Laser Fusion Project Plan

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Project Summary

In high-intensity laser systems, precision is critical. To maintain stability, accuracy, and most importantly, safety, beam diagnostics play an essential role. A beam diagnostic system continuously monitors key parameters of the laser to assess beam health and determine when corrective action is necessary. By collecting data at multiple stages of the laser, the system provides detailed information on performance, enabling operators to identify issues and implement solutions without physically checking each stage. This reduces downtime, minimizes alignment errors, and prevents potential damage to both personnel and equipment. In the event of unsafe conditions, the diagnostics system can automatically shut down the beam, ensuring safe and reliable operation.

Transporting the laser beam through multiple chambers for different areas of study also poses a significant challenge. The laser beam and the equipment that is used to direct it to the different chambers will all be vacuum sealed, directing the beam to a precise micron-scale target. Therefore, it is important that the operation of this motion is entirely automated, and when stationary completely free of any minor vibrations. Mirrors that focus the beam into these different chambers will be automated to either rotate on a single axis or translate linearly from one position to another. Earlier optic mount designs will be expanded upon to incorporate this motion with the precision needed to direct the laser beam without deflecting it from its target location. Maintaining precision and minimizing vibrational noise is critical because these factors directly determine whether the petawatt-class laser beam maintains its focus, avoids self-induced damage, and delivers the required intensity onto micron-scale targets. Without stringent control, both beam quality and experimental success would be compromised.

Revision History

Date	Comments	Version	Approved by
9/24	Initial document	1.0	John W

Project Statement

Our senior design project originates from Colorado State University's long history of leadership in ultra-high intensity laser science. Faculty members such as Jorge Rocca and Carmen Menoni have pioneered compact, high-power lasers that are used worldwide for generating X-rays and extreme ultraviolet light. Building on this foundation, CSU's laser research program has advanced the study of how ultra-intense, ultrashort pulses interact with matter, creating plasmas under conditions similar to those in stars. These interactions generate bursts of X-rays and fusion neutrons, contributing to both fundamental discoveries in physics and applied research in areas such as materials science and thin-film optical coatings.

In recent years, CSU has become a member of LaserNetUS, a U.S. Department of Energy–funded network that links the nation's most powerful lasers across universities and national laboratories. This partnership ensures that CSU's capabilities are integrated into a broader national effort to expand access to high-energy laser experiments. To further strengthen this role, CSU launched the construction of a new petawatt-class laser facility through a public-private partnership, combining federal research support with private investment. This facility will host one of the most advanced university-based petawatt laser systems in the world, placing CSU at the forefront of global high-power laser research.

Our project—the design and construction of equipment for this facility—directly supports that mission. By contributing to the infrastructure that enables petawatt-class experiments, we are helping prepare CSU's Laboratory for Advanced Lasers and Extreme Photonics to meet the technical demands of extreme light science and to expand opportunities for both fundamental physics and practical applications.

Multi-Year Project Status and Plans for This Year

Last year's senior design team concentrated their efforts on the optomechanical design of adjustable mirror mounts to precisely orient the petawatt laser beam. They created preliminary designs using SolidWorks and FEA, then machined prototype mounts with CNC equipment. Once assembled, these mounts were examined optically to evaluate their stability, wobble, and incremental adjustment accuracy. The results of these tests guided redesigns and refinements to ensure the mounts could meet the stringent tolerances required for high-powered laser applications. This work established a solid foundation for reliable beam alignment within the broader laser transport system.

Building on that foundation, this year's team will expand the functionality of the mounts by introducing translation capabilities with micron-level precision. The priority will be to automate the movement of the mirror mounts so that they can be repositioned accurately and repeatably without manual intervention. In addition to enabling fine translation, the mounts will still need to be thoroughly tested for vibrational stability, as even minor oscillations can degrade laser beam quality and alignment. By focusing on automation, precision, and vibration reduction, this year's team will advance the mounts from static alignment tools into dynamic, high precision optomechanical components that can reliably transport the petawatt laser beam to its target.

Goals & Objectives

- Design and implement measurement systems for beam profiling and power diagnostics.
- Develop calibration procedures for power meters, cameras, and photodiodes.
- Characterize beam quality (M2, spatial mode) and temporal stability.
- Integrate diagnostics with the amplifier testbed and produce reproducible measurement reports.
- Ensure safe measurement procedures and interlocks for high-power testing.
- Design and manufacture a beam transport assembly to move into two different locations.
- Automate the motion of the beam transport assembly using programmable logic controllers.
- Achieve >80 Hz eigenfrequency of final design, maintaining laser beam stability within 2 microradians.

Budget Justification

Most of the funding will be from the federal grant that was received in 2024. What materials and supplies that will be needed will be granted through our sponsors and Dr. Rocca.

Risk Analysis

#	Risk Event	Probability/100	Impact, weeks	Score, weeks	Effect	Risk Mitigation Plan	Person responsible for implementing control
1	Incorrect Feeds and Speeds of the cutting tool	30	2	20	Medium	Making sure the tool is set correctly in the tool holder and is properly zeroed and oriented with the correct feeds and speeds selected for the tool	Cameron
2		20	2	10 to 12	Medium	Backup control software versions, redundant sensors, frequent functional tests before runs.	Maxwell
3	When the linclamps activate, the change in force can cause misalignment	50	2	15	Medium	Proper testing and fit adjustments to the assembly.	Crawford
4	Misaligned CNC mirror base does nto route beam to camera	15	3	10 to 15	medium	Having a second person ensure measurements and diagrams in CAD before CNC	Jake
5	Incorrect Fresnel Shift estimation causing beam to improperly hit mirror	15	2	10 to 15	Medium	Having a second person ensure measurements calculations when mirror selection is made	Mitchell
			Total risk :	35			

Table1

FMEA Table

Process Step	Potential Failure Mode	Potenetial Failure Effect	SEV[1]	Potential Causes	OCC[2]	Current Process Controls	DET[3]	RPN[4]	Action Recommended
What is the step?	In what ways can step go wrong?	What is the impact on the customer if the failure mode is not prevented or corrected?	How severe is the effect on the customer?	What causes the step to go wrong (i.e. how could the failure mode occur)?	How frequently is the cause likely to occur?	What are the existing controls that either prevent the failure mode from occuring or detect it should it occur?	How probabale is detection of the failure mode or its cause?	Risk priority number calculated as SEV x OCC x DET	What are the actions for reducting the occurenece of the causes or for improving its detection? Provide actions on high RPNs and on severity ratings of 9 or 10
Milling raft assembly for mirror mounts	Wrong tool could be used.	If the wrong end mill is used, or wrong size diameter is selected for cutting, then the final product won't meet specified requirements.	3	Incorrect sizing in the design itself. Incorrect Mastercam commands from design to cut.	1	Design team needs to double check that all dimensions work in the assembly of the design phase. Operator of the cnc mill will then need to make sure that all sizing of the tools is chosen correctly before cutting takes place.	2	6	
Milling raft assembly for mirror mounts	Tool head can crash into the part the cnc is cutting or into the table.	If the cut isn't mapped correctly within Mastercam, the tool head could crash and fail.	3	Not monitoring the part as it's being cut. Poorly planning the cuts within the g-code.	1	Design team needs to double check that all dimensions work in the assembly of the design phase. Operator of the cnc mill will then need to make sure that all sizing of the tools is chosen correctly before cutting takes place.	2	6	
Assembling the ball screw to the raft assembly.	The ball screw could produce more backlash than we can account for.	If the backlash is to great, then precise movement of the mirror mount will be off from the required final location.	6	The resolution in the steps taken from the step motor will not be precise enough.	2	Testing the prototype to see if the ball screw needs to be fitted with a finer pitch as to provide for the increments in displacement that we are needing.	2	12	We will be able to determine the necessary specifications for the ball screw after testing and adjust accordingly.
Correct mirror alignement for each laser beam.	Misaligned CNC or wrong part selection	The camera down the beam will either miss or not see the entire beam profile or be aligned for an incorrect wavelength	3	Incorrect sizing in the design itself. Incorrect Master Cam commands from design to cut.	1	Design team needs to double check that all dimensions work in the assembly of the design phase. Operator of the cnc mill will then need to make sure that all sizing of the tools is chosen correctly before cutting takes place.	2	6	
Activating pneumatic clamps.	Air can leak from the line connections.	Any gases that leak into the vacuum chamber will compromise testing and produce poor results.	8	Poor seals in the line connections or the clamps themselves.	1	Testing the prototype and monitoring the air pressure during engagement of the clamps. If leaks occur, then locate where they are happening and determine next steps to fix the problem.	3	24	Monitoring air pressure during testing and make sure it stays constant during activation. If deactivating the clamps takes longer than normal, or more pressure is needed to disengage then there is most likely a leak. Make sure all connections are tight and secure.

Table 2

Project Timeline

- Sept 18 – Oct 1 (Weeks 1–2): Prototype Review and Baseline Analysis
    - Review existing prototype data for green and infrared beam diagnostics.
    - Identify performance gaps: sensitivity, stability, detector limits.

  - Deliverable: Initial assessment report summarizing diagnostic requirements for both beams.
  - Design the mirror mount transport assembly within SolidWorks, including all fasteners and electronics necessary for the development of the prototype.
- Oct 2 – Oct 15 (Weeks 3–4): Wavelength-Specific Diagnostic Evaluation
  - Select optical elements and detectors tailored to the green beam.
  - Repeat evaluation for the infrared beam, considering material response and sensor performance.
  - Deliverable: Technical memo with recommended component specifications for both diagnostic paths.
  - Procure all necessary materials needed for the assembly of the mirror mount transport prototype.
- Oct 16 – Oct 29 (Weeks 5–6): Design Optimization for Manufacturability
  - Refine CAD models and layouts to simplify assembly.
  - Standardize components (e.g., mounts, detectors) where possible across green and IR systems.
  - Deliverable: Updated design files and draft bill of materials (BOM)
  - Use Mastercam to bring the prototype from the design phase to the manufacturing floor.
- Oct 30 – Nov 12 (Weeks 7–8): Signal Routing and System Architecture
  - Define signal output strategy for near-field, far-field, and dark-field diagnostics.
  - Map routing architecture to Hub for synchronized acquisition.
  - Deliverable: System block diagram + integration plan for dual-beam diagnostics.
  - Assemble the mirror mount transport and get ready for testing.
- Nov 13 – Dec 3 (Weeks 9–10): Final Integration and Design Freeze
  - Consolidate all updates into a unified design package (schematics, CAD, BOM, routing).
  - Validate readiness through simulation and peer review.
  - Deliverable (End Goal): Complete design package finalized and ready for assembly after winter break.
  - Deliverable: Complete the building of the prototype.

Dates / Weeks	Optomechanics Team (Logan, Crawford, Cameron, Max, Michael)	Diagnostics Team (Paa, John, Jake, Mitchell)	Shared / Cross-Team Deliverables
Sept 18 – Oct 1 (Weeks 1–2)	Design mirror mount transport assembly in SolidWorks, including all fasteners and electronics for prototype development	Review existing prototype data for green and infrared beam diagnostics; identify performance gaps (sensitivity, stability, detector limits)	**Deliverable:** Initial assessment report summarizing diagnostic requirements; preliminary CAD design of mirror transport system
Oct 2 – Oct 15 (Weeks 3–4)	Procure materials for mirror mount transport prototype	Select optical elements and detectors for green beam; repeat evaluation for IR beam considering material response and detector performance	**Deliverable:** Technical memo recommending component specifications; purchasing orders submitted
Oct 16 – Oct 29 (Weeks 5–6)	Refine CAD models for manufacturability; prepare toolpaths in Mastercam for machining prototype components	Standardize detector/mount choices across green and IR systems; assist in BOM preparation	**Deliverable:** Updated CAD files + draft BOM; shop-ready manufacturing files
Oct 30 – Nov 12 (Weeks 7–8)	Machine and assemble mirror mount transport; integrate mechanical, electrical, and motion control subcomponents	Define signal output strategy for near-field, far-field, and dark-field diagnostics; map routing architecture to data Hub	**Deliverable:** System block diagram and integration plan; partially assembled mirror mount prototype
Nov 13 – Dec 3 (Weeks 9–10)	Complete assembly of mirror mount transport; perform initial motion testing for stability and micron-level precision	Consolidate diagnostics schematics, CAD, BOM, and routing diagrams; validate readiness through simulation and peer review	**Deliverable:** Unified design package (CAD, schematics, BOM, routing); fully assembled prototype ready for testing after winter break

Table 3: Fall Semester Timeline

Dates / Weeks	Optomechanics Team (Logan, Crawford, Cameron, Max, Michael)	Diagnostics Team (Paa, John, Jake, Mitchell)	Shared / Cross-Team Deliverables
Jan 13 – Jan 26 (Weeks 11–12)	Inspect assembled mirror mount transport for winter break storage issues; address alignment and tolerance concerns	Bench test diagnostic sensors with controlled input; confirm baseline performance	**Deliverable:** Winter break readiness review + restart checklist
Jan 27 – Feb 9 (Weeks 13–14)	Begin precision motion testing; refine PLC/motor control code for repeatability	Integrate sensors into preliminary DAQ system; validate signal acquisition for green and IR beams	**Deliverable:** Subsystem testing reports (motion + diagnostics separately)
Feb 10 – Feb 23 (Weeks 15–16)	Implement vibration damping strategies; upgrade mounts as needed for micron stability	Run dual-beam diagnostic tests; evaluate noise, calibration accuracy	**Deliverable:** Integration progress memo + updated calibration data
Feb 24 – Mar 9 (Weeks 17–18)	Assemble final motion system iteration; endurance test automation under repeated cycles	Finalize electronics layout; confirm Hub synchronization with multi-signal inputs	**Deliverable:** Full subsystem validation; final motion/diagnostics schematics
Mar 10 – Mar 23 (Weeks 19–20)	Prepare optomechanics stage for system-level integration; troubleshoot PLC control logic	Complete diagnostics calibration with mock laser inputs; finalize data acquisition scripts	**Deliverable:** System-level integration readiness report
Mar 24 – Apr 6 (Weeks 21–22)	Integrate mirror mount system with diagnostics stage; align optical paths	Assist with alignment; verify sensor data against expected optical outputs	**Deliverable:** System integration trial run + alignment log
Apr 7 – Apr 20 (Weeks 23–24)	Stress-test motion system under operational conditions; record precision drift data	Collect long-duration diagnostics datasets; ensure data consistency and storage reliability	**Deliverable:** Full system validation report (motion + diagnostics working together)
Apr 21 – May 4 (Weeks 25–26)	Polish system for final demonstration; finalize CAD, schematics, and BOM for paper	Document calibration curves, diagnostic limits, and data outputs	**Deliverable:** Final project report + poster + presentation; system ready for handoff

Table 4: Spring Semester Timeline

Citation

Booth, M. (2023, August 9). *CSU to build one of the world's most powerful lasers to study elusive nuclear fusion energy*. The Colorado Sun. https://coloradosun.com/2023/08/10/csu-marvel-nuclear-fusion-energy-research/

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Leland, A. (2023, December 7). *CSU to lead DOE-funded multi-institution hub to advance laser-driven Fusion Energy*. Walter Scott, Jr. College of Engineering. https://engr.source.colostate.edu/csu-to-lead-doe-funded-multi-institution-hub-to-advance-laser-driven-fusion-energy/