STUDY ON A NOVEL LASER ABORT SYSTEM FOR SUPERKEKB

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Abstract

To ensure stable and continuous commissioning of SuperKEKB, the machine protection system (MPS) plays a crucial role in safeguarding the accelerator's hardware from damage caused by beam loss. The response time of the MPS is a critical factor in mitigating hardware damage caused by the radiation of abnormal beams. In this study, we investigate a novel laser abort system for the SuperKEKB accelerator to reduce the response time of the beam abort trigger. The laser, serving as the trigger signal, is transmitted through free space. Compared to the traditional method, the transmission speed is 1.5 times faster than that in optical fiber. This faster signal transmission can shorten the abort time, enabling the realization of effective MPS. The optical design for long-distance laser beam propagation and measurement of coupled laser power have been studied. Investigation will be conducted regarding the long-term stability of the laser beam inside the accelerator tunnel.

INTRODUCTION

The SuperKEKB project set a world record for peak luminosity in June 2023, and marking its emergence as a true luminosity frontier machine. As increasing the beam currents, unexplained beam losses began to be observed. Compare to the usual beam loss case, within a few turns, most of the beam energy is lost, inducing a large amount of radiation inside the ring. We refer to this unexplained beam loss as Sudden Beam Loss (SBL) [1]. Due to the SBL, the abnormal beam caused damage to the accelerator hardware, such as the collimators. In addition, the resulting beam shower and radiation also caused damage to the pixel detectors of the Belle II detector and quenched the QCS. All the hardware damage has hindered the normal and continuous operation and commissioning of the SuperKEKB. Besides, to increase the luminosity in the following days, it is necessary to increase the beam current. Considering the existence of the SBL issue, increasing the luminosity will become extremely difficult since the amount of radiation is proportional to the beam current.

Therefore, the MPS is necessary to protect against hardware damage by SBL and ensure the normal and continuous commissioning of SuperKEKB. To realize an effective and reliable MPS, improving the current beam abort system is crucial, as it allows the abnormal beam to be dumped quickly before causing hardware damage. This can be addressed from two aspects. The first is to speed up the response time of the abort request signal. By installing additional high-response abort sensors (CLAWS detectors) upstream in the beamline, it was found that the abort response could be accelerated by 10 μs. Based on this, during the long shutdown from 2022 to 2024, a new CLAWS detector was installed near the newly established collimator, 750 meters upstream from the collision point. During the commissioning of this detector in 2024, it was demonstrated that the beam could be aborted 5 to 50 microseconds faster than with the existing beam abort system, and its implementation into operation was realized at the end of this March [2]. On the other hand, speeding up the transfer speed of the abort request signal is another method. Currently, all the abort request signals are transferred via silicon fiber. Compared to signal transmission in air, the transfer speed is lower due to the refractive index of silicon fiber. As shown in Fig. 1, the transfer time of the abort request signal can be sped up by transmitting the signal via a laser beam directly in air. For the same transmission distance, the new design will reduce the transmission time to about 67% of the previous transfer time. This experiment started in November 2022, and the results achieved until now will be introduced in this proceeding.

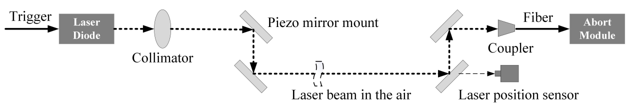

Figure 1: Fast laser abort system layout.

LASER FAST ABORT EXPERIMENTAL SYSTEM

As shown in Fig. 1, the laser fast abort experimental system consists of three main parts: the laser source, the transmission section, and the coupling section. In this section, all the components and the experimental setup will be introduced in this section. The laser beam travels a long distance through the air and is coupled into a fiber at the coupling section in the accelerator tunnel. The fiber is connected to the abort module located in the central control room. The logic for the abort request signal is such that the light is ON in the normal state and OFF in the abort state [3]. In the case that a trigger from the loss monitor is sent for a beam abort request, a homemade module can receive this trigger and turn off the laser diode to realize the beam abort. By using the abort request signal with a laser, it becomes possible to transmit the signal through the air, which has a refractive index of approximately 1. Traditional optical fiber

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with a refractive index of about 1.5, thus the signal speed can be approximately 1.5 times faster to realize the MPS.

Laser Source Section and Coupling Section

Taking into account the laser safety level and optical loss during the transmission section, a compact commercial laser diode module (Thorlabs CPS532-C2) with an output power of 0.9 mW was selected. The wavelength of 532 nm is well-suited to the optical components in this experimental setup and the abort module, which requires at least 30 μW for normal operation at 532 nm. The laser beam has a diameter of approximately 3.5 mm and a divergence of 0.5 mrad. For better long-distance transmission with less loss, the laser beam is enlarged by a telescope after the laser diode.

In the coupling section, another telescope is used to reduce the laser beam size in the long-distance transmission experiment. For higher coupling efficiency, a high-NA achromatic collimator for multi-mode fibers is selected. First, the coupling efficiency for different input laser beam sizes and optical fibers is tested, as shown in Table 1. It's clear that the coupling efficiency is higher for fibers with a large numerical aperture (NA). Meanwhile, the input laser beam size is an important factor to consider for different coupling fibers due to the fixed effective focal length of the collimator. In the early stages of the experiment, the fiber with 400 μm core diameter and NA0.5 is selected for coupling section. Recently, we purchased two costumed fibers with 600 μm and 1000 μm core diameter. Experimental results show that the fiber with a 600 μm core diameter is more effective for achieving high coupling efficiency with different input laser beam sizes. In the future, this fiber will be used to couple the laser from the tunnel to the abort module in the central control room.

Table 1: Coupling Efficiency for Different Beam Sizes (d [mm]) and Fibers (Core Diameter [μm], NA)

d **(mm)**	**2.5**	**3.5**	**7.2**	**9.0**
Φ105, NA0.10	67.56%	57.65%	17.97%	18.89%
Φ50, NA0.22	96.41%	92.71%	70.32%	59.74%
Φ105, NA0.22	95.86%	91.53%	56.71%	64.58%
Φ200, NA0.22	95.48%	88.47%	79.55%	61.75%
Φ200, NA0.39	95.71%	95.06%	93.16%	91.03%
Φ400, NA0.39	96.06%	97.29%	97.16%	90.79%
Φ200, NA0.50	96.64%	95.65%	94.82%	94.81%
Φ400, NA0.50	98.49%	98.00%	97.88%	97.64%
Φ600, NA0.50	99.77%	99.88%	98.25%	99.42%
Φ1000, NA0.50	94.63%	94.87%	92.18%	93.47%

Long-Distance Transmission Experiment with Transmission Telescope

A long-distance transmission experiment is carried out in the klystron gallery of the KEK Linac. The laser source section is placed at the starting point of Linac Sector 1, and the coupling section is placed at the end of the Linac, covering a total distance of about 400 meters. A 3x magnification telescope is placed after the laser diode, as shown in Fig. 2. Fine adjustment of the telescope is important to achieve a quasi-parallel laser beam with a diameter of 12 mm for long-distance transmission. Another 0.175x transmission telescope is used to reduce the laser beam size for coupling. Due to the large beam size and spatial fluctuations, the first lens of this telescope is a 2-inch lens to reduce loss.

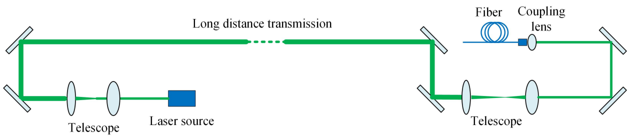

Figure 2: Experimental layout of the long-distance transmission experiment with transmission telescope.

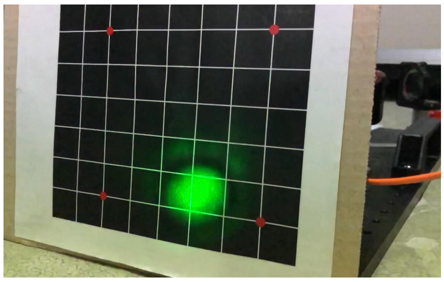

Figure 3: Laser beam pattern after 400 meters of transmission.

The laser beam pattern after 400 meters of transmission is shown in Fig. 3. At the end of the Linac, a plate with four fixed red spots is used to record the laser beam vibration. The distance between the two red dots is fixed at 10 cm for calibration during the processing of the recorded video. This allows us to determine the barycenter and the fluctuation using a Python program. This method is used in all our experiments to analyze laser beam stability by measuring the fluctuation. Fig. 4 shows the stability of the laser beam over 400 meters of transmission using the telescope configuration. Horizontal and vertical stability are measured and calculated, with standard deviations (SD) of 3.5 and 3.6, respectively, for this configuration. Due to the unstable temperature distribution in the Linac gallery, the fluctuation is significant, especially over 400 meters. The coupled laser power is also recorded for 600 seconds, as shown in Fig. 5. The power meter measures and records the power every 0.5 seconds. The laser power is averaged every 5 seconds, and the error bars for each dot in Fig. 5 represent the SD. 581 ±42 μW of laser power is coupled into the fiber, which is sufficient to trigger the abort module.

Although sufficient coupled power is obtained, there are still some drawbacks to this telescope configuration. Firstly, due to spatial fluctuation and the limited size of the lenses, it is very difficult to ensure the beam passes through the central part of the lenses for good beam quality. Secondly, for the final experimental setup in the ring accelerator tunnel, the laser beam needs to be transmitted along a curved path using some reflective mirrors. Creating a straight line for injection into the telescope is too complicated and costly. Thirdly, while it is possible to use larger lenses, the total weight of the setup will increase significantly. This approach is not advisable as all the supports would need to be designed to handle heavier loads, seriously compromising stability and practicality. Therefore, the application of reflective spherical mirrors with multifunctionality is designed..

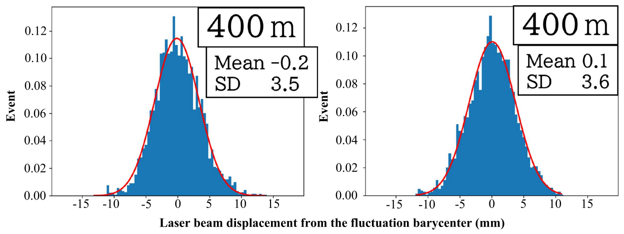

Figure 4: Laser stability in horizontal and vertical direction after 400 meters of transmission.

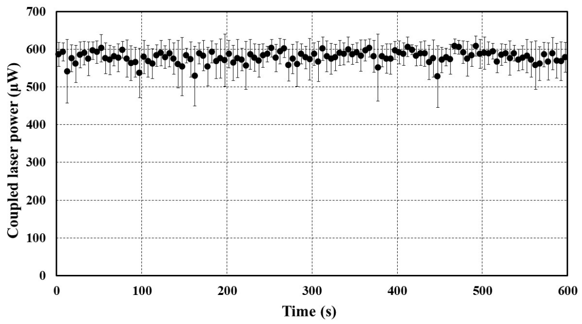

Figure 5: Coupled laser power after 400 m of transmission.

Long-Distance Transmission Experiment with Reflective Spherical Mirrors

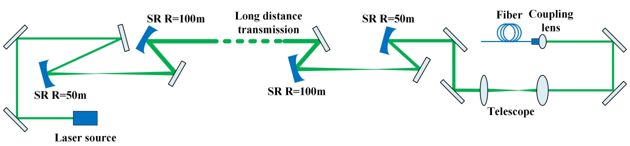

Figure 6: Experimental layout of the 400 m long-distance transmission experiment with spherical mirrors.

A spherical mirror has the same property to focus or defocus the laser beam as a lens. Meanwhile, it can be used as a reflective mirror to change the laser path in the ring accelerator. Compared to a telescope made with lenses, fewer optical components are required thanks to the multifunctionality of the spherical mirror. In addition, it is easy to manufacture large spherical mirrors. We repeated the 400 m transmission experiment using spherical mirrors with curvature radii of 100 m and 50 m. The experimental setup is shown in Fig. 6. After the laser diode, the first telescope made of spherical mirrors is used to enlarge the laser beam size by 2 times. After that, another telescope with spherical mirrors is placed to reduce the beam size again for better coupling efficiency. The laser beam pattern is shown in Fig. 7.

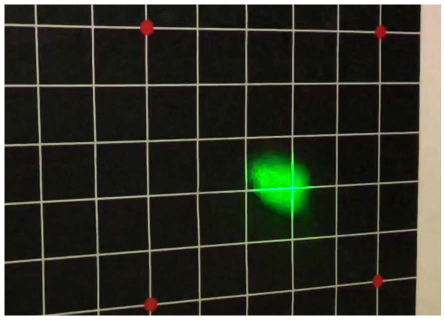

Figure 7: Laser beam pattern after 400 meters of transmission.

The laser stability and coupled power are measured in the same way as in the previous experiment, as shown in Fig. 8 and Fig. 9. Although the SD of laser stability is 1.5 times higher than the previous results, the laser beam size became smaller, and higher laser power of 694 ±27 µW was coupled with a lower SD value. This experimental setup has been decided to be used in the KEKB ring tunnel test.

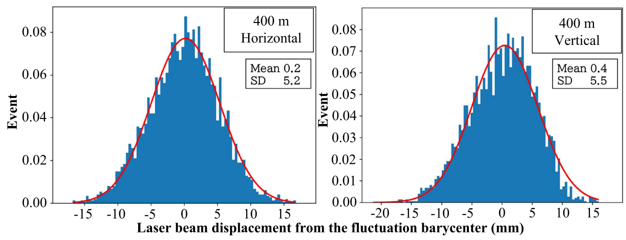

Figure 8: Laser stability after 400 meters of transmission with spherical mirrors.

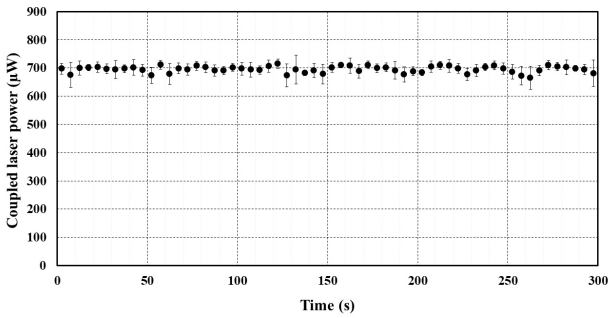

Figure 9: Coupled laser power after 400 m of transmission.

Long-Distance Transmission Experiment in KEKB Tunnel

We tested the previously verified spherical mirrors experimental setup in the KEK tunnel with a total distance of 244 meters, the experimental layout is shown in Fig. 10. Some temporary supports that can be fixed to the cable rack have been made for placing the optical components. The coupling part is placed near the D7 zone, where there is a hole from the tunnel to the ground. This hole will be used for the fiber that connects the coupling lens and the abort module. The laser beam pattern is shown in the Fig. 11. Compare to the case of 400 meters transmission, the laser beam pattern is much better for shorter distance transmission. Meanwhile, the laser stability has improved after 244 meters of transmission as shown in Fig. 12. One reason for this is the shorter distance compared to previous cases, but the most important reason is the more uniform temperature distribution inside the KEKB tunnel.

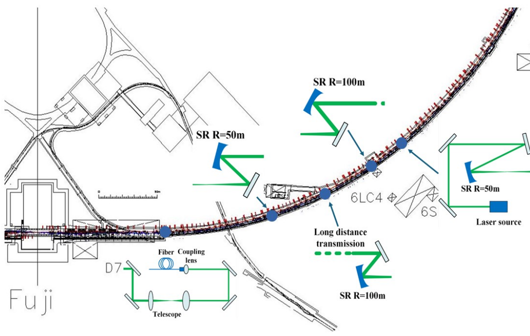

Figure 10: Experimental layout in the KEKB tunnel.

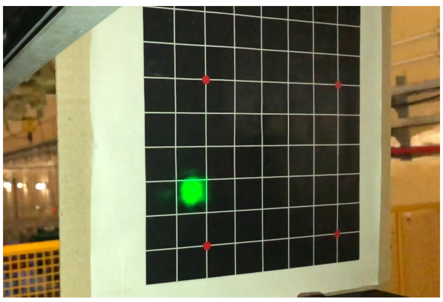

Figure 11: Laser beam pattern after 244 meters of transmission.

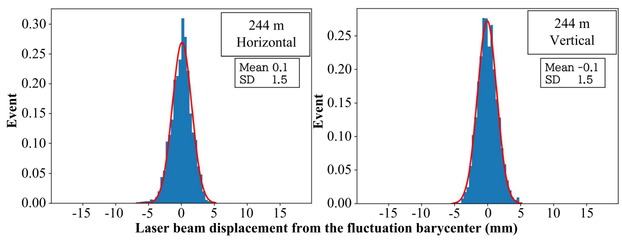

Figure 12: Laser stability after 244 meters of transmission in the KEKB tunnel.

The coupled laser power over 300 seconds is shown in Fig. 13. About 650 μW is coupled successfully with lower power fluctuation. This power is about 20 times higher than the power required for the abort module.The feasibility of this fast abort experiment is demonstrated for the first time in the KEKB tunnel, with a view towards practical application in the future.

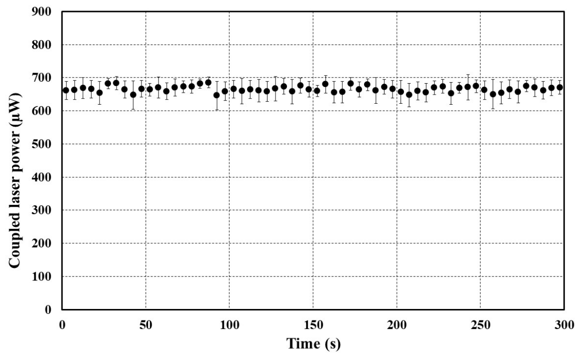

Figure 13: Coupled laser power after 244 m of transmission in the KEKB tunnel.

CONCLUSION

To realize the MPS for the smooth commissioning of SuperKEKB, we proposed a novel laser abort system. By transmitting a laser beam through free space as a trigger for the abort module, we can reduce the beam abort time thanks to the lowest refractive index of air. Measurements over a 400-meter distance have been completed. The coupled laser power is about 20 times higher than the power required for the abort module action. Measurements over a 244-meter distance have also been done in the KEKB tunnel, resulting in higher stability and increased coupled power. We will use larger spherical mirrors and thicker coupling fibers in the future to achieve higher coupled power. More stable support structures are also being investigated before their application in the SuperKEKB commissioning.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI(C) Grant Number JP24993974 and MDI Budget.

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