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STUDY ON A NOVEL LASER FAST 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 fast abort system for the SuperKEKB accelerator to reduce the response time of the beam abort trigger. The laser, which serves as the trigger signal, is transmitted through the 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

In December 2024, the SuperKEKB project set a world record for peak luminosity, establishing itself as a true frontier machine in luminosity performance. However, as the beam currents increased, unexplained beam losses began to occur. Unlike typical beam loss events, these losses resulted in the rapid dissipation of most of the beam energy within just a few turns, generating significant radiation within the ring. We refer to this phenomenon as Sudden Beam Loss (SBL) [1]. SBL events have caused abnormal beam interactions that damaged accelerator hardware, including collimators. Furthermore, the resulting beam showers and radiation led to damage in the pixel detectors of the Belle II experiment and triggered quenches in the QCS magnets. These hardware failures have impeded the stable and continuous operation and commissioning of SuperKEKB. Looking ahead, increasing the beam current is essential for achieving higher luminosity. However, the presence of SBL poses a major challenge, as radiation levels scale with beam current. Without addressing this issue, further luminosity improvements will be extremely difficult.

Therefore, MPS is necessary to protect against hardware damage from SBL and to 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 in two ways. 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 of 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 abort request signals are transmitted via silicon fiber. However, due to the refractive index of silicon, the transmission speed is slower compared to propagation through air. As illustrated in Fig. 1, the signal transfer time can be significantly reduced by transmitting the signal directly through air using a laser beam. For the same transmission distance, this new design reduces the transfer time to approximately 67% of that with silicon fiber. This experiment began in November 2022, and the results obtained to date are presented in this proceeding.

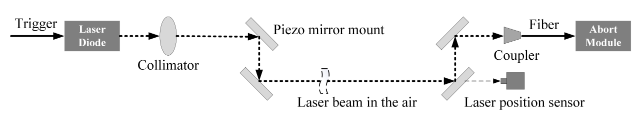

Figure 1: Fast laser abort system layout.

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. 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.

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 numerical aperture (NA) achromatic collimator for multi-mode

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fibers is selected. Several types of optical fiber with different core diameters and NA have been tested to achieve higher coupling efficiency. 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 [3].

The laser beam travels a long distance through air and is coupled into an optical fiber at the coupling section within the accelerator tunnel. This 40-meter-long fiber is connected to the abort module located in the ground power supply building. The logic for the abort request signal is such that the light is ON in the normal state and OFF in the abort state [2]. 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 a laser for the abort request signal, transmission through air, which has a refractive index of approximately 1, becomes possible. In contrast, traditional optical fiber has a refractive index of about 1.5, meaning the signal can travel roughly 1.5 times faster through air. This improvement contributes to realizing a faster Machine Protection System (MPS).

Long-Distance Transmission Experiment with Reflective Spherical Mirrors

A long-distance transmission experiment was carried out in the klystron gallery of the KEK Linac. A telescope with two convex lens (3x magnification) was used to achieve a quasi-parallel laser beam with a diameter of 12 mm for long-distance transmission [3]. Another 0.175x transmission telescope was used to reduce the laser beam size for coupling, and it was placed in front of the fiber collimator. The coupled laser power was recorded for 600 seconds using a power meter that measures and logs the power every 0.5 seconds. The recorded values were then averaged over 5-second intervals. About 580 µW was coupled successfully.

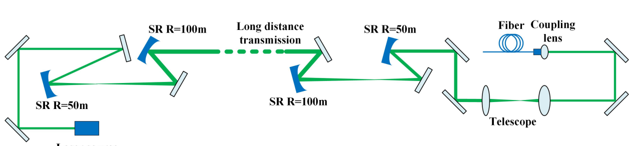

Figure 2: Experimental layout of the 400 m long-distance transmission experiment with spherical mirrors.

Despite achieving sufficient coupled power, the current telescope setup has some limitations, including restricted lens size and challenging alignment. 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. 2. After the laser diode, the first telescope made of spherical mirrors was used to enlarge the laser beam size by 2 times. After that, another telescope with spherical mirrors was placed to reduce the beam size again for better coupling efficiency. After that, another telescope with spherical mirrors was placed to reduce the beam size again for better coupling efficiency.

The laser stability and coupled power are measured shown in Fig. 3 and Fig. 4. Although the standard deviation (SD) of the laser stability was 1.5 times higher than in the previous results, the laser beam size was reduced, and a higher coupled laser power of 694 ±27 µW was achieved with a lower SD [3]. This experimental setup has been deployed in the SuperKEKB ring tunnel for testing.

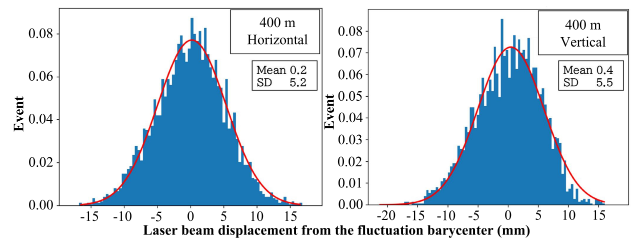

Figure 3: Laser stability after 400 meters of transmission with spherical mirrors.

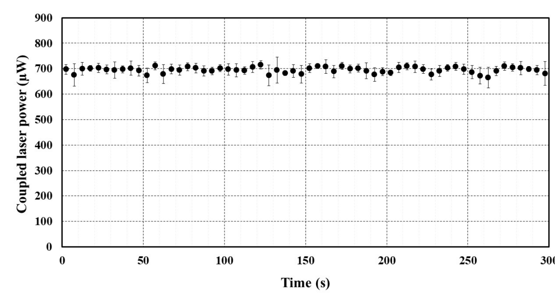

Figure 4: Coupled laser power after 400 m of transmission.

Long-Distance Transmission Experiment in the KEKB Tunnel

We tested the previously verified spherical mirror experimental setup in the KEK tunnel with a total distance of 244 meters; the experimental layout is shown in Fig. 5. Some temporary supports that can be fixed to the cable rack have been made for placing the optical components. The coupling part is located near the D7 zone, where there is a chimney from the tunnel to the ground. This chimney will be used for the fiber that connects the coupling lens and the abort module. The laser stability has improved after 244 meters of transmission, as shown in Fig. 6. 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.

The coupled laser power over 300 seconds is shown in Fig. 7. About 650 µW is coupled successfully with lower power fluctuation. This power is about 20 times higher than the

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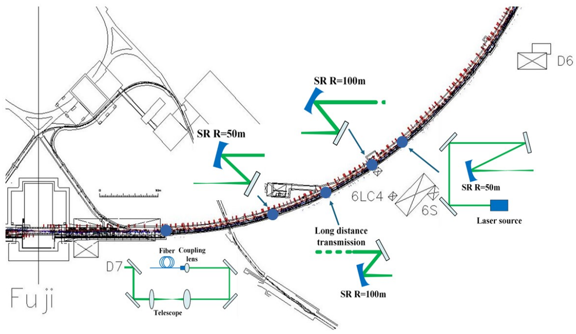

Figure 5: Experimental layout in the KEKB tunnel.

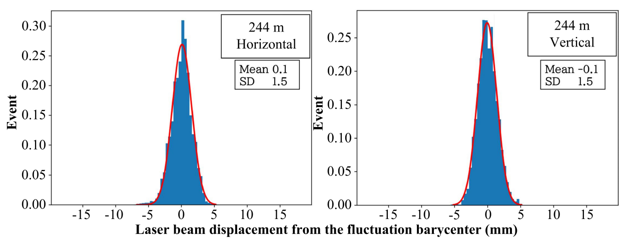

Figure 6: Laser stability after 244 meters of transmission in the KEKB tunnel.

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.

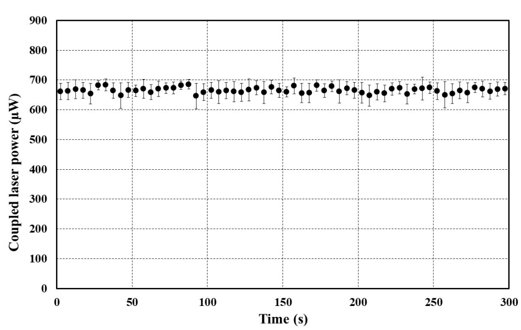

Figure 7: Coupled laser power after 244 m of transmission in the KEKB tunnel.

Evaluation of Long-Term Stability in the KEKB Tunnel

To ensure the feasibility of our setup for beam abort applications during the upcoming SuperKEKB commissioning, a long-term stability evaluation was conducted in March 2025. The coupled laser beam was transmitted through a 40-meter optical fiber from the tunnel to the ground power supply building, where the abort module is housed. A power meter was connected to the fiber for monitoring the laser output. A fiber splitter will be introduced for future use to route 90% of the laser to the abort module and 10% to the power meter for system status monitoring. As shown in Fig. 8, the system was operated continuously for 64 hours, except for a 2-hour pause due to a tunnel tour. An average laser power of 584 μW was maintained, with no dropouts to zero during the measurement period. The laser power exhibited greater fluctuation in the latter half of the measurement period compared to the first half. It is assumed that the fluctuations were induced by environmental temperature changes. Since the air conditioning was not functioning during the measurement period, significant variations in outdoor temperature may have caused deviations in the laser path. To stabilize the laser beam, future tests will involve a laser position sensor and a piezoelectric mirror mount.

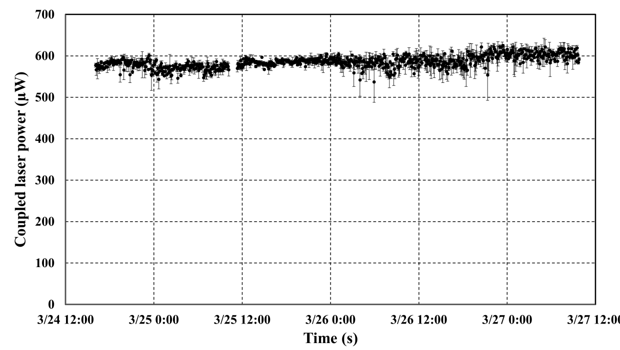

Figure 8: The 64-hour laser power history was recorded in the ground power supply building.

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. Long-term measurements over a 244-meter distance have also been done in the KEKB tunnel, the experiment verified the feasibility of the laser abort system. More laser position feedback parts are also being investigated before their application in the SuperKEKB commissioning.

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