser profile inside the optical cavity becomes elliptic under the influence of astigmatism [11]. According to the cavity design, the waist sizes of the sagittal and tangential planes were 80 μm and 20 μm, respectively. At the interaction point (IP) of the STF accelerator, the size of the electron beam would be 10 μm in 1-σ of round shape. In this setup, even though the laser and the electron beam were properly overlapped, those two beams had different profiles. So the majority of the laser in the sagittal direction could not contribute to the collision with the electron beam. This kind of deterioration in luminosity is a typical disadvantage of the 2-D 4-mirror optical cavity. If it is possible to achieve a 20-μm laser profile in the sagittal plane as well, then the calculated X-ray yield becomes 3.5 times greater than that of the elliptical laser profile. A round laser profile at the IP is required for a point-like X-ray source for many imaging applications, and necessary to satisfy the desired yield for the program. Introducing cylindrical mirrors instead of plane mirrors solved this problem.

Using the extended thin lens model, the reason for the asymmetry between sagittal and tangential laser sizes can be understood as the effect of the different focal lengths of the concave mirror in the sagittal and tangential planes. To compensate for these effectively different focal lengths, auxiliary lenses are required. The simplest case involves introducing a focusing

Fig. 1. The basic arrangement of the 4-mirror optical cavity. Two flat mirrors (M1 and M2) and two concave mirrors (M3 and M4) were used.
lens system only into the sagittal plane side. This focusing system is achieved by using cylindrical mirrors bent in the vertical direction. In Fig. 2, the calculated evolution of the laser beam inside the optical cavity is shown. The left-hand-side plot shows the entire evolution, and the right-hand-side plot shows a magnification of the waist point. Both evolutions of sagittal and tangential profiles show good matching with each other. This means that an almost round shape for the laser profile can be obtained anywhere inside the cavity. The cylindrical mirror was designed with a curvature of $6.4 \times 10^4 \, \text{mm}$. This calculation shows that the waist size at the IP is reduced to approximately $20 \, \mu\text{m}$, which satisfies the target value of the program, STF-QB.

Compared to the 2-mirror optical cavities used in past experiments, the new design of the 4-mirror optical cavity had no solid body component between the mirrors. Every mirror was mounted on movable mirror holders driven by actuators to adjust the angle and position to maintain optical matching. Prototypes of these movable mirror holders were constructed and underwent laser staking tests to confirm their stability and performance. The 4-mirror optical cavity was then installed into the STF accelerator, as illustrated in Fig. 3. The optical cavity was mounted on a stiff granite table with a stainless-steel thick plate interface. Only the mirrors and their actuators were fixed on the plate and table. The accelerator components, such as the two bending magnets, the wire scanner at the IP, and the quadrupole magnets, were separately mounted on independent tables. The electron beam lines and optical beam lines were surrounded by stainless steel chambers and were each connected as a part of the accelerator.

The electron beam, entered from the lower left-hand side (the quadrupole magnet side), was focused at the center IP position where the screen profile monitor and the wire scanner monitor were located, and then exited from the lower right-hand side. The 4-mirrors were mounted on various actuators, as shown in Fig. 4. To maintain the very smooth actuator action required for nanometer movement, a bellows chamber was connected to both sides of the mirror holder. The other end of the bellows chamber was fixed to the support on the table to cancel out the effects of atmospheric pressure on the mirror movement. For cylindrical mirrors, an independent 5-axis control was made in five independent stages. For the concave mirrors, the mirror mount plate was supported by a tripod with three small stepping motors (DRV001, ThorLabs). This structure allowed us to control two angle-direction movements, and one longitudinal position movement, for a total of three degrees of freedom. The remaining two degrees of freedom, lateral and height motions, were controlled by linear stages.

4. Mirror development

One key technology for achieving the above advantageous properties of the optical cavity was to form a cylindrical-shaped mirror from a flat mirror. Fig. 5 shows a diagram of the developed prototype mirror bender, and a photograph of the actual device. Even when using a flat mirror in the mirror bender, we could modify its curvature as desired for the 4-mirror optical cavity application. In general, the shallower the required curvature,
the more difficult it is to achieve with fine precision by mirror polishing. However, instead of polishing, modifying the shape by bending it in small increments was successful, and the designed curvature value was finally attained. During bending and confirmation of the curvature, a Zygo interferometer was used. The measurement results for the attained cylindrical mirror surface are shown in Fig. 6. Using this transforming technique, the measured curvature was close to the designed curvature, where the designed peak-and-valley ratio was 0.78 μm over a distance of 20 mm.

5. Mirror actuator performance

The performances of the mirror actuators, linear stages, rotation stages, and goniometric stages were investigated under atmospheric and vacuum conditions. Among them, the angle adjustment function played a quite important role in cavity tuning. Examples of the excursion tests using a laser displacement sensor (LK-G30, KEYENCE) are shown in Fig. 7 for the rotation stages, and in Fig. 8 for the goniometric stages. The backlashes were estimated as 800 nm for the rotation stage, and 100–200 nm for the goniometric stage under both conditions. The backlashes of the linear stages were also estimated to be 100–200 nm. The backlash was not an issue for the 4-mirror resonance tuning, as the resonance tuning was always performed in the same direction, thus avoiding the backlash effect. The spreads of the linear response of the stages were around 200 nm, which was also not a significant value, since their variation was smooth and not jumping.

6. 4-mirror optical cavity drive laser system

A Time-Bandwidth GE-100 oscillator was used as the drive laser. The parameters of the drive laser are summarized in Table 1. The wavelength and output power of the drive laser depend on a pumping laser diode current, and also on the operating temperature. The intrinsic cavity length of the drive laser is also affected by room temperature. The values in Table 1 were measured and guaranteed around a 23°C temperature. In the accelerator tunnel, the temperature is maintained for accelerator operations around 22°C, so we can use the oscillator in an appropriate environment during the ICS experiments.

A block diagram of the drive laser system is shown in Fig. 9. The output of the drive laser is modulated by the EO modulator, and injected into a photonic crystal fiber (PCF) amplifier, a burst amplifier, and then the 4-mirror optical cavity. Each component is connected using an optical matching system. The output of the 4-mirror optical cavity is monitored by a photo-diode monitor.
The boxes enclosing the components with a broken line represent isolated optical tables. The PCF amplifier amplifies the drive laser output from 500 mW to 6 W. The burst amplifier works over 2 ms with a 5-Hz pulse mode. The amplification factor is 50.

The resulting input power for the 4-mirror optical cavity is 300 W.

7. Cavity resonance control

In order to maintain the 4-mirror optical cavity in resonance, an error signal of Pound–Drever–Hall (PDH) feedback [12] was employed, as shown in Fig. 10. The error signal was created by...
phase detection between the photo-diode output of reflected light with function generator signal modulation and the function generator signal itself. The error signal included information on the 4-mirror optical cavity resonance, and was fed back to the proportional-integral-derivative (PID) controller module, and to the oscillator. The modulation RF from the function generator was 5 MHz and was supplied to the EO modulator and to the phase detector, denoted as “mixer”, through a phase shifter. On the whole, only the proportional and integral functions were used in this system.

The sharp spike signal at the central position of the plot in Fig. 11 corresponds to a resonance state of the 00-mode inside the optical cavity. The upper line (triangle points with a dotted line) shows the error signal made using a deflected laser intensity signal, which was simultaneously measured together with the lower line (circle points with a solid line). It can be seen that the upper line crosses the 0 V line (see the right vertical axis) when the lower line achieves the peak intensity of the transmitted laser signal. By using this error signal, we could maintain the cavity length at an optimum with the maximum stacked laser intensity.

### 8. Improvement of mechanical stability

As the PDH feedback control was hard to maintain, a vibration of the mirrors was suspected. Since direct measurement of mirror vibration with high sensitivity was difficult, the mechanical vibrations of the accelerator floor and granite table were measured using a seismometer. Enhanced frequency components from the 10–100 Hz region were observed in both cases. These were expected to have an effect on the mirror stability. To prevent these mechanical vibration effects from incoherently affecting each mirror’s position, an additive support system was introduced, consisting of a 20-mm-thick stainless steel main plate, mirror holder arms, and a main plate support from the table. These are shown in solid lines in Figs. 12 and 13 (other parts are shaded).

The mirror holders were fixed by screw bolts and the micrometer head screws into the stainless steel main plate after adjustment of the mirrors. The positions of the four mirrors are inter-connected by the additive plate.

The improvement in stability of the 4-mirror optical cavity can be seen in the histogram of the stacked laser intensity, as shown in Fig. 14. Prior to installation of the additive support, the stacked laser intensity was concentrated below 0.5 kW. After the installation, it shifted to approximately 2.8 kW. An improvement by a factor of 5 was observed in the stacked laser intensity.

### 9. Performance of the 4-mirror optical cavity

The light monitors used to tune the 4-mirror optical cavity were as follows: for the transmitted light from the mirror M2, a photo-diode (PDA36A, Thorlabs) was used, and for the reflected light from the mirror M1 and the optical path confirmation monitors at several places on the line, Thorlabs PDA100A another type of photo-diode (PDA100, Thorlabs) were used. The output signals of the photo-diode were connected to the oscilloscope. Their traces are shown in Fig. 15. The transmitted light signal (green trace) and the reflected light signal (yellow trace) were used for the resonance tuning. When the tuning became optimum, the reflected signal intensity became small (this means that the yellow trace line shows a steep depression toward the ground line), and the transmitted signal peak becomes large (upwards in the green trace line). Compared to the calculated value of the reflected laser intensity, which corresponds to 50% against full reflection, the lowest value is about 40%. After this tuning, feedback control was turned on.

When the burst amplifier in the input line was turned on, the error signal was greatly disturbed and feedback control was lost. Special treatment of the feedback was necessary. The control signal to the laser oscillator was tracked, held and fixed when the burst amplifier was turned on, with the expectation that conditions in the cavity would not change quickly during burst-amplified laser injection. After the burst amplifier was turned off, the feedback operation automatically occurred again. To further stabilize the feedback loop, a limiting amplifier was also used. By inserting the limiting amplifier just after the reflected laser intensity monitor, the output signal from this amplifier became almost saturated. Therefore, even though the burst amplifier was activated the error signal for the PID module was not affected.

Using a fast moving cavity mirror, the PDH signal displays a typical interference-damping pattern [13]. From this information, the cavity finesse can be estimated. To achieve that, the waveform
shown in Fig. 16 is fitted with an adiabatic damping factor and an oscillation damping factor that is applied for the positive time domain to obtain the cavity lifetime $t$. Using that, the cavity finesse ($F$) can be represented by

$$ F = 2 \pi c t / L $$

(6)

where $c$ is the speed of light and $L$ is the total length of the 4-mirror optical cavity. The evaluated finesse was $1.7 \times 10^3$. Comparing the designed values, the estimated finesse with the mirror reflectivity is $5.0 \times 10^3$, so a discrepancy of factor 3 still remains. The reason for this discrepancy is due to the difficulty in cavity tuning. When the cavity approaches the condition of the designed finesse, the measured transmitted signal width on the scope became extremely thin. The cavity still appeared to be insufficiently rigid against environmental mechanical vibration to stably reproduce those thin resonance signals. Therefore, despite having sufficient degrees of freedom for tuning, it became difficult to keep adjusting those actuators in the right direction.

To evaluate the achieved laser waist size, a laser profiler was used. Due to the beneficial properties of the 4-mirror optical cavity, the transmitted laser is almost parallel in the cavity except between M3 and M4. If we place the laser profiler behind the plane mirror, then we can measure the transmitted laser profile inside the cavity. This behavior is in common with the cylindrical mirror case, as shown in Fig. 2. By combining the measured laser profile and the estimated profile evolution along the laser path inside the cavity, it is possible to reconstruct the waist size between M3 and M4. The waist size can be calculated by only changing the mirror distance between the concave–concave and cylindrical–cylindrical mirrors to keep the total cavity length constant. The measured laser profiles behind the cylindrical mirror (M2) are shown in Fig. 17. The horizontal size was $1012.5 \pm 5.4 \mu m$ and the vertical size was $889.9 \pm 3.3 \mu m$. The resulting estimated profile evolution inside the cavity to reproduce the measurement size at M2 mirror is shown in Fig. 18.

From estimation of evolution required to reproduce the profile at M2 mirror, the obtained waist sizes are

$$ \sigma_V = 50.84 \mu m $$
$$ \sigma_H = 43.73 \mu m $$

The circularity, defined as $\sigma_H / \sigma_V$, is evaluated as 0.86. Comparing the designed value of 20 $\mu m$, the attained laser waist value seems rather large. The main reason for this discrepancy came from the lack of the margin of each actuator. From the above evolution estimation, the position mismatch is found to be several hundred micrometers. However, before reaching that designed point, the entire margin of the actuator range was used.

10. Conclusion

A 4-mirror optical cavity for the application of high-flux X-ray generation by inverse Compton scattering was developed in the Quantum Beam Technology Program at the Superconducting RF Test Facility accelerator at KEK. A mirror bender was introduced to modify a flat mirror to a cylindrical shape to make the stored laser beam round, and match it for collision with a round electron beam. The installation of five degree-of-freedom actuators for each mirror using bellows chambers on both sides made precise control possible by cancelling the atmospheric pressure force. Mechanical stiffnesses between the 4-mirror actuators were strengthened by a
Fig. 12. Top view of the granite table with the additive support system attached above the optical cavity. The additive support system is drawn in solid lines (other parts are shaded).

Fig. 13. Side view of the mirror holder mounted on the movers. The additive support system is drawn in solid lines (other parts are shaded).

Fig. 14. Histograms of the stacked laser intensity (left) prior to the improvement of the stability and (right) after the improvement.
stiff plate with mirror holder arms to reduce the incoherent motion of each mirror caused by the mechanical vibration in the accelerator. The measured performances of the 4-mirror optical cavity were $1.7 \times 10^3$ for finesse, 43.7 μm for the horizontal waist size, 50.8 μm for the vertical waist size, and 2.8-kW stored power for a 1-ms duration with 5 Hz. The degradation of performance from the design values was due to insufficient mechanical stability of the mirrors, and an insufficient tuning range to achieve the optimum resonance condition. The achieved value of the enhancement factor was quite low compared to the design value. For this reason, the optical cavity tuning was done only using a laser light amplified by a PCF fiber. When the burst amplifier was turned on, the incoming laser profile might be modified, and also cavity mirror distortion caused by heat might occur, so it seems reasonable to consider that the injection matching of the laser with burst amplifier was not sufficient. It is also mentioned here that the feedback system described above was still not stable enough; another feedback circuit for synchronization with the accelerator could not be closed. In the actual collision experiments, the X-ray signals were detected during a random timing scan. Further study to improve the performance is necessary and currently underway.

**Fig. 15.** The signals detected by the photo-diodes. In the 4-mirror cavity, a piezo-actuator was attached to M4 to change the total cavity length by several micrometers. The purple trace line represents the waveform of the piezo-drive monitor. The green trace line represents the transmitted light signal, and the yellow trace line represents the reflected signal. The pulse signal of the light appears periodically when the cavity length equals an integer multiple of the wavelength.

**Fig. 16.** The PDH signal with interference between the injected and stacked lasers. In the positive time domain, the typical modulation damping behavior was measured.

**Fig. 17.** The laser profile measured by a laser profiler behind the cylindrical mirror (M2). The horizontal size was $1012.5 \pm 5.4$ μm, and the vertical size was $889.9 \pm 3.3$ μm.
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References


Fig. 18. Laser profile evolution with reconstructed mirror configurations. Both the laser profile sizes behind the cylindrical mirror that do not contribute to the laser injection are adjusted with the above measurement results.