DESIGN AND IMPLEMENTATION OF AN INTERLOCK SYSTEM FOR SAFE LASER BEAM DELIVERY IN EXPERIMENTAL AREAS AT ELI-NP

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This work presents the design, implementation, and validation of a temporary laser interlock system for the High Power Laser System (HPLS) at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP). High-power laser facilities demand stringent safety mechanisms to prevent accidental exposure to hazardous radiation. As an interim solution, the proposed interlock system ensures controlled HPLS pulse delivery while integrating multiple fail-safe layers to regulate beam access and enhance operational safety. The system's effectiveness was validated through systematic testing, demonstrating accurate control of laser pulse delivery, rapid emergency response, and full compliance with laser safety standards. The results confirm that this interlock system effectively safeguards personnel and experimental areas, ensuring uninterrupted, secure operation of high-intensity laser experiments.

Keywords: high power laser system, interlock system, analog electronics, CMOS, signal processing

1. Introduction

The operation of high-power laser systems demands rigorous safety protocols due to the extreme laser intensities involved. The Extreme Light Infrastructure – Nuclear Physics (ELI-NP) High Power Laser System (HPLS) [1],[2],[3] is capable of delivering multi-petawatt laser pulses, making an interlock system essential to regulate beam access and prevent inadvertent exposure. High-intensity optical radiation poses severe risks without proper safety mechanisms, including accidental exposure, beam misalignment, and potential equipment damage. To mitigate these risks, laser safety standards such as ISO 11553-1 and IEC 60825-1 [4] dictate strict requirements for interlock systems. Many high-power laser facilities implement permanent, centralized interlock solutions integrating digital controllers, and automated safety shutoffs [5],[6]. Previous works have proposed interlock mechanisms focused on software-driven control systems, remote monitoring, and automated fault detection. However, these solutions often

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require complex integration, extensive infrastructure, and costly upgrades, making them impractical for temporary experimental setups.

Unlike conventional systems, this work presents a temporary yet highly reliable interlock solution tailored for experimental areas at ELI-NP. In the absence of a fully developed permanent interlock, a robust interim system is required to ensure controlled HPLS pulse delivery while maintaining beam path integrity, prevent unauthorized personnel access to hazardous laser radiation, enable rapid emergency shutdown in case of system breaches, and integrate fail-safe mechanisms that function independently of complex digital controls. This study distinguishes itself by offering a hardware-based, electronic interlock system that is fail-safe by design, ensuring immediate laser shutdown upon safety breaches, standalone and adaptable, deployable without modifying permanent facility infrastructure, and capable of achieving emergency stop times below 50ms. The interlock logic is designed with redundant fail-safe measures, incorporating beam path sensors, emergency stop buttons, warning signals, and pulse gating mechanisms to enhance safety and control.

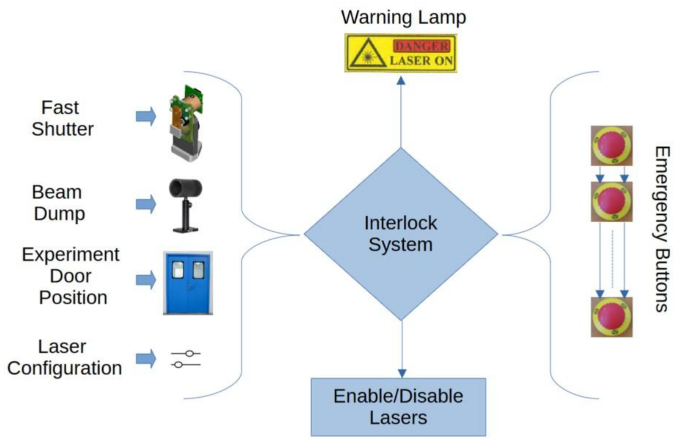

Fig. 1. Principle schematic of the interlock system

Fig. 1 presents a schematic overview of the interlock system, illustrating the relationship between key components involved in laser pulse safety regulation. The system operates by continuously monitoring input sensors, including the fast shutter, which ensures immediate beam blocking if required; the beam dump, which redirects or terminates the laser beam when necessary; the experiment door position, which monitors room access to prevent exposure, and the laser configuration, which verifies beam alignment and power settings. These inputs feed into the Interlock System, which processes signals and triggers appropriate safety actions. If any safety breach is detected, the system can activate warning lamps to alert personnel, disable lasers to prevent hazardous exposure and trigger emergency buttons, allowing manual shutdown in critical situations. This temporary interlock system is crucial to securing experimental high-power laser operations at ELI-NP. Combining proven analog electronic mechanisms with a fail-safe approach bridges the gap between fully automated permanent interlock solutions and on-demand experimental safety needs.

The interlock system's electronic component continuously monitors the input sensors' status and generates the corresponding output signals based on the selected mode of operation (OFF, ALIGN HPLS, ALIGN EA, RUN). These signals control critical functions such as enabling or disabling lasers, activating the warning lamp, and displaying the selected operation mode. Table 1 provides an overview of the interlock system's operation modes and their respective requirements.

Table 1

Operation modes of the interlock system and requirements

OFF	ALIGN HPLS	ALIGN EA	RUN
Class IV lasers are disabled There is no laser beam in experimental area (EA) The corresponding beam dump is in position	Class IV lasers are enabled The beam dump is in position The beam is enclosed in laser room (No beam toward experimental area)	Class IV lasers are enabled (Ensuring low power beam) Corresponding beam dump is removed The laser configuration is properly selected The warning light is on	Class IV lasers are enabled (Ensuring full power beam) Corresponding beam dump is removed The laser configuration is properly selected The door of the experimental area is closed The warning light is on

2. Experimental details

2.1 System Architecture and Functional Description

The proposed interlock system is systematically developed, encompassing circuit design, control logic implementation, safety integration, and validation through structured experiments. The system incorporates multiple critical safety mechanisms to prevent accidental laser exposure. These include beam path sensors, which continuously monitor the optical trajectory of laser pulses to detect any misalignment or unintended beam propagation. An emergency stop (E-Stop) mechanism is strategically installed at key locations, enabling an immediate laser shutdown in case of safety breaches. The system has warning signals and indicator lights to provide real-time operational feedback, ensuring personnel are constantly informed of the laser's operational state.

Fig. 2 presents a detailed schematic diagram of the interlock system, illustrating the electrical interconnections and interactions between components, including control units, safety modules, and sensor interfaces. The central processing module acts as the core control unit, receiving signals from multiple sensors and switches, processing the information, and executing corresponding actions such as activating safety alarms, disabling laser emission, or initiating emergency shutdown protocols.

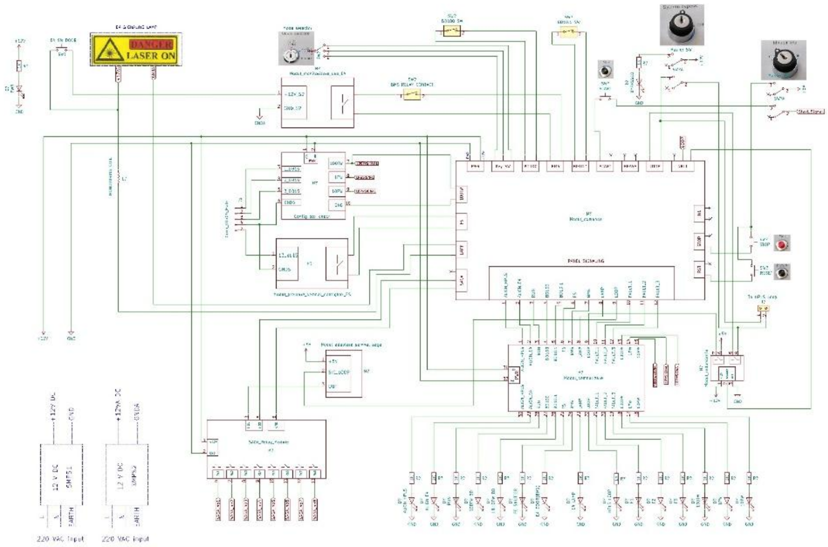

Fig. 2. Block diagram of the interlock system

The interlock system consists of several electronic modules, each playing a distinct role in ensuring safe and controlled laser pulse delivery. The Control Module is the core processing unit, gathering logical signals from various field sensors and determining the appropriate system response based on the selected operating mode. Depending on whether the system is in OFF, ALIGN HPLS, ALIGN EA, or RUN mode, the control module processes input data and generates corresponding output control signals, such as enabling or disabling lasers, activating warning indicators, and triggering emergency safety mechanisms.

The Control Module is designed with fail-safe principles, ensuring that fault detection or unauthorized system access results in an immediate safety response. The circuit comprises multiple IC components, each responsible for processing logic signals, verifying sensor inputs, and executing command relays to maintain laser safety compliance [7],[8]. This Control Module is pivotal in the interlock system's functionality, acting as the decision-making unit that continuously monitors and regulates laser operation. The detailed functionality and interaction with other interlock subsystems will be explored further in the subsequent sections. Fig. 3 presents the electronic circuit diagram of the Control Module, illustrating its core design based on CMOS logic circuits:

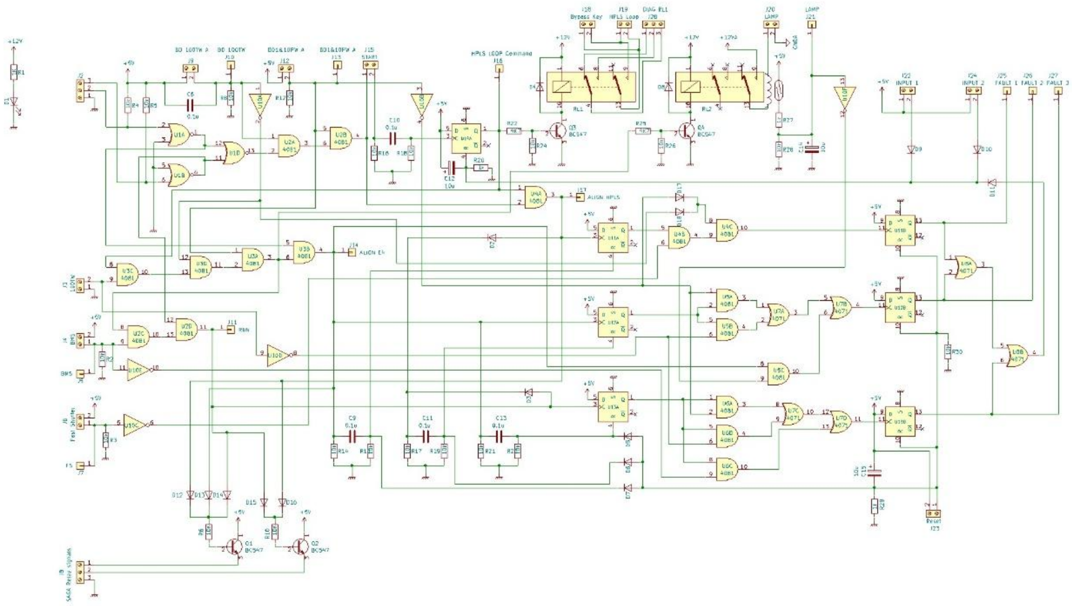

Fig. 3. Electronic circuit diagram for control module

The interlock circuit is constructed using a combination of NAND, AND, OR, and NOT gates, ensuring both combinational and sequential logic operations. This design allows for accurate signal processing and decision-making, enabling the system to regulate laser pulses effectively. The selection of CMOS technology for the interlock circuit is based on two fundamental advantages: low power consumption and high noise immunity. Special emphasis has been placed on signal filtering and stabilization to enhance reliability and safety further. The circuit includes strategically placed capacitors to eliminate unwanted signal activations, preventing erroneous triggering due to transient noise. Additionally, the system uses CMOS D flip-flops to store and maintain logical states correctly during operation [9].

The functional diagram for the electronic control module of the interlock system is shown in Fig. 4. This diagram illustrates the operating principle of the electronic control module designed for the interlock system, highlighting the essential stages of signal processing. The process begins with receiving input signals from sensors or equipment, which are transmitted to the integrated electronic logic. This circuit processes signals based on logic, stores important data temporarily, and generates outputs to control devices as needed. A critical aspect of this process is that the diagnostic system continuously monitors each stage, detects issues, and adjusts parameters to ensure optimal performance and safety.

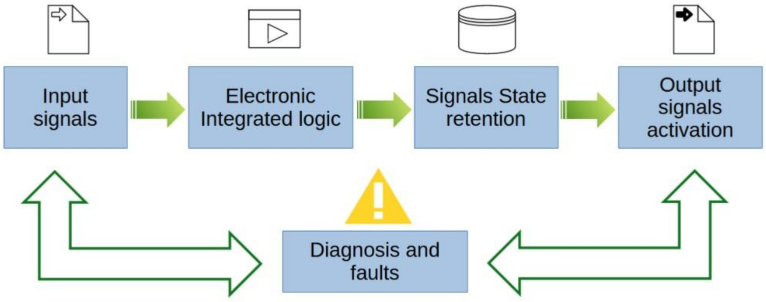

Fig. 4. Functional diagram for control module of the interlock system

In addition to the main electronic control module, two other electronic modules play a critical role in ensuring the proper functioning of the interlock system. The first module (Fig. 5) configures the laser based on system indicators, ensuring proper setup and operation. The second module (Fig. 6), equipped with electromagnetic relays, is designed to suppress the power supply of specific lasers.

Fig. 5 illustrates the electronic design of the configurator box module, which plays a crucial role in acquiring and processing status signals from the laser system. These signals, represented as a sequence of bits, indicate the current HPLS configuration and are essential for ensuring proper system operation. This module functions based on sequential logic, generating logical output signals (0V or 5V) according to the selected laser configuration. The design incorporates optocouplers to ensure accurate signal acquisition and system reliability, which provide electrical isolation between the laser system and the interlock electronics.

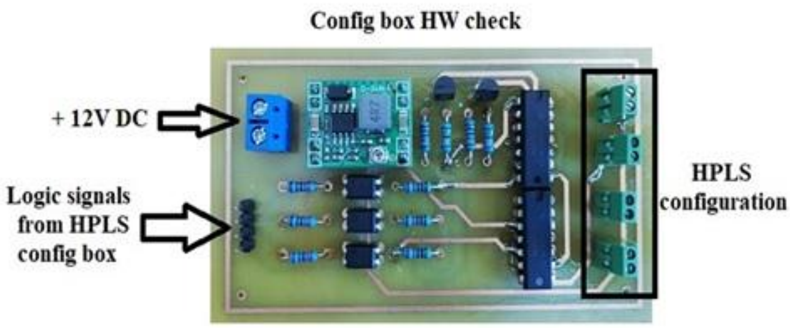

Fig. 5. PCB for configurator box hardware check electronic module

Fig. 6 illustrates the electronic module responsible for controlling laser power supplies, ensuring interlock functionality for safe laser operation in the experimental room. This module regulates the transmission of a low-power laser beam for alignment purposes, allowing the operation of one or two lasers out of eight, depending on the required power level. The module receives command signals, processes them through relay contacts, and directs the appropriate power supply outputs toward the lasers. These modules ensure precise configuration management, enhancing the accuracy and safety of laser system operations.

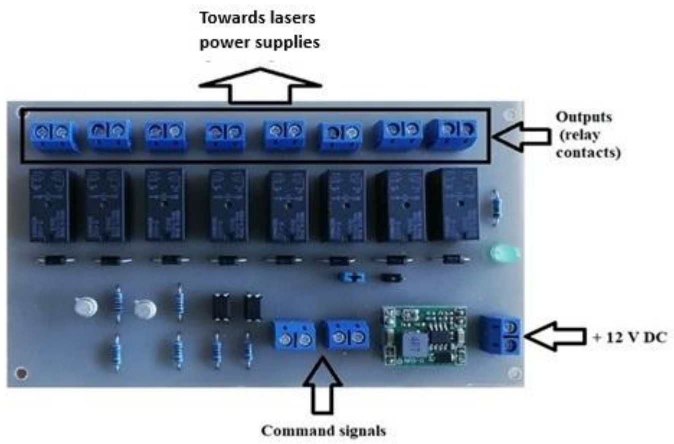

Fig. 6. Laser power supply suppresses electronic module

2.2 Functional and logic description of the interlock system

The interlock system has four modes of operation implemented as follows:

- OFF: In this operation mode, all IV class lasers are disabled.
- ALIGN HPLS: In this operation mode, the class IV lasers are enabled, but the laser beam is enclosed in the laser room, so no laser beam towards experimental areas. This mode is used for laser system alignment and for maintenance periods.
- ALIGN EA: In this mode of operation, the laser beam is sent toward experimental areas attenuated (with low power) for optical setup alignment.
- RUN: This operation mode permits sending full-power laser beams toward experimental areas to perform experiments.

Fig. 7 depicts the state machine regarding the operation of the interlock system. Each state corresponds to a specific level of access and functionality and can be selected via a mechanical key switch (mode selector), which ensures sequential and restricted transitions between modes. In the OFF state, the system is in a fully safe configuration, with all Class IV lasers disabled. This state represents the default condition when the system is not armed. Transitioning to the ALIGN HPLS state enables the high-power laser system while preventing the laser radiation from reaching the experimental areas. The beam is blocked, making this mode suitable for maintenance procedures or internal calibrations

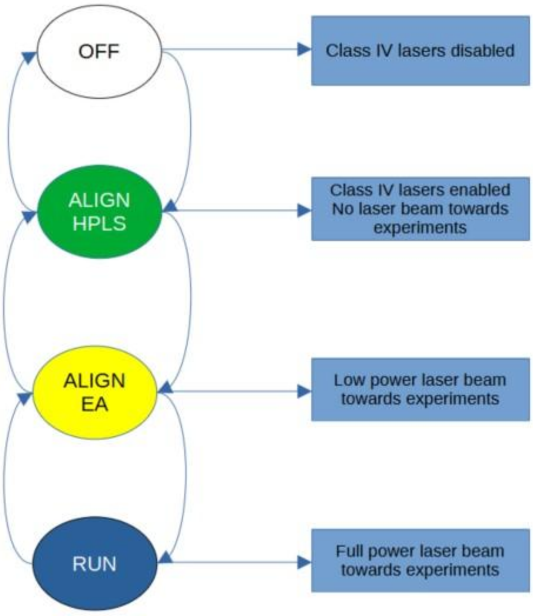

Fig. 7. State machine for operation modes of the interlock system

The ALIGN EA state is intended for aligning the laser beams within the experimental areas. In this mode, the laser radiation is attenuated to a safe level, which is monitored and validated by the interlock system. Operation in the ALIGN EA mode is permitted only when this attenuation condition is confirmed. In the RUN state, the system allows the full-power laser beam to propagate towards the experimental areas. This mode is used for actual experiments and requires that all safety and configuration conditions be fulfilled and validated. Transitions from a higher to a lower operating mode (e.g., from RUN to ALIGN EA or OFF) are also performed via the mode selector, allowing operators to maintain strict, step-by-step, and traceable control over the operational state of the entire laser system.

3. Results and Analysis

The validation results of the interlock system demonstrated high accuracy in beam path monitoring, rapid emergency response, and reliable pulse regulation. Fig. 8 illustrates the laser power response after triggering the emergency stop (E-STOP). The blue line represents the laser power, which remains 100% before activation. The red dashed line marks the time the E-STOP is triggered, approximately at 50 ms. The shaded region represents the shutdown phase, where laser power decreases until it reaches 0%. The green dashed line indicates the point where the laser is fully off, around 100 ms. This graph confirms that the interlock system rapidly reduces laser power, ensuring safe operation by minimizing exposure risks to experiment personnel. The shutdown process occurs quickly enough (~50 ms) to effectively prevent potential hazards of high-power laser radiation.

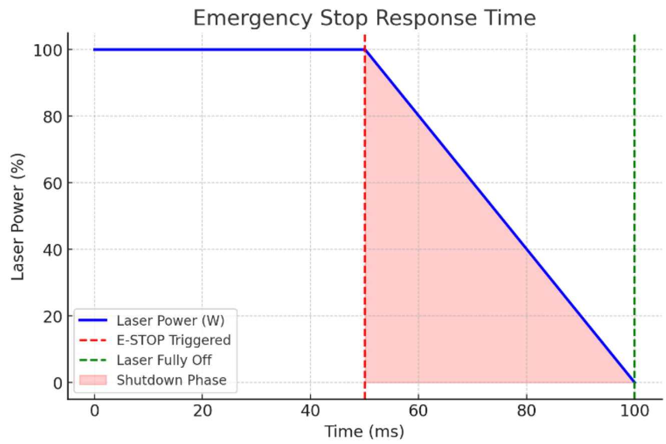

Fig. 8. Plot from trigger to laser shutdown

This performance represents a significant improvement over conventional interlock architectures, which are often based on electromechanical relays or standard PLC logic. These traditional systems typically experience response times in the 100 to 500 millisecond range due to relay switching delays and slower execution cycles [10]. The reduced shutdown time achieved by the proposed implementation directly contributes to increased safety by reducing the duration of potentially hazardous exposure, thus meeting the stringent safety requirements associated with high-power laser operation. In Fig. 9 it is shown a response time comparison between conventional systems and the interlock system described in this article.

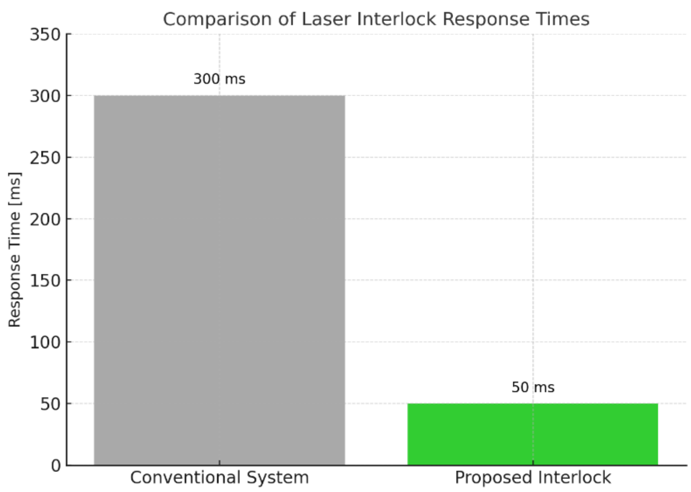

Fig. 9. Comparison of laser interlock response times

4. Conclusions

The interlock system implemented at ELI-NP has demonstrated high reliability and effectiveness in ensuring the safe operation of the HPLS. It successfully restricted unauthorized access, monitored beam path integrity, and delivered a rapid emergency response to safety breaches. Experimental validation confirmed that the system meets laser safety compliance standards, positioning it as a robust and scalable prototype for future high-power laser safety systems.
Future developments should focus on real-time predictive safety monitoring, AI-driven anomaly detection, and cloud-based remote safety control to further enhance its capabilities. These advancements will enable high-power laser facilities to anticipate and mitigate risks proactively, improving overall safety, operational efficiency, and system resilience.

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