NSF OPAL: a next-generation, user facility for studying ultra-high-intensity laser–matter interactions

# OPAL

Optical Parametric Amplifier Line

## FY25 Annual Report

S-OP-M-037 Rev A

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NSF

UNIVERSITY of ROCHESTER

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# Annual Report 2025

# NSF OPAL Midscale Research Infrastructure (RI-1)
# Design and Prototype Project

**Led by the**
**University of Rochester**
**Rochester, NY**

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# Contents

# 1. Cover Page

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| NSF Award number: | 2329970 |
| Title: | Research Infrastructure: Midscale RI-1 (M1:DP): OMEGA-EP-Pumped Optical Parametric Amplifier Line (EP-OPAL) Facility Design [Rebranded NSF OPAL] |
| Recipient Organization: | University of Rochester |
| Submitted by: | Jonathan Zuegel (Principal Investigator)<br>Ani Aprahamian, University of Notre Dame (Co-Principal Investigator)<br>Antonino Di Piazza (Co-Principal Investigator)<br>Franklin Dollar, University of California Irvine (Co-Principal Investigator)<br>Eva Zurek, University at Buffalo (Co-Principal Investigator) |
| Period of Award: | 10/01/2023-09/30/2026 |
| Reporting Period: | 07/01/2024-06/30/2025 |
| Report Submission Date: | 8/29/2025 |

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# 2. Introduction

The NSF OPAL RI-1 award supports the design of a new, world-leading, high-power laser user facility led by the University of Rochester (UR). This design project envisions two new powerful lasers to be located at the UR. NSF OPAL will employ a technique developed at UR for the generation of very powerful, ultrashort laser pulses that was recognized by the 2018 Nobel Prize in Physics. This project was awarded, in part, as a response to the Multi-Petawatt Physics Prioritization (MP3) workshop and recommendations from a 2018 National Academy of Science Report "Opportunities in Intense Ultrafast Lasers: Reaching the Brightest Light" that advocated for the construction of midscale university-based intense laser facilities in the US, as well as other studies and reports that led to the MP3 workshop.

NSF OPAL aims to push beyond the current state of the art in peak laser power to achieve and study extreme physical conditions, such as ultrahigh electromagnetic fields, temperatures, and pressures that represent the frontier of science in studying matter in the Universe. The design effort engages U.S. industry to develop critical laser optics and include hands-on training of a new generation of laser facility designers, builders, and users. The main aims of the project are to: (1) design the NSF OPAL facility, including lasers, experimental systems and engage the user community to design diagnostics, to address a wide array of compelling science; (2) design and prototype high-energy laser amplifiers with shot-cycle times of a few minutes; (3) design and prototype large-optics production and characterization systems.

## 2.1 Overview

The second year of the NSF OPAL RI-1 design and prototyping project focused on conceptual design. Numerous peer reviews of subsystems were held before the overall project Conceptual Design Review (CDR) held on April 22-23, 2025. A complementary effort funded by the University of Rochester completed conceptual design of new buildings that would house and support NSF OPAL.

**FY24Q4 (project Q4)** included 11 peer reviews of subsystem designs to prepare for CDR. RI-1 project team members and scientific colleagues participated in a four-session mini-conference (MC) on Multi-Petawatt Physics at New and Future Laser User Facilities at the American Physical Society – Division of Plasma Physics (APS-DPP) Annual Meeting in Atlanta, GA, October 7-11, 2024. Despite being scheduled at the end of the APS-DPP meeting, attendance proved robust.

**FY25Q1 (project Q5)** included seven remaining peer reviews of subsystem designs to prepare for the CDR. Considerable effort was applied to commissioning the AMICA laser in the FLUX project, a complementary effort. The AMICA laser plays a critical role pumping optical parametric amplifiers in both the FLUX and NSF OPAL system designs.

**FY25Q2 (project Q6)** included hosting an NSF site visit panel on January 21-23, 2025, and an external advisory board (EAB) meeting on February 10-11, 2025.

**FY25Q3 (project Q7)** focused on preparing for and holding the RI-1 conceptual design review (CDR). It was streamed on Zoom with 224 members of the scientific community registered from 59 institutions. Based on feedback from the CDR, the project identified two areas where additional technical risk could be pursued to reduce the potential construction project cost: (1) prototyping low-cost, lightweight, mirrors and (2) improving the laser induced damage threshold (LIDT) of gratings and short-pulse transport optics to enable smaller optics. RI-1 project team members presented talks and posters about NSF OPAL at the Omega Laser Facility User Group (OLUG) meeting held May 20-22, 2025, as well as a presentation at the annual ELI User Meeting held in Szeged, Hungary, on June 18-20, 2025. The team finalized the language of an MOU with LLNL on a path to acquire $D_2O$ needed for growing boules of DKDP.

Section 3 summarizes the RI-1 project management and organization. Section 4 highlights project accomplishments during the reporting periods, while Sec. 5 reflects the project's impacts. Section 6 lists project products that include numerous activities by the extended NSF OPAL RI-1 team that provided significant exposure to the project. These included published papers and submitted manuscripts (4), conference and workshop presentations (30), and colloquia and seminar presentations (7) supported directly by the RI-1 project, as well as published papers and submitted manuscripts (2), and conference and workshop presentations (5) by collaborations and complementary programs not supported by RI-1 project. The project team participated in summer schools (6), and technical visits and exchanges (13).

Section 7 summarizes participation by early-career team members in the RI-1 project team at several levels of education, training, and employment that included post-doctoral fellows (5), graduate students (8), recent college graduates (4), undergraduate students (13), and high-school students (2). Section 8 identifies two changes to the project and Sec. 9 provides a financial summary. Section 10 includes one appendix listing Facility Design Peer Reviews and when they were held.

The third annual project report will cover the next four quarters of the project, FY25Q4 through FY26Q3.

## 2.2 Vision and Mission

The NSF OPAL user facility conceptual design, shown in Fig. 2.1, will further missions to conduct research and development and to provide education and training in four areas of frontier research, including particle acceleration and advanced light sources (PAALS), high-field physics and quantum electrodynamics (HFP/QED), laboratory astrophysics and planetary physics (LAPP), and laser-driven nuclear physics (LDNP), as well as high-power lasers and materials technologies. These scientific goals guide the design of NSF OPAL.

The NSF OPAL RI-1 project engages members of all four scientific communities (PAALS, HFP/QED, LAPP, and LDNP) through frontier science working groups (FSWGs) led by the co-PIs and composed of established and early-career professionals, as well as graduate and undergraduate students, at UR and other participating universities. The project leverages scientific and technical expertise across the community, including subawardees, as well as colleagues at U.S. and international universities and facilities. Several companies engaged with the RI-1 project involve professionals and students to address scientific and technical challenges.

The conceptual design evolved significantly from the initial version included in the first annual report. Figure 1(a) shows a layout that progressed to a more compact and efficient configuration with a significant reduction in estimated building construction cost. A key design change involved replacing independent experimental areas (EA1 and EA2) with a single target bay with upper and lower levels along with a single-level laser bay with beam transport at ground level to maximize OPAL beam stability. The new design also swaps the two 25-PW "Alpha" OPAL beams locations along with changing their focusing configurations in the main target chamber located in the upper target bay. An orange "colonnade" shown in Fig. 2(a) and 2(b) supports beam delivery to the main target chamber and it supplements radiation shielding toward the laser bay. Simulations also showed that less concrete is required generally to meet radiation shielding requirements than originally estimated, which significantly reduces building construction costs.

Based on feedback from the CDR, the project identified two areas where additional technical risk could be pursued to reduce the potential future construction project cost. To pursue these areas, the WBS 2.2 extra-large (XL) grating subaward to Plymouth Grating Laboratory (PGL) was paused while the project team reassessed the needed funding profile to complete the Nanoruler5 (NR5) design and to defer NR5 construction after the RI-1 project. NR5 construction costs will be redirected to (1) prototyping low-cost, lightweight, mirrors and (2) improving the laser induced damage threshold (LIDT) of gratings and short-pulse transport optics to enable using smaller aperture optics.

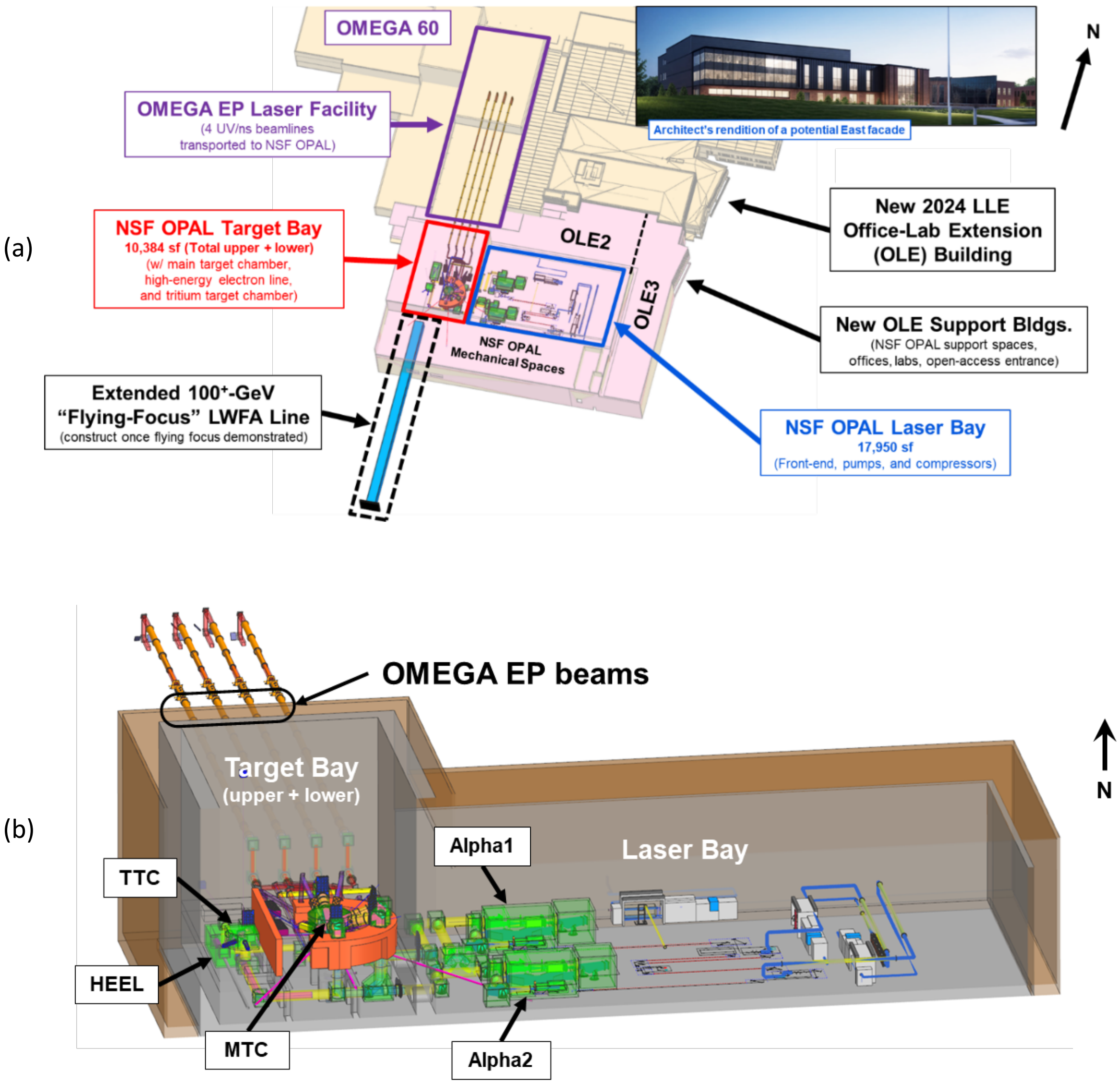
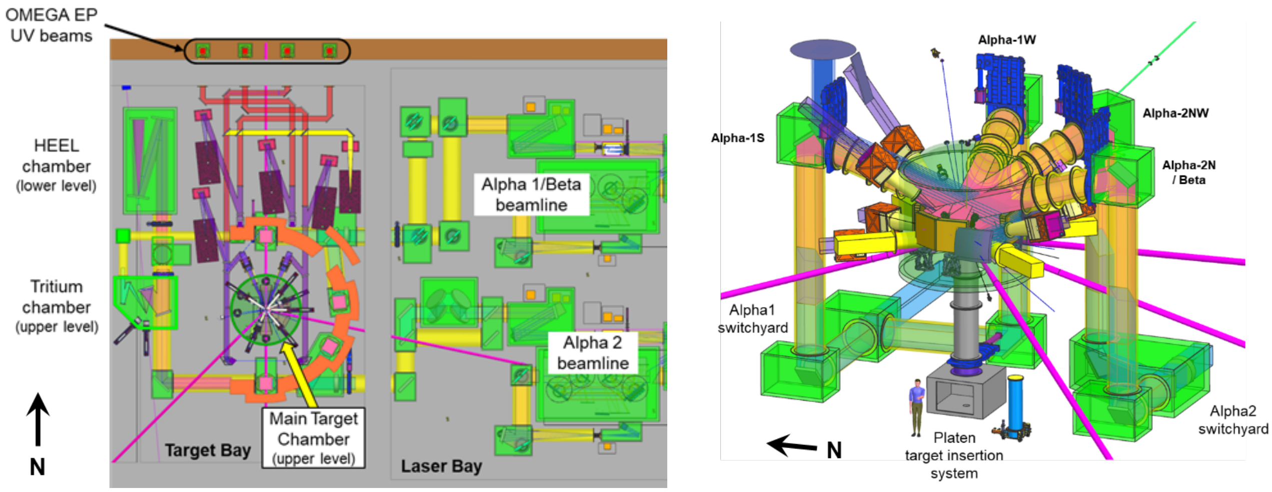



Figure 2.1 – Conceptual design of the NSF OPAL user facility. (a) Two new buildings adjoin the existing UR/LLE facility: the NSF OPAL facility with associated mechanical spaces, and additional office/lab extensions (OLE2/OLE3). Inset shows an architectural rendering of the OLE3 East façade. (b) A cutaway view of the NSF OPAL facility shows the ground-level laser bay with beam transport and the high-energy electron line (HEEL) chamber in lower target bay and the main target chamber (MTC) and tritium target chamber (TTC) in the upper target bay.




(a) (b)

Figure 2.2 – NSF OPAL layouts. (a) Plan view of target and laser bays (upper target bay floor removed to show lower target bay). The two OPAL beamlines run East to West from their respective grating compression chambers with vacuum beam transport into the lower target bay at grade level. The beam transport delivers beams to the main target and tritium target chambers in the upper target bay, and the high-energy electron line (HEEL) in the lower target bay. A semi-circular concrete structure (orange) supports the OPAL beam transport and provides additional radiation shielding in the eastward direction. (b) Isometric view of main target chamber (structures removed for clarity) with switchyards that direct each Alpha beam to one of two configurations designated by the direction of the beam towards target chamber center. A platen target insertion system in the lower laser bay provides an air lock to deliver platforms pre-configured for experiments.

Section 4.1 describes the activities and progress made by the NSF OPAL frontier science working groups (FSWGs) during this reporting period, while sections 4.2 and 4.3 describe the facility design and prototyping efforts, respectively.

The NSF OPAL facility is envisioned to serve as a learning environment and a hub for diverse scientific networks, offering opportunities for fundamental research and innovation, as well as medical, industrial and national security applications. The NSF OPAL facility design effort engages collaborators at the University of Buffalo, the University of California - Irvine, the University of Notre Dame, the Ohio State University, the University of Maryland - College Park, the University of Michigan - Ann Arbor, and an industrial partner, Plymouth Grating Laboratory.

# 3. Management and Organization

## 3.1 Roles and Responsibilities

The NSF OPAL RI-1 Design Project is managed by an integrated project team drawn from experienced scientists, engineers, and technicians. Figure 3.1 shows the management structure of the project. This management structure generally follows the approach used in the OMEGA Upgrade Project completed in 1995 and the OMEGA Extended Performance (OMEGA EP) Project completed in 2008 that were similarly sized projects in funding and scope.

The UR Principal Investigator/Project Director (PI/PD) and external co-Principal Investigators (co-PIs) work with the UR/LLE science team composed of senior personnel (SP) to build the short-pulse science community and ensure that users are engaged and prepared for experiments on NSF OPAL. The PI, co-PIs, and SP will ensure that the laser and experimental systems will support the scientific objectives.

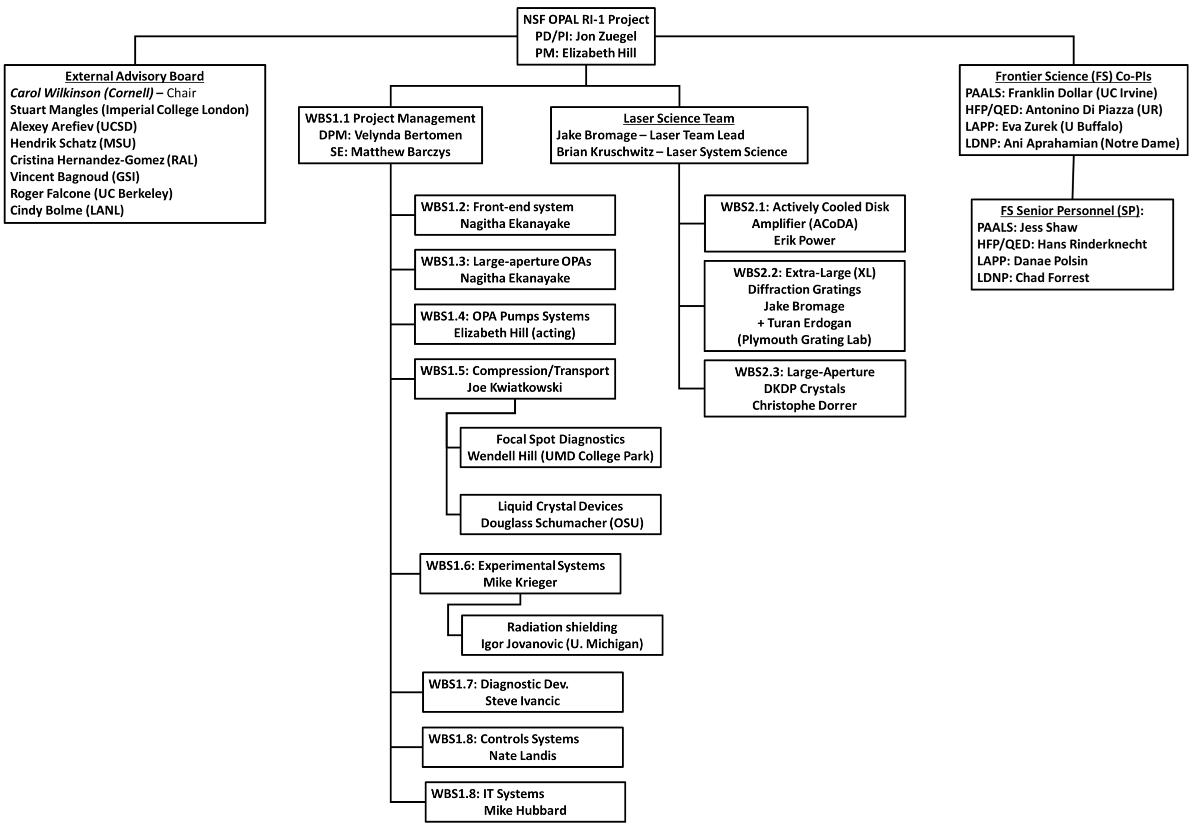



Figure 3.1 – NSF OPAL project team organization.

The UR project team comprises experimental scientists, laser scientists, and engineers that represent additional senior personnel (SP). The PI/PD reports to the UR/LLE Director. The Project Manager oversees the efforts of the WBS 1 facility-design work breakdown structure (WBS) sections (Sec. 4.2) in close coordination with the frontier science (co-PIs and SP) and laser science teams. The laser science team leads the WBS 2 prototyping efforts (Sec 4.3). Expertise outside of the University of Rochester is engaged via subawards to design and/or develop key components or techniques, as indicated in Fig. 3.1 in blue text.

## 3.2 External Advisory Board

The External Advisory Board (EAB) is charged with executive-level monitoring of the project and assessment of progress, principally regarding the milestones as defined at the initial stages of the project and documented in the Project Execution Plan (PEP). In addition, the EAB will provide feedback, strategic advice and a community perspective on key considerations for the laser and target area design and subsequent operation of NSF OPAL as a potential future user facility.

The NSF OPAL project team reports twice per year on project progress to the External Advisory Board. One meeting per year will be held in person with a second virtual meeting per year, as needed. The EAB will provide feedback to the NSF OPAL RI-1 project team about key aspects of the project deliverables to ensure focus and direction. It will:

- receive reports from the project director and project manager on progress and technical details including work completed, spend to date, future work plans and future financial plans, administrative management of the project, institutional commitments, and any other matters that relate to the project;
- advise and evaluate progress on the design of the NSF OPAL facility, including final technical design, risk management, and adherence to stated performance metrics review and evaluate the technical design, scientific progress and direction of the project;
- advise on preparations of NSF OPAL for potential future construction and operations as an NSF user facility;
- advise on community outreach and other activities; and
- complete an annual report evaluating project's progress and providing forward-looking recommendations.

The EAB comprises scientists and technical experts external to the University of Rochester and any RI-1 project subawardees. Members of the EAB serve in an individual capacity without remuneration and shall not be associated with the RI-1 project contractually. EAB members will serve for the duration of the three-year RI-1 project. The Chair prepares the agenda for EAB meeting in consultation with the project team, conducts meetings of the EAB, and reports findings to the RI-1 Project Director. Current EAB members include:

- Dr. Carol Wilkinson [Chair] – Wilkinson Consulting (USA)
- Prof. Alexey Arefiev – University of California San Diego (USA)
- Dr. Prof. Vincent Bagnoud – GSI Helmholtz Centre for Heavy Ion Research (Germany)
- Dr. Cindy Bolme – Los Alamos National Lab (USA)
- Prof. Roger Falcone – University of California Berkeley (USA)
- Dr. Cristina Hernandez-Gomez – Rutherford Appleton Laboratory (UK)
- Prof. Stuart Mangles – Imperial College London (UK)
- Prof. Hendrik Schatz – Michigan State Univ. (USA)
- Prof. Janet Tsai – Univ. of Colorado Boulder (USA) [Resigned during reporting period]

The EAB will meet at times collectively determined by the EAB and NSF OPAL project team. Meeting minutes are drafted by a University of Rochester facilitator and sent to all EAB members for review and approval.

# 4. Accomplishments

## 4.1 NSF OPAL Frontier Science Working Groups (FSWGs)

The second year of the RI-1 project focused on community building and completing conceptual design efforts to address four areas of frontier research identified by the 2022 Multi-Petawatt Physics Prioritization (MP3) workshop:

- Particle Acceleration and Advanced Light Sources (PAALS)
- High-Field Physics and Quantum Electrodynamics (HFP/QED)
- Laboratory Astrophysics and Planetary Physics (LAPP)
- Laser-Driven Nuclear Physics (LDNP)

### 4.1.1 Particle Acceleration and Advanced Light Source (PAALS) – Co-PI Franklin Dollar

The PAALS Frontier Science Working Group organized several major activities related to down selection for CDR, outreach, and experimental development. These efforts culminated in the successful CDR and a broader presence of OPAL with respect to the PAALS community.

Two flagship-level experiments include a Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams (PAALS1) and Multi-Messenger Probing of Ultra-Intense/Relativistic Light-Matter Interactions (PAALS2). Flagship teams and champions performed investigations into these experiments, publishing and presenting them in major journals and conferences, respectively. Working with the design team, PAALS1 requires both a flexible focusing geometry and a specialized target chamber to accommodate the large plasma length. PAALS2 flagship requires specific Alpha beam geometries with respect to precisely positioned targets in the main target chamber. PAALS1 was selected as a flagship and prioritized for the CDR.

The FSWG teams and champions for the proposed flagship experiments participated in numerous conferences to increase visibility of both the flagship projects and NSF OPAL, notably presentations at the mini-conference on Multi-Petawatt Physics held at the American Physical Society Division of Plasma Physics Annual Meeting. The PAALS team also participated in the Multidisciplinary Science in the Multi-messenger Era (TDAMM) workshop, a new venue for the PAALS community. The joint LaserNetUS/NSF ZEUS workshop also had presentations on NSF OPAL, and an upcoming Kavli workshop will focus on PAALS-relevant topics.

Advances on the experimental development of the flagships also commenced. Co-PI Dollar performed the first experimental run on the NSF ZEUS facility at 2-PW peak power and demonstrated electron beams with several GeV energies. Initial experiments on scaled versions of dephasingless electron acceleration were performed at UR, and planning commenced for experiments on MPW facilities, such as NSF ZEUS. Numerical modeling of both flagship experiments is being performed by many participants and FSWG members, including undergraduate researchers.

Inverse Compton scattering (ICS) source development efforts are reported in Sec. 4.1.3.

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The FSWG will continue to meet to determine scientific goals for NSF OPAL and to aid the design team on the path towards PDR. The co-PI will continue to organize these events, and FSWG members will attend a new Working Group Meeting (WGM) to help with this regard.

We plan on better tracking PAALS activities and experiments, working towards community development and sharing of resources such that the flagship projects can be ready to implement once OPAL construction is complete.

We will work to engage students across the board, including undergraduate researchers who may want to use OPAL for their dissertation work, to graduate students whose science can build towards the Flagship experiments. Co-PI Dollar will work with APS to facilitate OPAL related activities at the upcoming APS DPP Annual Meeting.

### 4.1.2 High-Field Physics and Quantum Electrodynamics (HFP/QED) – Co-PI Antonino Di Piazza

The activities of the HFP/QED working group have been closely related to the three flagship experiments: Fully Non-Perturbative Regime of Strong-Field QED (HFP/QED1), Stimulated Photon-Photon Scattering (HFP/QED2), and Precursor of a QED Cascade (HFP/QED3). Although HFP/QED1 and HFP/QED3 have been selected as future flagship experiments, the group has worked on projects related to all three experiments:

HFP/QED1 (Fully Non-Perturbative Regime of Strong-Field QED): The newly enrolled graduate student Adrian Hosak (UR Horton Fellow) has computed the first-order radiative correction to nonlinear Compton scattering and nonlinear Breit-Wheeler pair production accounting for the fact that the outgoing (incoming) photon in nonlinear Compton scattering (Breit-Wheeler pair production) can temporarily transform into an electron-positron pair after (before) the main process occurs. Due to the complexity of the calculation, he has been assisted by the newly hired post-doc Misha Lopez-Lopez. The calculations agree with the Ritus-Narozhny conjecture and the corrections are predicted to become substantial at NSF OPAL. We expect to submit the results in the next couple of months.

HFP/QED2 (Stimulated Photon-Photon Scattering): The team lead by Hans Rinderknecht and coordinated by co-PI Antonino Di Piazza has completed and submitted the manuscript entitled “On Measuring Stimulated Photon-photon Scattering using Multiple Ultraintense Lasers” to Physics of Plasmas in the special collection associated to the APS-DPP mini-conference on Multipetawatt Physics. The manuscript has been recently accepted for publication. We have contacted a team lead by Luis Silva (IST Lisbon) and Peter Norreys (Oxford Univ.) that has developed a numerical code to simulate extremely accurately the process of stimulated photon-photon scattering. We have already provided the numerical parameters to perform simulations tailored to NSF OPAL and wait for the results. On the technical side, we continue to develop our internal model to predict the effects of realistic NSF OPAL beam parameters on the flagship SPPS experiment results, with a goal of incorporating realistic near-field profiles and focusing, and spatio-temporal focal distortions. In collaboration with the project team, we have reviewed polarization options in the experimental layout and identified beam pointing correlations that will affect the statistical performance of an NSF OPAL stimulated photon-photon scattering campaign. We have begun a project to demonstrate temporary absolute vacuum generation via electrostatic sweeping, which will culminate in experiments on OMEGA-EP in FY 2026.

HFP/QED3 (Precursor of a QED Cascade): The team led by Gianluca Gregori and Arseny Mironov, a post-doc in the group of Caterina Riconda, has completed and submitted the manuscript titled “Testing strong-field QED with the avalanche precursor” to Physics of Plasmas in the special collection associated to the APS-DPP mini-conference on Multipetawatt Physics. We have received the referees’ reports and we are preparing the response to the referees’ remarks. Based on the reports, we are confident that the manuscript will be accepted. In the meantime, Gianluca Gregori and Antonino Di Piazza have discussed multiple times with Kale Weichman from UR/LLE, who has proposed a related but different setup to observe a QED cascade at NSF OPAL. They suggested putting two micro-cones at the sides of the thin target and focusing the two NSF OPAL beams onto the micro-cones. According to their simulations, the latter would further focus and then intensify the beams making it feasible to observe a QED cascade rather than only the precursor. Kale has been introduced to the rest of the team, which is excited about Kale's preliminary results.

Other members of Co-PI Antonino Di Piazza's UR research group worked on projects closely related to NSF OPAL. Reshad Rahman (Horton Fellow) continues his activities on the production and transportation of electron-positron beams by using flying-focus beams with orbital angular momentum. Thomas de Vos (Horton Fellow) started with the group recently and work on fundamental techniques based on non-equilibrium QED to study systems of electrons, positrons, and photons in the presence of a strong electromagnetic field. Recently hired post-doc Sapan Karki (NSF-GACR Fellow) works on coherence effects in the collision of dense particle bunches with ultra-intense laser beams with the overarching goal of ascertaining the feasibility of a gamma-ray free-electron laser. Finally, John Palastro and Bernardo Barbosa, a visiting student at UR/LLE, continue their collaboration on the head-on collision of an ultra-relativistic electron beam and a high-intensity laser pulse in plasma.

*Plans for FY26*

We plan to continue all the projects mentioned above and submit manuscripts when ready. We plan to perform experiments at OMEGA EP to demonstrate temporary absolute vacuum generation via electrostatic sweeping.

### 4.1.3 Laboratory Astrophysics and Planetary Physics (LAPP) – Co-PI Eva Zurek

The LAPP flagship experimental capability aims to examine materials under intense pressure and high temperatures, exploring a broad range of conditions to enhance dynamic compression techniques in conjunction with frontier methods for impulsive femtosecond heating and particle and photon probing. The ultimate flagship capability aims to shock and ramp-compress planetary materials to TPa pressures and use the femtosecond PW beams to create ultrafast probes for time-resolved X-ray and electron diffraction, radiography and phase contrast imaging, and X-ray emission and absorption spectroscopy. The following work progressed on the three stages of experiments leading to the flagship:

<u>Relativistic pair plasmas</u>: Hui Chen (LLNL) is collaborating with LULI in pair plasma experiments at the Apollon laser at 5E22 W/cm^2 to benchmark the yield scaling. In addition, the team is improving the diagnostics for pair plasmas in terms of energy range of detection sensitivity.

<u>Dense plasma spectroscopy</u>: The UR/LLE HED experimental and theoretical teams collaborated with LLNL to use DFT-based atomic kinetic codes coupled with the MERL line shape code to inform the design of novel short pulse buried layer experiments for the MTW and TITAN lasers to study the effects of non-thermal electrons on atomic structure and spectroscopic line shapes in dense plasmas.

<u>Planetary materials</u>: Zurek, Polsin, and Racioppi participated in NSF OPAL-related experiments at the National Ignition Facility to characterize the structure of planetary materials ($SiO_2$, $Al_2O_3$, Na, etc.) in the terapascal regime.

<u>Inverse Compton scattering (ICS) source</u>: Colleagues at LANL developed two concepts for enhancing the x-ray output from an ICS source for LAPP experiments were proposed and awarded three weeks of beam time on the Accelerator Test Facility at Brookhaven National Laboratory (BNL-ATF) to test the theories. Some tabletop work on laser alignment and damage limits of optics has begun at LANL and a proceedings paper was written and will be published in FY25 by Gerrit Bruhaug (LANL), who also presented at two conferences in FY25 about our work and concepts.

*Plans for FY26*

Relativistic pair plasmas: The plasma experiments are ongoing, as is the development of the diagnostics.

Dense Plasma Spectroscopy experiments: Experiments designed in FY25 will be performed on the MTW and TITAN lasers. These experiments will be used to improve our understanding of line shapes in dense plasmas and the effects of relativistic electrons on atomic structures of low to mid-Z materials. New high-resolution spectrometers will be designed to conduct detailed line shape measurements in the unique and challenging environments created during short pulse laser experiments.

The LAPP and PAALS teams continue evaluating the feasibility of using NSF OPAL to generate secondary electron and x-ray sources for their use as probes. We plan on doing preliminary experiments at BNL first focused on beam control and then later focusing on x-ray production and benchmarking our models.

### 4.1.4 Laser-Driven Nuclear Physics (LDNP) – Co-PI Ani Aprahamian

The LDNP working group plans nuclear physics experiments using powerful lasers that can explore in the laboratory nucleosynthesis reactions that occurred during the earliest times of the universe and study fundamental symmetries on light nucleons. Ongoing experiments at current facilities are critical to the design of the proposed NSF OPAL laser facility. LDNP proposed two flagship experiments for NSF OPAL: tritium-induced nucleosynthesis (LDNP1) and neutron-neutron scattering (LDNP2).

LDNP1 progress:

- Published a paper describing the importance of tritium-induced reactions during Big Bang Nucleosynthesis (BBN) and laboratory experiments to constrain theoretical models [1]. Ani Aprahamian, co-PI, presented the paper in a recorded seminar at Rutgers University on April 30, 2025, titled, "Were the Superheavy Elements Made in Nature?"
- Completed first $^{3}$H-Li proof-of-principle experiment on OMEGA (DiagTime-J-25A) using OMEGA EP short pulses to generate a triton beam directed into a lithium target. The results led to initiating a project to develop a cryogenic target that will be fielded in October 2025.
- Completed design and engineering of a cryogenic target needed for the October 2025 experiment on OMEGA.
- Completed design and Initial Qualification Review (IQR) for a TIM-Based Phoswich Detector (also known as the Short-Lived Isotope Counting System, SLICS) that will be used first in two days of OMEGA EP experiments scheduled in August 2025. The experiments will use a deuteron beam to measure the $^{7}$Li(d,p)$^{8}$Li reaction cross section to qualify the phoswich detector developed in a collaboration led by two local, undergraduate colleges (Houghton University and SUNY Geneseo).

LDNP2 progress: Neutron-neutron scattering experiments require high-flux neutron beams given the low but unmeasured elastic-scattering cross sections. The neutron intensity is essential to initiate neutron-neutron scattering. Leixi Chen, a 2025 Pittsford Mendon high-school summer high-school student, started developing simulations to estimate the requirements to deliver intense neutron bursts from high powered lasers to perform this experiment.

1 Ani Aprahamian et al. "Nucleosynthesis with tritium," J. Phys. G: Nucl. Part. Phys. 52 063001; https://doi.org/10.1088/1361-6471/addc86.

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The design and engineering of a cryogenic target has been completed, and a cryogenic target will be fielded in the first quarter and third quarter of FY26. In these proposed experiments, the Phoswich detector will be used for tritium-induced nuclear reactions. These experiments will focus on $^{7}Li(t,\alpha)^{6}He$ and $^{9}Be(t,\alpha)^{8}Li$ reactions.

## 4.2 NSF OPAL Facility Design (WBS 1)

### 4.2.1 WBS 1.1: Project Management

Jon Zuegel serves as principal investigator/project director (PI/PD), Elizabeth Hill serves as project manager (PM), Velynda Bertomen serves as deputy project manager (DPM), and Matthew Barczys serves as system engineer (SE).

**Project Management:**
In the past year, the project management team worked to optimize the WBS structure, improve the risk management approach, coordinate various reviews (NSF Site Visits, EAB meetings, community updates, peer reviews, and the Conceptual Design Review (CDR)), and identify opportunities to manage potential future construction costs through additional advanced prototyping.

The WBS structure was optimized by:

- separating the Controls and IT systems into distinct WBS 1, Level-2, elements;
- providing greater clarity on the project's potential timeline to advance from the current RI-1 phase through construction, enabling WBS Level-2 leads to better refine their schedules for the current project period;
- shifting the focus of the diagnostic development effort towards community building;
- identifying appropriate WBS Level-2 leads; and
- moving the Liquid Crystal (WBS 1.5), Focal Spot Intensity (WBS 1.5), and Shielding (WBS 1.6) sub-awards to appropriate WBS-1 section for improved tracking.

The project risk management approach has significantly evolved since the beginning of the RI-1 project. Initially, many project uncertainties were intermingled with risks on the register. The project management team shifted toward standard uncertainty assessment approaches, using design maturity and judgment factors as part of schedule and contingency development. As part of the Conceptual Design Review preparation, the design team thoroughly scrubbed the risk register to ensure a complete identification of discrete risks that could threaten the project.

In the past four quarters, the project management team organized two NSF Site Visits, two EAB meetings, 15 peer reviews (Appendix A), and the project Conceptual Design Review. Action items are captured and tracked to ensure the design team addresses any noted concerns about project direction or areas for improvement.

Following the CDR, it became clear that the cost of the proposed facility would likely exceed supportable levels. The project team identified multiple options: either descope the RI-1 or expand it to explore additional prototyping efforts that would allow higher-risk options to be included in the proposed facility design. Two primary areas for the RI-1 project to explore were identified: advanced mirror technology and advanced coatings for femtosecond-class lasers. To support these two technologies, the scope of the existing PGL subaward was modified to provide funds for two new WBS 2 elements, WBS 2.4 (Advanced

Mirrors) and WBS 2.5 (Advanced Coatings), that will be incorporated in a forthcoming revision to the Project Execution Plan.

*Plans for FY26*

In the coming year the project management team will continue to support the design team members, coordinate reviews, work to improve communication and engagement within the community, and continue to provide bi-weekly, monthly, quarterly, and annual reports.

**System Engineering:**

Systems Engineering (SE) focused on developing subsystem functional requirements, key facility concepts of operation, and a project change control process. SE selected and began implementation of a requirements management tool, interface management strategy, and change control workflow. The SE group also added a University of Rochester third-year Computer Science undergraduate student, offering the opportunity for her to learn and practice key project leadership skills: systems engineering, project management, and scientific/technical communication skills as part of the overall NSF OPAL workforce development effort.

SE completed the initial release of the overall facility concept of operations. Building on that effort, SE developed multiple key "end-to-end" concepts of operations that coordinate the activities of multiple subsystems, such as co-timing, co-pointing, debris management, laser energy adjustments, radiation management, beam & target alignment systems, campaign preparation, and facility hazard mitigation.

SE implemented enterprise-level applications, Azure DevOps and Modern Requirements4DevOps, and uses them for change control and requirements/interface management, respectively. They will be used throughout the life of the NSF OPAL project, including a potential future construction project.

*Plans for FY26*

For FY26, main tasks include completing implementation of the change control workflow, assembling a complete set of threshold requirements to define a construction project proposal, refinement of concepts of operation, and development of an integrated plan for facility capability maturation from construction project completion to flagship experiment implementation.

### 4.2.2 WBS 1.2: Front-End System

The WBS 1.2 team completed compilation of subsystem requirements, documentation of interfaces, concept of operations, and peer reviews of the conceptual design prior to presenting at the conceptual design review (CDR). Beyond the CDR, the team engaged in critical prototyping and testing of a second-generation ultrabroadband front end (UFE2.0) for the MTW-OPAL front end that will serve as a prototype for NSF OPAL.

The UFE2.0 block diagram, shown in Figure 4.1(a), builds on the existing ultra-broadband front end for the MTW-OPAL with several upgrades. UFE2.0 uses an industrial-grade, femtosecond Yb:KGW laser system (Pharos from Light Conversion) to replace the custom-built Yb fiber amplifier as the femtosecond driver. The Pharos laser has been widely adopted and proven in numerous broadband laser systems with outstanding system performance and long-term serviceability. The shorter 1030-nm wavelength compared to UFE1.0 requires red-shifting [highlighted in Fig. 4.1(a)] to drive the white-light continuum (WLC) needed for OPAL ultra-broadband seeding. This red shift is required to avoid complicated spatiospectral coupling of both the amplitude and phase in the vicinity of the driver wavelength, which can degrade the focused laser intensity.

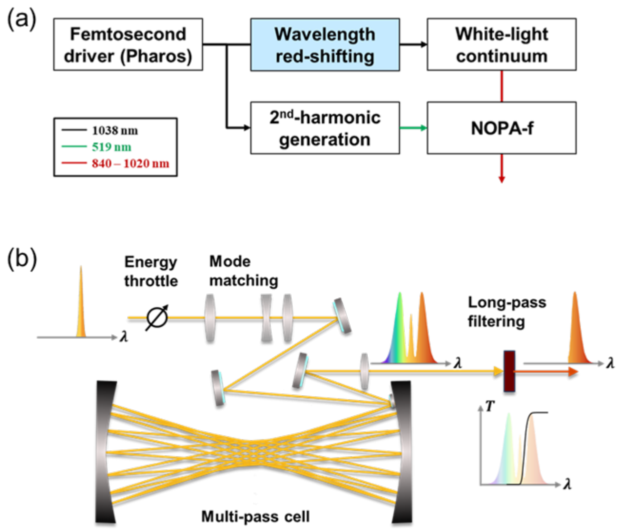


Figure 4.1 – (a) Block diagram of the new ultra-broadband front end (UFE2.0) including the femtosecond noncollinear optical parametric amplification (NOPA-f) stage; (b) Schematic of the multi-pass cell (MPC) setup for nonlinear spectral broadening followed by long-pass spectral filtering to generate femtosecond pulses at the wavelength required to drive white-light continuum that produces the spectrum required to seed MTW-OPAL and NSF OPAL.

Several petawatt laser facilities, such as PEARL [2] and SEL [3], have reported ways to generate ultra-broadband seed pulses in their front-ends, but all have involved multiple nonlinear optical stages. UFE2.0 employs only one nonlinear optical stage, a multi-pass cell (MPC) for spectral broadening that has proven useful in other applications [4]. Long-pass spectral filtering [see Figure 4.1(b)] selects the wavelengths required to drive white-light continuum generation. The MPC nonlinear spectral broadening is a state-of-the-art technique that has been developed over the past few years and has already been commercialized by several companies, indicating its robustness for our application.

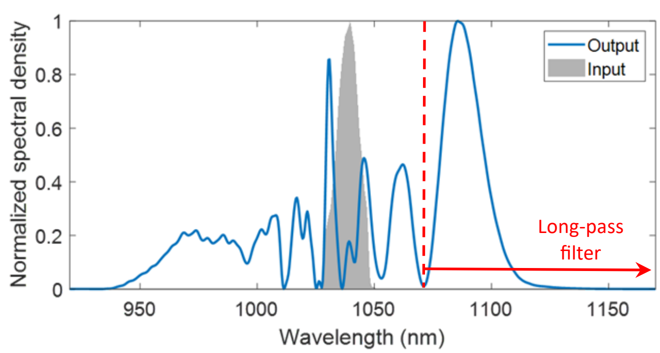


Figure 4.2 – Measured multi-pass cell (MPC) input and output spectra. The right-most sidelobe in the output spectrum will be selected using a custom long-pass filter to drive white-light continuum (WLC), as shown schematically in Fig. 4.1.

2 I. B. Mukhin, K. A. Glushkov, A. A. Soloviev, A. A. Shaykin, V. N. Ginzburg, I. V. Kuzmin, M. A. Martyanov, S. E. Stukachev, S. Yu. Mironov, I. V. Yakovlev, and E. A. Khazanov, "Upgrading the front end of the petawatt-class PEARL laser facility," Appl. Opt. 62, 2554-2559 (2023); https://doi.org/10.1364/AO.483533.

3 Li Y, Shao B, Peng Y, et al. Ultra-broadband pulse generation via hollow-core fiber compression and frequency doubling for ultra-intense lasers. High Power Laser Science and Engineering. 2023;11:e5. https://doi:10.1017/hpl.2022.44.

4 Jan Schulte, Thomas Sartorius, Johannes Weitenberg, Andreas Vernaleken, and Peter Russbueldt, "Nonlinear pulse compression in a multi-pass cell," Opt. Lett. 41, 4511-4514 (2016); https://doi.org/10.1364/OL.41.004511.

Over the past year, UFE2.0 made the following progress:

- fully integrated the Pharos laser into a UFE2.0 testbed;
- completed optical design of the MPC setup and procured hardware for preliminary testing; and
- built and tested a MPC that achieved nonlinear spectral broadening that produces a strong signal in the needed wavelength range shown in Fig. 4.2.

*Plans for FY26*

The front-end team will complete the preliminary design of the front-end, including all necessary diagnostics and control points, followed by a preliminary mechanical design of the front-end and all ancillary equipment.

### 4.2.3 WBS 1.3: Large-Aperture Optical Parametric Amplifiers (OPAs)

Activities primarily consisted of conceptual designing of the top-level subsystem layout for the Beamline section that comprised of three large-aperture non-collinear optical parametric amplifiers (NOPAs) and an optical switchyard. In addition, further theoretical modeling of the optical parametric amplification stages was performed to facilitate the updated top-level system design requirements, optimization of the energy stability, and availability of suitable large-aperture non-collinear (LBO) crystals.

Theoretical modeling of the optical parametric amplification stages indicated improved energy stability for NOPA-J using lithium triborate (LBO) crystals compared to DKDP originally planned, so the NOPA-J baseline design now uses LBO.

Figure 4.3 shows the conceptual optical design for the OPAL beamlines, including the NOPA-J and NOPA-K pump lasers, the NOPA-J and NOPA-K amplifier stages, and the grating pulse compressors. Design efforts identified primary control points, performed a risk analysis, and defined preliminary concepts of operation.

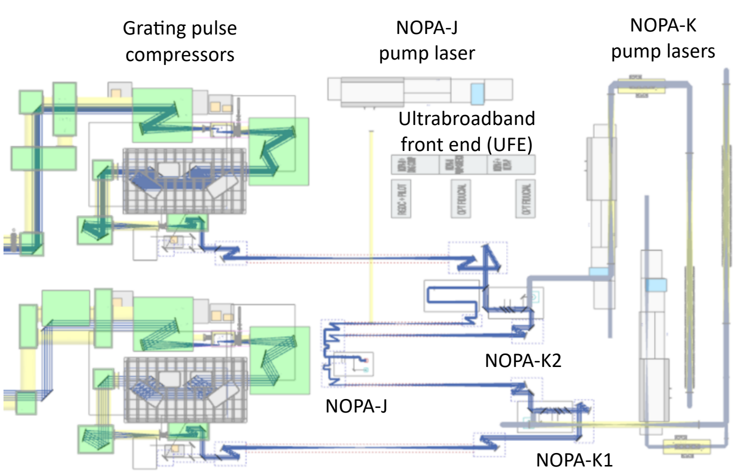


Figure 4.3 – OPAL beamlines layout including the ultra-broadband front end (UFE) that seed the NOPA-J stage before splitting the amplified pulse and injecting into two NOPA-K stages. The two grating pulse compressors receive the output of the OPAL beamlines and compress them before short-pulse beam transport delivered them to the target bay (not shown).

*Plans for FY26*

Planned FY26 activities will focus on initiating and completing a detailed preliminary design of the OPAL beamlines section, including all necessary diagnostics and control points, followed by a preliminary mechanical design for all large-aperture OPA stages and the optical switchyard.

### 4.2.4 WBS 1.4: OPA Pump Laser Systems

The WBS 1.4 team completed identification of subsystem requirements, documentation of interfaces, development of concept of operations, and conceptual design for the OPA pump laser systems. Part of the design and development for these pump lasers was completed as part of the complementary MEC-U project funded by SLAC, until it was paused.

Figure 4.3 shows the NOPA-J and NOPA-K pump laser layouts in the NSF OPAL laser bay along with the optical systems that deliver pump beams to their respective OPA stages. The NOPA-J pump laser comprises an active, multi-pass imaging cavity amplifier (AMICA) laser system with an actively cooled disk amplifier (ACoDA, see Sec. 4.3.1). Each of the NOPA-K pump lasers include an AMICA laser system followed by a booster amplifier.

The team worked closely with the Actively Cooled Disk Amplifier (ACoDA) team to ensure that WBS 1.4 requirements flowed down to the amplifier design and that the ACoDA modules design will integrate seamlessly into the pump laser systems.

*Plans for FY26*

The front-end team will complete the preliminary design of the pump laser systems, including all necessary diagnostics and control points, followed by a preliminary mechanical design of the pump and all ancillary equipment.

### 4.2.5 WBS 1.5: Beam Compression/Transport

Joe Kwiatkowski led extensive WBS 1.5 efforts aimed at conceptual design of the NSF OPAL beamlines that include pulse compression and beam transport. He worked closely with WBS 1.6 and:

- Completed Conceptual Design Review of compression and beam transport.
- Reoptimized transport design for reduced building cost and improved pointing stability.
- Developed active stabilization concepts to achieve demanding co-pointing and co-timing requirements.
- Implemented beam size reduction from 86.5 cm to 62.0 cm to reduce project cost. Transport design will provide flexibility for multiple grating design options to take advantage of future improvements in grating damage thresholds.
- Initiated discussions with numerous vendors on lightweight, large optic fabrication techniques. The team is pushing cost-reduction and manufacturing capacity.
- Brought on 3 new engineers to complete the WBS 1.5 team: Dave Irwin (Grating Compression Chamber and Short Pulse Diagnostics), Preston Hooser (Short Pulse Transport, Focal Spot Microscope), Nermina Mahmutovic (EP Beams).

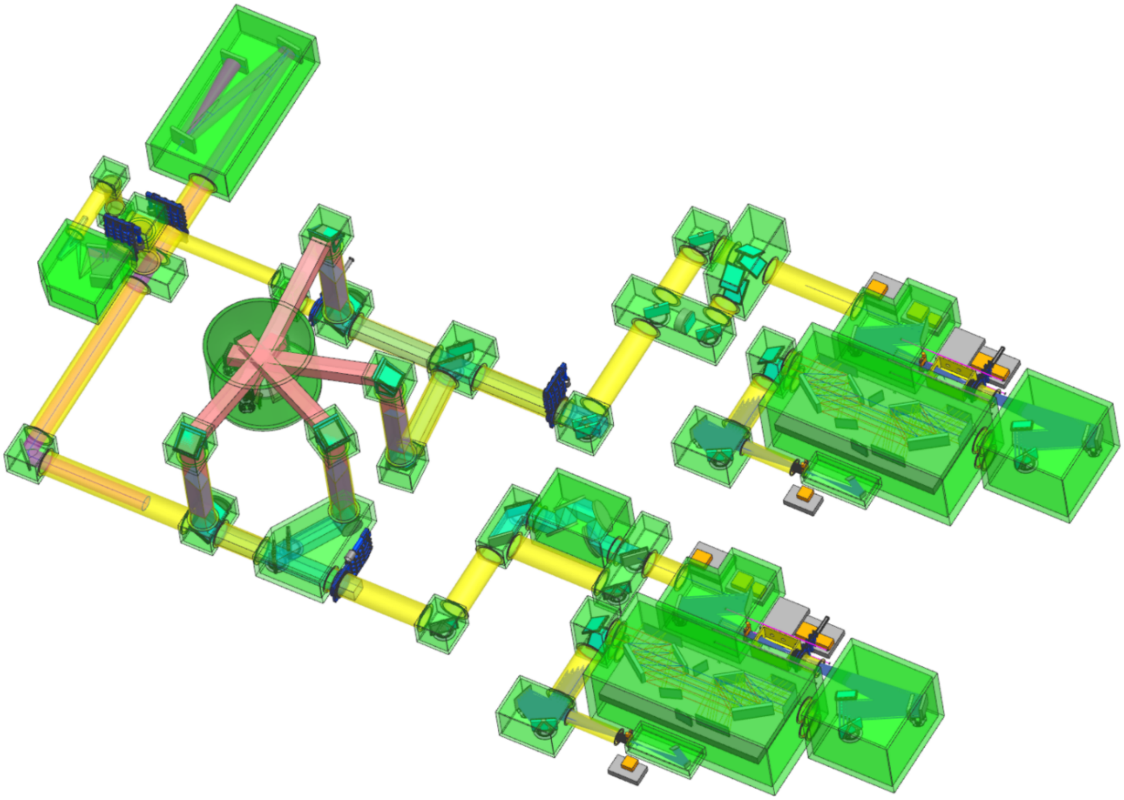

Figure 4.4 – Post-CDR layout of Beam Compression and Transport system

*Plans for FY26*

- Continue preliminary design of compression and beam transport systems with priority on detailed design of large optics and mounts, vibrational analysis to maximize baseline stability, diagnostic pickoffs and table layouts, Focal Spot Microscope, EP beam transport, active pointing and timing stabilization systems, Dual Plasma mirror implementation.
- Initiate new sub-award to prototype sub-scale light-weight optics. Emphasis will be validating fabrication and coating techniques and identifying viable vendor options.
- Continue refining petawatt SHG implementation concept based on ongoing modeling and sub-scale testing.

#### 4.2.5.1 Focal Spot Intensity Diagnostic (UMD subaward)

Project Execution Plan (PEP) Rev. C moved the original WBS 2.4 (Focal Spot Intensity Diagnostic) effort to WBS 1.5. Prof. Wendell Hill III (University of Maryland, UMD) leads these efforts.

We have shown that vacuum acceleration of electrons born in the focal volume of a loosely focused (paraxial conditions) relativistic laser pulse and ejected at an angle θ with respect to the laser propagation direction, $\vec{k}$, can be exploited to assess the intensity [5,6,7] and quality [8,9] of the focal volume in real time at full power. We have explored the electron dynamics under tightly focused conditions to assess OPAL focal volumes. We accomplished three tasks in this respect.

First, we demonstrated that the two plane-wave relationships [2, 3],

$$\text{(i)}\tan\theta_c = \sqrt{\frac{2}{\gamma-1}} \quad \text{and} \quad \text{(ii)}\, \gamma - 1 = \frac{a_0^2}{2}, \tag{1}$$

approximately hold under paraxial conditions up to about $10^{20}$ W/cm$^2$. Equation 1 links $\theta_c$, the minimum ejection angle, (i) to the maximum kinetic energy of the ejected electron, $(\gamma_{max} - 1)m_e c^2$, and (ii) to the peak intensity through the normalized vector potential (i.e., $a_0 \propto \sqrt{I_p}$, the peak intensity). We explored the dynamics in an experiment at ZEUS in the $0.5\times10^{20}$ to $5\times10^{20}$ W/cm$^2$ intensity region. Specifically, we measured $\gamma(\theta)$ to couple (i) and (ii) of Eq. 1. Figure 4.5 compares the measured and simulated ejected electron signals. It is important to note that the simulated signal assumed a focused Gaussian, scalar pulse and electrons generated via barrier-suppression ionization. The upper set of traces are the result of loosely focused pulses by an $f/5$ optic (approximately paraxial), while the bottom set represents tightly focused pulses with an $f/1.8$ optic (definitely not paraxial). Clearly, the two spectra are in reasonable agreement for the loosely focused pulses. The same cannot be said of the tightly focused pulses.

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5 C. Z. He, A. Longman, J. A. Pérez-Hernández, M. de Marco, C. Salgado, G. Zeraouli, G. Gatti, L. Roso, R. Fedosejevs, and W. T. Hill, "Towards an in situ, full-power gauge of the focal-volume intensity of petawatt-class lasers," Opt. Express 27, 30020-30030 (2019); https://doi.org/10.1364/OE.27.030020.

6 Smrithan Ravichandran, Marine Huault, Roberto Lera, Calvin Z. He, Andrew Longman, Robert Fedosejevs, Luis Roso, and Wendell T. Hill, III, "Imaging electron angular distributions to assess a full-power petawatt-class laser focus," Phys. Rev. A 108, 053101 (1 November, 2023); https://doi.org/10.1103/PhysRevA.108.053101.

7 A. Longman, S. Ravichandran, L. Manzo, C. Z. He, R. Lera, N. McLane, M. Huault, G. Tiscareno, D. Hanggi, P. Spingola, N. Czapla, R. L. Daskalova, L. Roso, R. Fedosejevs, W. T. Hill, "Toward direct spatial and intensity characterization of ultra-high-intensity laser pulses using ponderomotive scattering of free electrons," Phys. Plasmas 30 (8): 082110 (1 August 2023); https://doi.org/10.1063/5.0160195.

8 A. E. Raymond, S. Ravichandran, S.-W. Bahk, A. Longman, L. Roso, R. Fedosejevs, C. Mileham, I. A. Begishev, S. Qin, N. Dauphin, J. Shamlian, W. T. Hill, III, and H. G. Rinderknecht, "On-shot, high-intensity laser aberration measurements via ponderomotive electron ejection," Phys. Rev. A 111, 013121 (28 January, 2025); https://doi.org/10.1103/PhysRevA.111.013121.

9 A. E. Raymond, S. Ravichandran, S.-W. Bahk, A. Longman, L. Roso, R. Fedosejevs, C. Mileham, I. A. Begishev, S. Qin, N. Dauphin, J. Shamlian, W. T. Hill, III, and H. G. Rinderknecht, "Laser aberration signatures in expelled electrons from a tenuous gas," Phys. Plasmas 32, 062101 (2025); https://doi.org/10.1063/5.0272444.

A second activity started exploring the disagreement for the tightly focused case and developing an articulation of the focused field of a flattop beam that includes all the primary vector components after reflection from an off-axis parabola. This articulation [5] proves easier to code numerically than the classic Stratton and Chu description [10]. Simulating the electron dynamics with this new vector field has started.

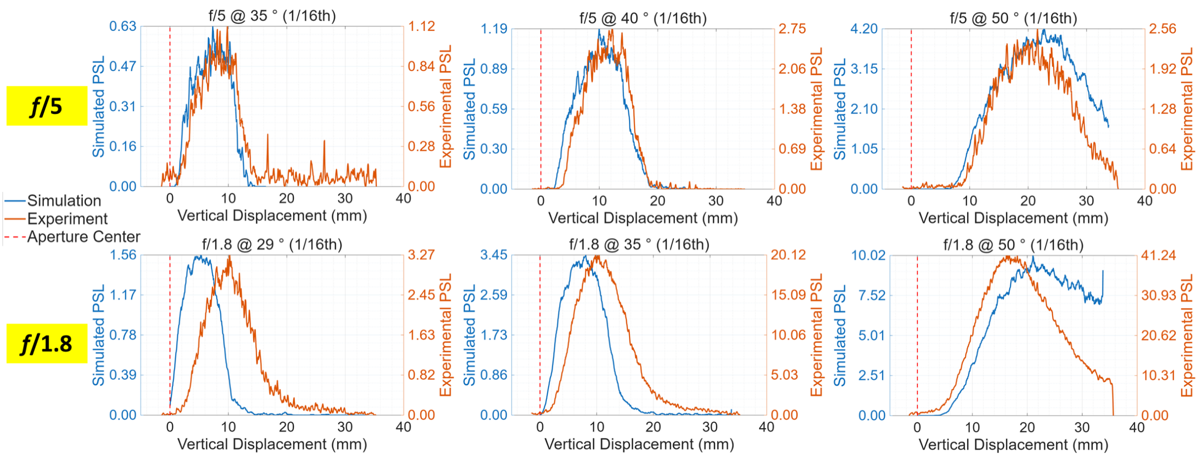


Figure 4.5: Experimental (red) and simulated (blue) electron signals vs displacement in a magnetic spectrometer, where energy is inversely proportional to displacement.

The third activity was to develop a new magnetic spectrometer capable of measuring electron kinetic energies up to about 3 GeV, which is shown in Fig. 4.6. This will allow us to probe the coupling in Eq. 1 to higher intensities.

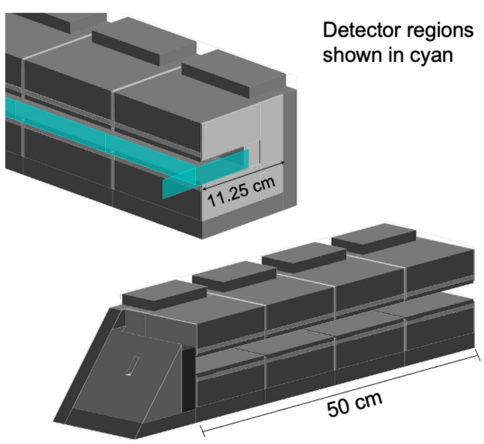


Fig. 4.6: Two views of new electron spectrometer consisting of a permanent magnet with 50-cm long, 0.3-T region capable of measuring electron kinetic energies from a few MeV to a few GeV. Electrons are measure along the side (low energy) and back of the spectrometer.

10 J. A. Stratton and L. J. Chu, "Diffraction Theory of Electromagnetic Waves," Phys. Rev. 56, 99 (1 July, 1939); https://doi.org/10.1103/PhysRev.56.99.

### *Publications/Presentations*

**Publications**

L. Roso, S. Ravichandran, A. Raymond, S.-W. Bahk, R. Mahnot, E. Fiala, P. P. Marques, Y Fang, R. Lera, D. Gutiérrez, J. A. Pérez-Hernández, R. Fedosejevs and W. T. Hill III, "The focus of an ultraintense laser," Progress in Ultrafast Intense Laser Science XVIII, Topics in Applied Physics (In Press).

W. T. Hill III, "Rousing the quantum vacuum with extreme laser light," Innovation News Network (London, 2025), https://www.innovationnewsnetwork.com/ebook/rousing-the-quantum-vacuum-with-extreme-laser-light/.

**Presentations**

"Multi-petawatt, multiple-beam real-time diagnostics and tools," W. T. Hill, III, S. Ravichandran, R. Mahnot, E. Fiala, A. Raymond, P. T. Campbell, L. Tower, J. Nees, J. M. Rebenstock, C. Mendez, T. C. Ramirez, J. L. Henares, R. Fedosejevs and L. Roso, 66th Annual APS DPP Meeting Mini-Conference: Multi-Petawatt Physics, October 7-11, 2024, Atlanta, GA.

"Exploiting petawatt pulses to prepare electron-free focal volumes," S. Ravichandran, T. Cebriano, J. L. Henares, C. Mendez, J. A. Pérez-Hernández, L. Roso, R. Fedosejevs and W. T. Hill, III, ELI User Meeting, June 18-20, 2025, Szeged, Hungary. (This poster won "The Most Innovative Idea" Award.)

"Real-time assessment of multi-petawatt focal-spot via relativistic electron dynamics," W. T. Hill, III, S. Ravichandran, R. Mahnot, E. Fiala, A. Raymond, P. T. Campbell, L. Tower, J. Nees, J. M. Rebenstock, C. Mendez, T. C. Ramirez, J. L. Henares, R. Fedosejevs and L. Roso, 33rd Annual International Laser Physics Conference (LPHYS'25), June 30 – July 4, 2025, Szeged, Hungary.

**Student Awards**

Smrithan Ravichandran, campus winner of the U. Maryland 3MT (Three-Minute Thesis) Award:
https://gradschool.umd.edu/sites/default/files/2023-06/3mt_history_and_overview_2022.pdf

Smrithan Ravichandran, winner of the Most Innovative Idea Award among student posters at the 2025 ELI Users Meeting, June 18-20, 2025, Szeged, Hungary.

### *Plans for FY26*

Our activities planned for FY26 fall into three categories. First, we plan to complete our simulations of electron dynamics in a focused flattop field. This will require further modifications to our numerical code. We will update the ionization module to include tunnel ionization in addition to barrier suppression by including an ADK component, following Mironov et al [arXiv:2501.11672]. This will allow us, as our second activity, to complete our analysis of ZEUS data and determine the culprit responsible for the disagreement displayed in Fig. 1. The third activity is to test the equations in Eq. 1 and our simulations at higher intensities in a four-week run at Apollon. In that run we will explore intensities between a few $\times 10^{21}$ and a few $\times 10^{22}$ W/cm$^2$. These three activities will inform our implementation of electron-dynamics and vacuum acceleration for the OPAL beams.

#### 4.2.5.2 Liquid-Crystal Devices (OSU subaward)

Project Execution Plan (PEP) Rev. C moved the original WBS 2.5 (Liquid crystal devices) effort to WBS 1.5. Prof. Douglass Schumacher (Ohio State University, OSU) leads these efforts.

Liquid crystal (LC) freestanding film technology advances, led by OSU, have found novel applications for renewable, ultrathin plasma mirrors (PMs) that improve laser pulse temporal contrast. PM operation is destructive, but the use of LC avoids rastering or replacement of anti-reflection coated substrates in this approach. Ultrathin plasma mirrors enable unique capability such as laser beam redirection with low emittance degradation of laser-wakefield accelerated electrons. They show promise for preventing dangerous back-reflections from solid-density targets because the plasma mirror will go under-dense and cease to be reflective by the time a back-reflected pulse returns to it. Thin LC films can also serve as targets to produce higher energy ions using target-normal sheath acceleration (TNSA) and deuterated LC films can facilitate laser-based, high-repetition-rate neutron sources.

Design and prototyping efforts include: (1) large-scale plasma mirrors suitable for NSF OPAL; (2) new LC compositions to control film flatness; (3) new LC compositions to control film thickness; (4) prefabricated glassy liquid crystal (GLC) plasma mirrors; and (5) potentially tritiated LC compositions for nuclear physics experiments.

Specific Objectives: Develop liquid crystal plasma mirrors and targets suitable for use with NSF OPAL 25-PW Alpha beams.

Significant Results: The OSU team has developed what is expected to be a >4 PW renewable PM prototype and, guided by the UR/LLE team consisting of Kenneth Marshall, Nathaniel Urban, and their students, completed a study of LC mixtures showing substantial improvement in film quality for careful choice of LC mixture and temperature. Efforts resulted in the following results:

- Constructed a new film characterization set-up that can handle large diameter optics in vacuum (Fig. 4.4) and validated it to better than λ/10 where λ represents the ALPHA central wavelength of 1064 nm. (All flatness measures in the following are listed as multiples of λ and are peak-to-valley values. Peak-to-valley is a conservative measure with RMS measures ~5x smaller.)

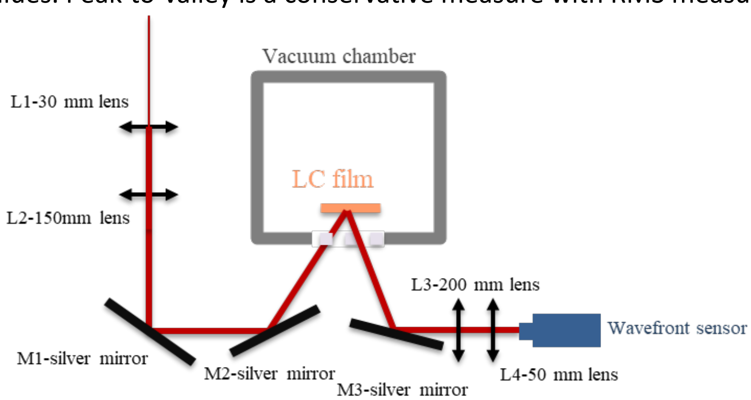


Fig. 4.7 – Apparatus for measuring film flatness of large diameter optics. Telescopes were needed to handle the small detector used by the wavefront sensor.

- Showed that vertical (film normal perpendicular to the line of gravity) and horizontal films behave similarly with little effect on film surface shape.

- Based on Year 1 development of 3 LC film inserters, constructed a 4th LC film inserter for "single shot" formation of 24 mm diameter films with greatly improved performance, achieving 0.15λ across the central 6 mm region (Table 4.1) when using pure 8CB. This is sufficient to support 4 PW pulses assuming near-normal (up to 30°) incidence.

Table 4.1 – Measured flatness of central 6 mm of a 24-mm diameter film of 8CB for three temperatures spanning the range of successful film formation. Flatness in waves (1064 nm wavelength) of maximum peak-to-valley variation.

| Liquid Crystal | Measured variation over central 6 mm of a 24-mm film | | |
|---|---|---|---|
| T (°C) | 22.0 | 25.0 | 28.0 |
| Flatness (λ) | 0.15 | 0.14 | 0.16 |

- Designed a 4 PW prototype *repetition-rated* film inserter whose construction by OSU mechanical shots is approximately half complete at the time of this writing (Fig. 4.5).

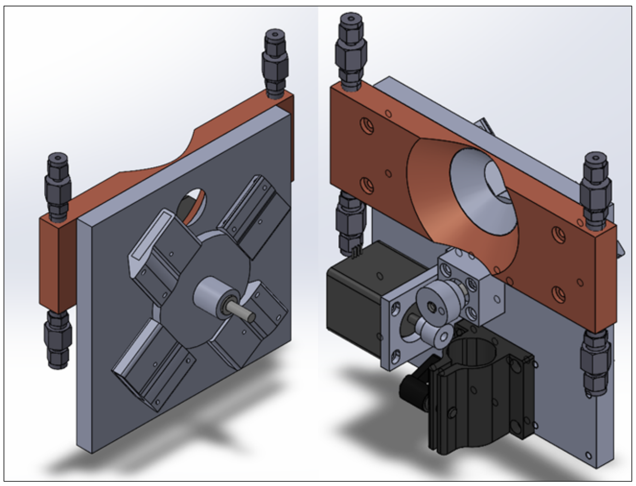

Figure 4.8. CAD rendering of a prototype renewable plasma mirror inserter that is capable of operating at > 4 PW. Left: Front view side with laser incident on hole over which four wipers spread a thin film of liquid crystal. Right: Rear view: motor and gear train that drives wipers, plus heat sink (orange) that temperature controls LC film properties.

- Applied for time on the NSF ZEUS laser to test the new prototype (proposal still pending).
- Completed study of the three candidates for LC mixtures identified by the UR/LLE team in Year 1: ZLI-1167, ZLI-1409, and CCH2. The temperature ranges over which stable film formation was possible were identified and 15 permutations of mixture and temperature were explored. To speed testing, which is laborious, 8 mm diameter films were used and results are reported here for the central 30%. As a baseline, pure 8CB films achieved a flatness of only 0.29λ. All of the mixtures were as good or better than pure 8CB (Tables 4.2, 4.3), with 5% weight CCH2 at 18°C achieving 2.2x flatter films than pure 8CB. These results, if translatable to our 24 mm films (not yet demonstrated) would result in our prototype supporting up to 10 PW laser pulses assuming an intensity on the plasma mirror of 2 x $10^{16}$ W/cm$^2$ using an 8-mm FWHM laser spot size.

Table 4.2 – Measured flatness over the central 2.5 mm of an 8-mm diameter film composed of 8CB mixed with ZLI 1167 and ZLI 1409. Small-diameter films were used to speed testing. Small films tend to be less flat and, for comparison, under these conditions pure 8CB films were no better than 0.29 λ. Flatness in waves (1064 nm wavelength) of maximum peak-to-valley variation.

| Liquid Crystal | 5% ZLI-1167 | | | | 10% ZLI-1167 | | 7.5% ZLI-1409 | | |
|---|---|---|---|---|---|---|---|---|---|
| T (°C) | 20 | 22 | 25 | 28 | 24 | 26 | 22 | 25 | 28 |
| Flatness (λ) | 0.25 | 0.22 | 0.24 | 0.30 | 0.24 | 0.24 | 0.24 | 0.20 | 0.27 |

Table 4.3 – Measured flatness over the central 2.5 mm of an 8-mm diameter film of a mixture of 8CB and CCH2 liquid crystals. Flatness in waves (1064 nm wavelength) of maximum peak-to-valley variation.

| Liquid Crystal | 5%wt CCH2 | | | | 10%wt CCH2 | |
|---|---|---|---|---|---|---|
| T (°C) | 18 | 20 | 22.5 | 25 | 17 | 19 |
| Flatness (λ) | 0.13 | 0.25 | 0.22 | 0.25 | 0.17 | 0.23 |

- The UR/LLE team has started studying on the rheology and phase behavior of the LC mixtures to explore why their performance is superior to that of pure 8CB. Additionally, they are using an Elcometer blade coater to cast freestanding LC films in order to perform faster initial testing than possible at OSU so that a greater range of LCs can be explored in Year 3.

### *Publications*

D. W. Schumacher and P. L. Spingola, "Novel plasma mirrors for petawatt (PW)-class lasers using ultrathin films of liquid crystal", Proceedings SPIE 13121, Liquid Crystals XXVIII, 131210E (30 September 2024); https://doi.org/10.1117/12.3028421

### *Presentations*

[Invited] D. W. Schumacher and P. L. Spingola, "Novel plasma mirrors for petawatt (PW)-class lasers using ultrathin films of liquid crystal," 2024 SPIE Liquid crystals XXVIII.

D. W. Schumacher, “Renewable plasma mirrors for repetition-rated, multi-PW lasers using ultrathin liquid crystal films,” Multi-Petawatt Physics at New and Future Laser Facilities mini-conference, APS Division of Plasma Physics, October, 2024.

P. L Spingola, N. Urban, K. Marshall, J. F. Zhao, M. Ross, D. W. Schumacher, “Liquid Crystal Films For Plasma Mirrors,” 2024 LaserNetUS Annual Meeting.

### *Plans for FY26*

- Bench test 4-PW prototype and then laser test at available laser facilities.
- Extend size of central working region of our 4 PW prototype using the new LC mixtures.
- Continue exploration of innovative LC mixtures identified by the LLE team.
- Work with the UR/LLE team to develop an understanding of the physics of film formation of the LC mixtures.

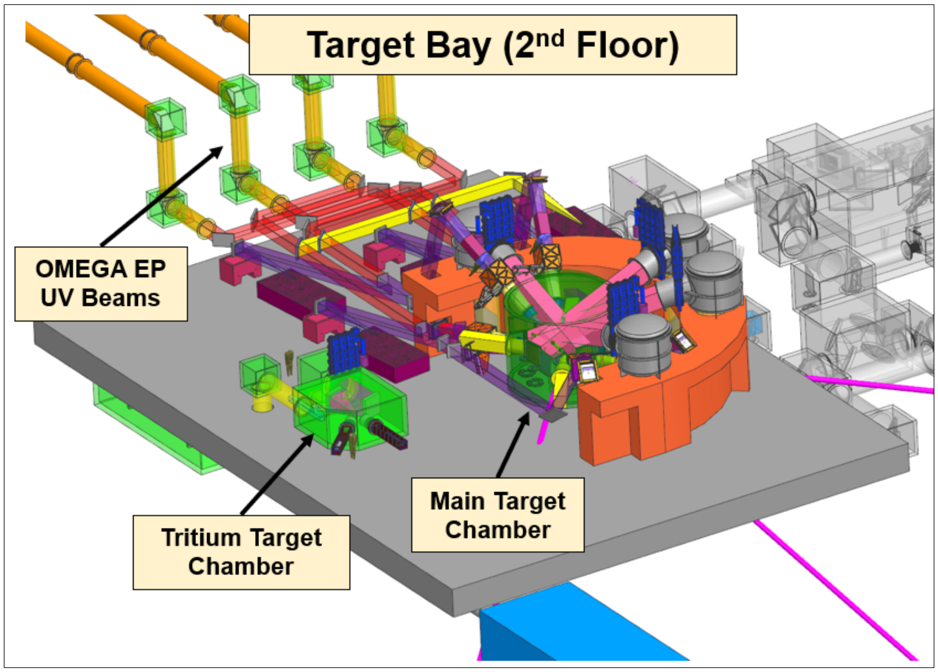


Figure 4.9 – Post-CDR Target Bay (2nd Floor) Layout

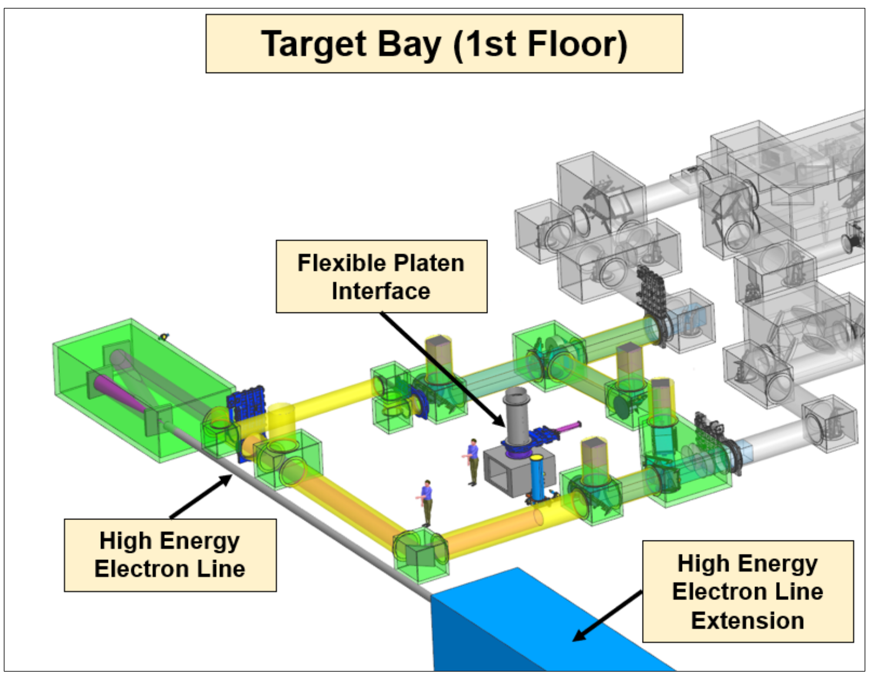


Figure 4.10 – Post-CDR Target Bay (1st Floor) Layout

### 4.2.6 WBS 1.6: Experimental Systems

- Presented a CDR which captured high-level design changes needed to make more efficient use of space.
- Worked through several major iterations to the Experimental Systems design that optimize cost, personnel/equipment flow, and experimental flexibility. We settled on a floorplan that eliminates the separation of "EA-1"/"EA-2" and will proceed with a single Target Bay (TB) space.
- Onboarded several new members to the 1.6 team.
- Finalized top-level requirements for all 1.6 subsystems.
- Began mechanical design of the Flexible Platen Interface (FXPI).
- Continue to iterate on the layout of diagnostic deployment locations within the Multipurpose Target Chamber (MTC) based on feedback from FSWGs.
- Completed a baseline assessment of radiation shielding for the facility and are moving forward to optimize for cost.
- Made offer to hire a scientist to fill the role of Experimental Platform Development lead responsible for interfacing between the Design Team's WBS leads and FSWG members.

*Plans for FY26*

- Progress designs for all subsystems to a PDR-ready state.
- Hold a series of peer reviews with relevant external experts to feed into the design effort.
- Finalize path to Final Design.
- Determine plan to reach Threshold and then Objective deliverables.

#### 4.2.6.1 Radiation Shielding (UM subaward)

Project Execution Plan (PEP) Rev. C moved the original WBS 2.6 (Radiation Shielding) effort to WBS 1.6. Prof. Igor Jovanovic (University of Michigan, UM) leads these efforts.

Intense laser-matter interactions can produce copious amounts of energetic ionizing radiation, both in primary and secondary beams. As energetic particles propagate through experimental chamber walls, interact in the experimental area, and stop in beam dumps, they lose energy through electromagnetic showers, producing energetic gamma rays, pions, and muons via bremsstrahlung and collisions. Photodisintegration and photofission can yield energetic hadrons, including neutrons and protons. Energetic protons and other ions are effective in charge exchange, breakup, and transfer reactions. Neutrons and high-energy photons also create major sources of secondary radiation, and the production of muons becomes significant when the electron energy exceeds 1 GeV. In addition to prompt radiation, studies assessed the activation of beamline components and surrounding materials (e.g., shielding, walls, air, water).

The radiation shielding design group composed of experts from the University of Michigan (UM) and UR/LLE interfaced closely with facility designers to simulate the expected radiation environment. This involved the development of facility models that include the relevant design features and materials, as well as the expected sources of radiation. Designs employed the Monte Carlo FLUKA code that validated results using the Geant4 framework based on the recent experience with the design and simulation of radiation environments in the NSF ZEUS project at the University of Michigan. This cross-validated simulation of the expected radiation environment in NSF OPAL together with the optimized beam dump configurations, predicted activation rates, and the quantification of the tradeoff between the shielding size/cost and the permitted shot rate/beam parameters. These results fed into the overall NSF OPAL facility conceptual design with the goal of maximizing the allowable laser shot rate and consequently the scientific productivity of the facility.

We have developed a streamlined framework for FLUKA shielding simulations, enabling rapid conversion of CAD drawings into FLUKA geometry and efficient extraction of phantom dose at key locations around the facility. Simulations have been carried out across a wide range of building geometries and beam configurations. Simulated particle types included protons (up to 500 MeV), deuterons (up to 200 MeV), neutrons (up to 40 MeV), 10-GeV electrons, and 125-GeV electrons. We have also investigated activation from ion generation and conducted preliminary "sky-shine" simulations.

*Plans for FY26*

We will continue supporting the building design process by providing simulation feedback on shielding performance for the continually updating facility layouts. This includes refining both global and local shielding strategies to maximize radiation protection while minimizing cost. Our aim is to deliver actionable design recommendations that maintain flexibility for future experiments while ensuring compliance with dose limits.

*Publications/Presentations*

M. Krieger, M. Barczys, E. M. Hill, J. D. Zuegel, Poster: "NSF OPAL Experimental Facility Design Concepts", OMEGA Laser Users Group (OLUG) Workshop, May 21, 2025.

T. Cracium, M. Krieger, E. M. Hill, and J. D. Zuegel, Poster: "An Introduction to Target Systems on NSF OPAL", OMEGA Laser Users Group (OLUG) Workshop, May 21, 2025.

T. Cracium, M. Krieger, "From SUNY Geneseo to NSF OPAL", SUNY Geneseo Annual Lab Tours, Laboratory for Laser Energetics at University of Rochester, July 2, 2025.

X. Li, C. Forrest, A. Raymond, M. Krieger, I. Jovanovic, "FLUKA Simulation Studies for Radiation Transport, Shielding, and Activation in ZEUS and OPAL Laser Facilities", LaserNetUS + ZEUS Meeting, July 8-10, 2025.

### 4.2.7 WBS 1.7: Diagnostic Development

Steve Ivancic led WBS 1.7 efforts aimed at conceptual design experimental diagnostics.

Over the past year, work on developing the diagnostic capability for NSF was organized under WBS 1.7 Diagnostic Development. The team developed concepts for essential instrumentation required to support the scientific objectives of NSF OPAL. Major efforts to establish key diagnostic lines-of-sight led to a conceptual design for the main target area and auxiliary target chambers within the target bay. The design effort culminated in three major public presentations: a working group breakout session at the National Diagnostics Working Group Annual Meeting in November 2024, a "Community Update" held in January 2025, and the NSF Conceptual Design Review, held at LLE in April 2025.

In response to the growing national interest in ultra-intense laser experiments, the diagnostics development team is broadening the scope of contributors to include additional academic partners. A diagnostic community development effort has superseded the diagnostics development WBS. In the coming year, the newly organized diagnostics community development WBS will organize a workshop to explore topics in diagnostics for multi-PW laser systems.

#### 4.2.8 WBS 1.8: Controls

Nathan Landis led WBS 1.8 efforts to conceptually design control systems. Information technology (IT) systems were separated from controls and implemented in a new WBS 1.9.

Controls was part of the CDR this past year presenting our concept of how various subsystems will integrate into the NSF OPAL facility and with the existing OMEGA EP facility. Subsystems like Hardware Timing System (HTS), Vacuum Control, Motion Control, Digital Imaging, and Safety Systems were all part of this review. Part of this discussion also touched on the interfacing plans between the various hardware and software systems.

*Plans for FY26*

The primary focus for this next fiscal year will be for controls to follow along as the design matures to provide input that will allow the controls team to have the best chance of being successful when it comes to integrating into the new facility. This will be done by attending working group meetings, updating best practices document, and meeting with members of the community. As questions come up for unique design details various subject matter experts from the ECE group will be called on for their guidance.

#### 4.2.9 WBS 1.9: Information Technology (IT) Systems

- Created WBS 1.9 conceptual design schedule.
- Worked with other WBS areas to define software and IT requirements for the NSF OPAL system.
- Provided IT infrastructure requirements to building design working group.
- Defined IT asset requirements to support NSF OPAL operation.
- Created IT asset cost estimation.
- Created conceptual design for IT physical layout, and necessary IT services.
- Created conceptual design for software controls and facility management.
- Peer reviewed conceptual design.
- Presented conceptual design to stakeholders.
- Created staffing resource plan for production design phase.
- Developed schedule for production design phase.

*Plans for FY26*

- Work with other WBS areas to refine IT and software requirements based on iterative design work done within those WBS areas.
- Work with WBS 1.8 (Controls) to define connection specifics between software and controls subsystems.
- Refine concepts for IT services such as cyber-security, and data collection and dissemination.
- Define specifics of software modifications necessary for each software system planned for use in NSF OPAL.
- Develop PDR documentation for both IT and Software sections.

## 4.3 NSF OPAL Prototyping and Subawards (WBS 2)

Three critical component technologies with the highest risk for implementing NSF OPAL require design and prototyping or manufacturing process validation:

(1) high-shot-rate, high-energy laser amplifiers. A UR/LLE team works on the actively cooled disk amplifier (ACoDA) design and prototyping effort;
(2) extra-large (XL), monolithic diffraction gratings. A subaward to Plymouth Grating Laboratory (PGL) aims to develop new equipment to produce XL gratings; and
(3) large, highly deuterated potassium dihydrogen phosphate (DKDP) nonlinear crystals.

Other prototyping activities accomplished by complementary programs will use existing UR/LLE laser systems, such as MTW-OPAL, to evaluate new design concepts.

### 4.3.1 WBS 2.1: Actively Cooled Disk Amplifier (ACoDA)

ACoDA activities for FY25 centered on modeling and design for the single-cassette prototype. A selection of CF, HCF, and HFO coolants were obtained for evaluation after the team determined that the most desirable coolant, $D_2O$, was unobtainable in the volumes needed for cooling. Development of waterproof coatings for laser glass was put on hold until further need arises. Work began on re-creating the Livermore laser glass epoxy used to bond cladding glass to LHG-8 laser glass. This work continues – current batches are prone to yellowing during the curing process but meet all mechanical specifications. Additional tuning of the mixture ratios and cure schedule are being tried to mitigate the noted discoloration.

In FY25/Q2 the prime vendor for bonding laser and cladding glass assemblies informed us that they were declining future work on these products to focus on their datacenter business. Unfortunately, there are no alternates waiting in the queue, and without a vendor to supply us with clad laser glass the team made the decision to pivot to unclad disks. Removing the cladding necessitates using an antireflective (AR) coating or AR surface treatment on the disk edges to frustrate transverse oscillation and mitigate amplified spontaneous emission (ASE). Current modeling suggests that an upper bound for reflectivity is $R < 0.6\%$ over a broad angular range. Removal of the cladding eliminates the dominant heat source in the system – the lack of this heat source means we no longer need liquid coolants to maintain performance at a 5-minute shot rate and can instead use forced convection. In turn, this means we no longer need windows on the cassettes to contain the liquid. Removal of the thick glass windows from the design greatly reduces the B-integral accumulated through the amplifier, which is a major concern, especially at the scale of the booster amplifiers.

The new ACoDA baseline cassette is now defined as: 2 disk cassettes with no windows, unclad LHG-8 laser glass disks with AR coatings on the edges and forced convection cooling (between the disks as well as on the outer surfaces).

*Publications/Presentations*

No publications or external presentations.

*Plans for FY26*

FY26 activities will focus on AR development for the disk edges and mechanical design of the prototype cassette, cavity, and test stand. The prototype will move forward with solgel AR coatings, since we can apply these in-house and the antireflective performance of these coatings is sufficient. Applying even, defect-free solgel coatings on the edges of the disks is non-trivial, however, and we expect to run the prototype with some amount of sub-par AR performance – operation of the prototype at maximum lamp currents may not be possible due to ASE defeating the solgel coatings in difficult-to-coat locations. Other coating techniques are under investigation but are not expected to be ready for the initial prototype. Thin film coatings will require some significant mechanical work to reconfigure a large deposition chamber; etched ARSS (moth eye) coatings are also under investigation. The prototype test stand will be built during FY26 – primary diagnostics include full-aperture wavefront sensing, full-aperture gain mapping, and energy measurements. A single-cassette prototype cavity and a single ACoDA cassette will be deployed that include options not expected to persist in production versions: additional feedthroughs for in-situ thermistors, options for reconfiguring the flashlamp spacing to provide some mitigation for gain nonuniformity, and multiple mounting options for cooling gas nozzle placement to allow some amount of cooling optimization.

### 4.3.2 WBS 2.2: Extra-Large (XL) Diffraction Gratings – PGL subaward

Turan Erdogan (PGL President) serves as PI for this subaward.

UR/LLE partnered with Plymouth Grating Laboratory, Inc. (PGL) in the RI-1 project to develop extra-large (XL) diffraction gratings suitable for NSF OPAL to compress the Alpha beams. This requires scaling up their manufacturing processes to produce full-scale NSF OPAL compressor gratings. PGL manufactures gold-over-glass (Gold) gratings for broadband compression of short ($\tau < 500$ fs) pulses and multilayer dielectric (MLD) gratings for narrower bandwidth that support longer pulse durations. PGL has also experimented with hybrid MLD/gold (Hybrid) gratings that show promise for ultrashort pulses but this is not a mature technology. An NSF OPAL compressor design will require Gold or Hybrid compressor gratings. Gold grating damage-fluence limits requires gratings larger than presently available.

The NSF OPAL project covers designing Nanoruler5 (NR5), an instrument for scanning-beam Interference lithography and grating metrology; construction of NR5 will be accomplished under a complementary program funded by the UR/LLE-NNSA cooperative agreement that also covers scaling other process steps to produce XL gratings for OMEGA EP and NSF OPAL. Currently, PGL manufactures MLD diffraction gratings as large as $960 \times 630$ mm$^2$. Replacing tiled gratings used in OMEGA EP with monolithic $1410 \times 430$ mm$^2$ gratings will simplify its pulse compression system, recover energy lost to shadowing the region of the grating gaps, and improve beam wavefront quality.

Based on feedback from the RI-1 project CDR in April 2025, the project team identified two areas where additional technical risk could be pursued to reduce the potential construction project cost. To pursue these areas, the WBS 2.2 Grating subaward to PGL was paused while the project team reassessed the needed funding profile to complete the Nanoruler5 (NR5) design and amend the PGL subaward to defer NR5 construction. NR5 construction costs will be redirected to (1) prototyping low-cost, lightweight, mirrors and (2) improving the laser-induced damage threshold (LIDT) of Gratings and SP Transport Optics to enable smaller optics.

*Technical progress*

Fringe Locking: Completed design and troubleshooting and successfully demonstrated fringe locking on a test platform.

Exposure optics and laser: All optical and opto-mechanical components are ready to be ordered. Completed installation of a new solid-state Genesis laser in NanoRuler2, the main workhorse for writing gratings at PGL, to replace the legacy Argon-ion laser. The Genesis CX SLM-Series is a high-power, single-longitudinal-mode laser that delivers up to 100mW UV output. Successfully wrote a CEA focusing 3w grating on NR2 using. Continuing its use for grating production to demonstrate long-term suitability. Continued using Genesis laser on NR2 for grating production. Made design changes to NR5 optics based on experience.

2m x1m X-Y stage: Completed box-beam structure design. Received quotes and ready to order granite for stage base. Received delivery of X-axis guide rail. Completed Y-axis guide beam design and received very competitive quote from US-based supplier (CoorsTek). Ordered Zygo ZMI laser; TMC Vibration Isolation System; Super Invar lens mount; Cube Farm prisms. Completed stage carriage and work holder designs.

Enclosure: Built and tested fan control module and balanced fans.

*Plans for FY26*

Complete NR5 preliminary design and submit design report.

### 4.3.3 WBS 2.3: Large-Aperture DKDP Crystals

The development of the image-based phase-matching mapping technique has been completed. An oral presentation was made at the CLEO conference, and a manuscript describing these developments has been submitted to the Optical Materials Express journal. This work was led by PhD student Rhett Wampler.

The design of a large-aperture mapping station for nonlinear crystals and the procurement of the hardware have been completed.

Collaborative work with two companies has been performed to develop bonding techniques for scaling the aperture of lithium triborate (LBO), a nonlinear crystal that would be advantageous over DKDP for broadband OPCPA. This work resulted in the first demonstration of seamless bonding of a nonlinear crystal.

A path to procure large-aperture DKDP crystals, including procurement of heavy water (D2O), has been identified. Discussions with other parties (LLNL, G&H) are on-going.

*DKDP Crystals Publications/Presentations*

Christophe Dorrer, "Demonstration of Controlled Spatial Incoherence for Laser Beam Smoothing," at CLEO 2025 held May 4-9, 2025, Long Beach, CA.

Rhett Wampler, "Mapping the Phase-Matching Conditions of the Crystal Sector Boundary in Partially Deuterated Potassium Dihydrogen Phosphate (DKDP) ," at CLEO 2025 held May 4-9, 2025, Long Beach, CA.

*Plans for FY26*

- The large-aperture mapping station will be assembled and tested on large nonlinear crystals.
- Modeling of OPCPA performance with non-ideal nonlinear crystals will be performed.
- The testing of bonded LBO samples from companies will continue.
- Established an MOU with LLNL to fund a pilot process for enriching $D_20$ and qualifying a source to provide $D_20$ for DKDP crystal growth.
- Develop an alternate NOPA-J designs using LBO for broadband OPCPA. Recent technical developments (rapid growth of large boules and composite crystals fabricated by bonding crystals into a large-aperture mosaic) have increased the likelihood that large-aperture LBO would be available at time scales relevant to NSF OPAL.

# 5. Impacts

The NSF OPAL RI-1 project advances student training and increases the participation of underrepresented groups to increase diversity among the NSF OPAL designers, builders, implementers, and users. Outreach activities have started to engage scientists of all ages, the public, and the international research community to ensure the rich new frontiers in science and technology enabled by NSF OPAL prove broad, impactful and enduring.

NSF OPAL will be the highest power laser facility in the world and will be available to researchers working in plasma physics, high-field physics, high-energy-density (HED) sciences, laboratory astrophysics, materials science, and nuclear physics. NSF OPAL will provide experimental access to state of-the art high power laser systems to graduate students, postdoctoral researchers, and research scientists at universities and laboratories worldwide.

A tangible benefit to wider U.S. research community and international collaboration opportunities would result from establishing a **globally unique ultrahigh-intensity laser user facility** with two multi-petawatt lasers that is collocated with multi-kJ high-energy UV lasers **at a university-based, open-access facility**. This **positions the U.S. to better collaborate with research groups around the world and enhance access to other international facilities**. Furthermore, coordinated development of laser and experimental diagnostic capabilities and comparing experimental results from other ultraintense facilities enables important synergistic relationships.

## 5.1 Broader Technical Impacts

<u>LDNP FSWG</u>: LDNP team members at LLE hosted a visit by researchers from Florida State University (FSU) working to establish a triton beam using conventional accelerator technology. The main component of this Triton Beam Project is a dedicated injector with a Multi-Cathode Source of Negative Ions by Cesium Sputtering (Multi-SNICS), which will provide triton beams from tritium-loaded titanium cathodes. The visit included presentations and discussions on tritium handling (M. Sharpe, LLE), tritium facility operations (R. Janezic, LLE), tritium beam motivation (I. Wiedenhoever, FSU), and tritium beam status (A. Morelock, FSU), plus tours of the LLE tritium research lab, the OMEGA operations tritium facility (Room 157), and the OMEGA target chamber tritium recovery system (TC-TRS).

Co-PI Ani Aprahamian mentored a nuclear physics undergraduate student at Notre Dame University, who subsequently applied to graduate programs and accepted an offer from MIT.

<u>ACoDA prototyping</u>: The L4 ATON laser at ELI-Beamlines with liquid-cooled amplifiers demonstrated greater than 1-kJ pulse energies based on a concept first introduced by UR/LLE. Access to this proprietary design has proven elusive and new concepts could further advance the state of the art that research institutions worldwide have expressed interest in implementing. Designs for high-energy ACoDA amplifiers with 20- and 30-cm clear apertures meet a need recognized by the 2023 Basic Research Needs Workshop on Laser Technology sponsored by DOE and NSF. Scaling these designs to a 40-cm aperture should be straightforward and would significantly increase the experimental productivity of large facilities, such as OMEGA EP. Several institutions, including GSI (Darmstadt, Germany), European XFEL (Schenefeld, Germany) and SLAC, have contacted UR/LLE about incorporating ADoDA technology in their planned facility upgrades.

<u>XL Gratings</u>: Establishing the capability to fabricate diffraction gratings for pulse compression up to 1×2-$m^2$ will enable high-energy, ultraintense lasers worldwide. This need was recognized by the Broader

Technology Impacts – NSF OPAL aligns with key findings of the 2023 Basic Research Needs Workshop on Laser Technology sponsored by DOE and NSF. A new surface-figure and diffracted-wavefront-metrology capability developed for testing XL gratings will also enable testing other large planar laser optics. Cost-effective ion-beam figuring and long-throw-sputtered thin-film coating of XL planar substrates will improve laser optics quality and affordability.

DKDP prototyping: Improving methods to characterize nonlinear crystals will enable improvements to crystal growth and finishing processes for large and highly deuterated DKDP crystals that have already been applied to other important nonlinear crystals, like LBO and BBO.

Focal Spot Diagnostics subaward: Accurately measuring focal spot intensity proves essential to controlling the laser and understanding experimental results. NSF OPAL research and development in this area will develop concepts for an integrated diagnostics approach that provides preshot setup and characterization, and on-target/on-shot performance verification. These experiments will be performed on a range of laser facilities (NSF ZEUS, Scarlet, MTW and MTW-OPAL, and ELI) and new methods shared with the broad scientific community. Two graduate students have been involved in this investigation.

LC Devices subaward: These activities directly advance OSU graduate student Pedro Spingola towards his PhD. The experimental work on film formation is done by him with advising from Schumacher. Four undergraduate students are on the project. Alex Frye (OSU) is working with Spingola. Abby Bonino (UR), Prathiksha Mangalasubaskaran (UR) and Jenny Zhao (UR) are working under the direction of Ken Marshall and Nate Urban. Maia Ross (UR) worked on the project doing substantive work. Spingola is giving an invited talk on this work at the upcoming 2025 SPIE XXIX Liquid Crystals meeting.

The 4-PW prototype, if shown to be successful, can benefit most multi-PW laser facilities in the world today. In addition to helping to improve pulse contrast at reduced cost, such PMs can enable more advanced beam geometries that can currently be attempted, facilitating improved experiments.

LC device development in the NSF OPAL project involves and coordinates development efforts and advances made by several institutions including Lawrence Berkely National Laboratory (LBNL), U. Michigan, and the Extreme Light Infrastructure in Europe. This need was recognized by the Broader Technology Impacts – NSF OPAL aligns with key findings of the 2023 Basic Research Needs Workshop on Laser Technology sponsored by DOE and NSF.

Radiation Shielding subaward: The project has provided a direct opportunity to train a new PhD student at the University of Michigan in laser facility design, radiation interactions and transport, and shielding design for high-energy particle facilities. Radiation shielding design and monitoring requires specialized tools and training. Designs for NSF OPAL shielding will exercise methods used for NSF ZEUS that will be compared with other operating facilities like ELI Beamlines and ELI Nuclear Physics, as well as other facilities in the design stage, like Vulcan 20-20 in the UK and a new facility at Colorado State University (CSU) funded by a public-private partnership with Marvel Fusion and a DOE Office of Science Inertial Fusion Energy Science and Technology Accelerated Research (IFE-STAR) hub.

Laser mirror R&D: Based on feedback from the CDR, the RI-1 project team committed to changing the size of the NSF OPAL compressed beam to 62 x 62 cm2 as part of an effort to reduce the overall cost of a future construction project. Additionally, new efforts will explore approaches with potential to increase the damage thresholds of compressed-pulse, and to develop and prototype low-cost methods for constructing lightweight substrates for transport and focusing mirrors to support these overall cost savings. This new scope shows promise to realize broader technological impacts that would benefit other high-power laser important applications, like laser fusion and directed energy.

## 5.2 Outreach, Engagement and Education

PAALS FSWG: The PAALS co-PI mentored two undergraduate students for summer undergraduate research fellowships (Amy Martinez and Sarine Yeghiayan). The students participated in projects for simulations on OPAL relevant conditions for PAALS as well as for diagnostic development needed to scale towards multi-Petawatt facilities. PAALS FSWG members were active across multiple venues, making concerted efforts to be present in conferences with the goal of broadening participation with fields that have had limited engagement with PAALS prior, including the Multi-Messenger Workshop and the Kavli Relativistic Astrophysics series. The PAALS co-PI was involved in several press releases discussing both ZEUS and OPAL, including NSF podcasts and press releases. He also led the first 2-PW experimental campaign by outside users at the ZEUS facility, and worked with strategic communications staff to highlight this milestone in multi-petawatt science in public news such as The Verge, Tech Explorist, and Phys.Org.

HFP/QED FSWG: Graduate students and post docs supervised by Antonino Di Piazza mostly carried out the work required for preparing the three HFP/QED flagship experiments and the related projects. Reshad Rahman (graduate student, Horton fellow) continues his simulations on nonlinear Breit-Wheeler pair production in flying-focus beams. Adrian Hosak (graduate student, Horton fellow) has completed the computation of one part of the 1-loop radiative corrections in an intense field with the assistance of Misha Lopez-Lopez (post doc). Thomas de Vos (graduate student, Horton fellow) has recently started the study of a plasma in a strong laser field with particular attention to spin effects by means of non-equilibrium QED methods. Finally, Sapan Karki has almost completed his first project on comparing the coherence properties of radiation by several bosons versus several fermions.

One undergraduate worked on the development of the SPPS project during the fall of 2024 and spring and summer of 2025. Emily Dill (UR, undergrad) used a code to quantify the sensitivity of the SPPS experiment to co-pointing and co-timing, to validate more realistic beam models, and to provide input on requirements to the laser team and the diagnostic development project; due to her input she is the second author on a manuscript submitted to Physics of Plasmas. Ms. Dill also developed code to validate the effectiveness of a scheme for electrostatic sweeping of the residual gas to reduce background in the SPPS experiment and worked on hardware and detector development for an experiment to test this scheme on MTW-OPAL in fall of 2025.

LAPP FSWG: Postdoctoral scholars, including Stefano Racioppi (UB), Heath LeFevre (UM), and Arnold Schwemmlein (UR), as well as Jihoon Kim (Cornell), have been involved in organizing and contributing to the FSWGs and the LAPPS1 flagship experiment proposal.

The second year of a formal undergraduate (UG) program at UR/LLE includes 13 students working on various projects ranging from lasers to spectroscopy. The UG program includes seminars exposing the students to activities at UR/LLE, including the NSF OPAL RI-1 project.

LDNP FSWG: Co-PI Ani Aprahamian mentored a nuclear physics undergraduate student at Notre Dame University, who subsequently applied to graduate programs and accepted an offer from MIT.

Graduate student research: Seven new Horton Fellowships were awarded to Ph.D. students at the University of Rochester in areas related to NSF OPAL.

The RI-1 project funded two students, Amanda Elliott (Physics and Astronomy) and Rhett Wampler (Optics). Rhett Wampler's research, supervised by Christophe Dorrer, entails characterizing nonlinear crystals using a novel test station and techniques. Amanda Elliott's research project, supervised by John Palastro, investigates nonlinear optical phenomena driven by space-time structured ("flying focus") laser pulses that present a unique opportunity to investigate regimes in which flying focus pulses provide an advantage over traditional, fixed-focus Gaussian pulses, including self-focusing, nonlinear wave-mixing for supercontinuum generation, two-color THz generation, optical rectification, and free-space quasi-phase matching. Her research makes use of the 3-D propagation code SUPER (Simulation for the Unidirectional Propagation Equation at Rochester) for nonlinear optics. Close collaboration with experimental scientists will motivate the parameters, so that the concepts and simulations can inform experimental designs.

Jon Zuegel (PI) gave an invited talk titled "NSF OPAL-Reaching for the Brightest Light" at the 2025 Omega Laser Facility Users Group (OLUG) meeting held May 20-22, 2025, in Rochester, NY. The talk presented the status of the NSF OPAL RI-1 project to OLUG members and encouraged them to join the effort. Matthew Barczys and Mike Krieger presented two poster presentations titled "NSF OPAL Experimental Facility Design Concepts" and "NSF OPAL Facility Concept of Operations," respectively.

Jon Zuegel (PI) presented part of an invited talk during a dedicated NSF AccelNet Extreme Light in Intensity, Time and Space (X-*lites*) session at the ELI User Meeting held in Szeged, Hungary, on June 18-20, 2025. The talk introduced the X-*lites* Science and Technology (S&T) working group and opportunities for this international network of networks to accelerate progress and address grand challenges at the frontiers of laser-matter coherent interactions at the highest intensities, the fastest times, and the shortest distances (i.e., extreme light).

# 6. Products

## 6.1 Supported by the RI-1 project

### *6.1.1 Papers published and manuscripts submitted*

1. Ani Aprahamian *et al*. “Nucleosynthesis with tritium,” J. Phys. G: Nucl. Part. Phys. 52 063001; https://doi.org/10.1088/1361-6471/addc86.
2. Hans Rinderknecht, *et al*, “On Measuring Stimulated Photon-photon Scattering using Multiple Ultraintense Lasers” published online in Physics of Plasmas; https://doi.org/10.1063/5.0272791.
3. Jess Shaw, *et al.*, “Path to a Single-Stage, 100-GeV Electron Beam via a Flying-Focus-Driven Laser-Plasma Accelerator” Physics of Plasmas, Phys. Plasmas 32, 083107 (2025); https://doi.org/10.1063/5.0274780.
4. Eva Zurek contributed to "Roadmap for Physics of Warm Dense Matter" submitted to *Plasma Physics & Controlled Fusion (PPCF)* journal of the Institute of Physics Publishing, under review; posted to arXiv Plasma Physics arXiv:2505.02494 or https://doi.org/10.48550/arXiv.2505.02494.

### *6.1.2 Conference + workshop presentations*

1. C. Forrest, “Two Laser-Driven Nuclear Physics Flagship Experiments Have Been Identified for the NSF OPAL Laser Facility” at New Opportunities and Challenges in Nuclear Physics with High Power Lasers, July 1-5, 2024, Trento, Italy.
2. Antonino Di Piazza, “Coherence effects in the collision of high-energy electron-positron bunches with an intense laser field”, 50th European Physical Society (EPS) Conference on Plasma Physics, July 8-12, 2024, Salamanca, Spain.
3. Pedro Spingola presented at the 2024 LaserNetUS Annual Meeting held in in Austin, TX on July 16-18, 2024.
4. Antonino Di Piazza Physics in Intense Fields (PIF24), August 26-30, 2024.
5. RI-1 team Multi-Petawatt Physics at New and Future Laser User Facilities mini-conference at the APS DPP Annual Meeting held October 7-11, 2024, in Atlanta, GA.
6. Antonino Di Piazza “High-Field Physics at Multipetawatt Laser Facilities and the Case of NSF OPAL” at International Conference on Ultra-Intense Lasers (ICUIL) held September 9-13, 20XX, in Cozumel, Mexico.
7. J. P. Palastro, “Space-Time Structured Waves,” 37th European Conference on Laser Interaction with Matter on September 17, 2024, in Lisbon, Portugal.
8. Chad Forrest, “Cross-Section Measurements of Triton-Induced Reactions with Lithium,” at APS DNP Annual Meeting held October 7-11, 2024, in Boston, MA.
9. RI-1 team at International Laser Operations Workshop (ILOW) held October 7-11, 2024, in Bordeaux, France.
10. RI-1 team at Conceptual Design Update (CDU) streamed to community members on Zoom on October 31, 2024.
11. J. P. Palastro, “Flying Focus” at Optica Incubator on Spatiotemporal Structuring of Light on November 13-15, 2024, in Washington, DC.
12. Steve Ivancic at National Diagnostics Working Group meeting held at LANL on November 19-21, 2024.
13. 2024 STFC-CLF Christmas Meeting of the High-Power Laser User Community, December 16-18, 2024.
14. Antonino Di Piazza, Fundamental Research and Applications with the EuPRAXIA facility on December 4, 2024 at LNF in Frascati, Italy.

15. Eva Zurek, “Extreme Chemistry and New States of Matter at Extreme Pressures” at NIF and Jupiter Laser Facility User Group Meeting on January 29, 2025, at LLNL in Livermore, CA.
16. Jake Bromage, “NSF OPAL: Laser System Design and Critical Technologies” at 4th Technical Meeting on Laser Modeling and Performance of ICF Laser Facilities on January 30, 2025, at LLNL in Livermore, CA.
17. Chad Forrest, “Nuclear Reactions Using a Tritium Ion Beam at the University of Rochester's Omega Laser Facility,” at Workshop for Applied Nuclear Data Activities (WANDA) 2025, February 11, 2025, in Arlington, VA.
18. Antonino Di Piazza at Austin 2025 International Conference on Fundamental Plasma Physics (invited talk) held on March 25, 2025, in Austin, TX.
19. Rhett Wampler, “Mapping the Phase-Matching Conditions of the Crystal Sector Boundary in Partially Deuterated Potassium Dihydrogen Phosphate (DKDP) ,” at CLEO 2025 held May 4-9, 2025, in Long Beach, CA.
20. Trajen Cracium, “An Introduction to Target Deployment Systems for NSF OPAL,” at Target Fabrication Workshop on April 7, 2025, in Oxford, United Kingdom.
21. Jake Bromage invited talk: “NSF OPAL: Laser System Design and Critical Technologies,” SPIE Optics + Optoelectronics held April 7-10, 2025, in Prague, Czech Republic.
22. Danae Polsin, “Probing Phase Transitions Using Time-Resolved X-Ray Diffraction” at CMAP Annual Meeting on May 1-2, 2025.
23. M. Krieger, *et al*, Poster: “NSF OPAL Experimental Facility Design Concepts,” OMEGA Laser Users Group (OLUG) Workshop, May 21, 2025.
24. T. Cracium, *et al*, Poster: “An Introduction to Target Systems on NSF OPAL," OMEGA Laser Users Group (OLUG) Workshop, May 21, 2025.
25. Jonathan Zuegel invited talk: “NSF OPAL – Reaching for the Brightest Light," OMEGA Laser Users Group (OLUG) Workshop, May 21, 2025.
26. Eva Zurek invited talk at WATOC2025 meeting (World Association of Theoretical and Computational Chemists) held on June 22-27, 2025, in Oslo, Norway.
27. Danae Polsin, “Probing Phase Transitions Using Time-Resolved X-Ray Diffraction,” OMEGA Laser Users Group (OLUG) Workshop on May 21, 2025.
28. Hans Rinderknecht, invited talk “On Measuring Stimulated Photon-Photon Scattering Using Multiple Ultraintense Lasers” at the EPS Conference on Plasma Physics held in Vilnius, Lithuania on July 10, 2025.
29. X. Li, C. Forrest, A. Raymond, M. Krieger, I. Jovanovic, “FLUKA Simulation Studies for Radiation Transport, Shielding, and Activation in ZEUS and OPAL Laser Facilities”, LaserNetUS + ZEUS Annual Meeting on July 8-10, 2025.
30. J. D. Zuegel, invited talk: “NSF OPAL – Reaching for the Brightest Light," LaserNetUS + ZEUS Annual Meeting on July 8-10, 2025.

### *6.1.3 Colloquia + seminars presented*

1. Antonino Di Piazza, “Modern tests of Quantum Electrodynamics in the strong-field regime” on November 13, 2024, at U. Michigan Physics.
2. Reshad Rahman, “Strong Field QED and Nonlinear Breit Wheeler Pair-Production in Flying Focused Pulses” on November 26, 2024, at UR/LLE.
3. Antonino Di Piazza, “Modern tests of Quantum Electrodynamics in the strong-field regime” on December 9, 2024, at ELI-NP in Măgurele, Romania.

4. J. L. Shaw at UCLA Physics Colloquium on February 14, 2025, at Los Angeles, CA.
5. Antonino Di Piazza at College of William and Mary on April 25, 2025.
6. Ani Aprahamian presented a seminar (recorded) at Rutgers University titled "Were the Superheavy Elements Made in Nature?" at the Physics Department of University of Rutgers on April 30, 2025.
7. T. Cracium, M. Krieger, "From SUNY Geneseo to NSF OPAL", SUNY Geneseo Annual Lab Tours, Laboratory for Laser Energetics at University of Rochester, July 2, 2025.

## 6.2 Collaborations/complementary programs not supported by RI-1 project

### *6.2.1 Papers published and manuscripts submitted*

1. Arseny Mironov submitted "Testing strong-field QED with the avalanche precursor" to Physics of Plasmas, under review.
2. Gerrit Bruhaug submitted "Hollow-Core Anti-Resonant Fiber Optics as a Path Towards Practical Laser-Undulator Based X-Ray Sources," to Proceedings of 2025 North American Particle Accelerator Conference (Sacramento, CA).

### *6.2.2 Conference + workshop presentations*

1. M. V. Ambat, poster "Programmable-trajectory ultrafast flying focus pulses," Advanced Accelerator Concepts Workshop held July 21-26, 2024, in Naperville, IL.
2. C. Jeon, "Development of a Broadband Reflective Phase Retarder and Compensators to Generate and Maintain Circularly Polarized Light for MTW-OPAL and Multipetawatt Lasers" at International Conference on Ultra-Intense Lasers (ICUIL) held September 9-13, 2024, in Cozumel, Mexico.
3. G. Bruhaug, "Experimental Designs for Probing the Quantum FEL Regime" at Q-BASIS24 held November 11-14, in Osaka, Japan.
4. C. Feng, "Design and Performance of a New Ultra-Broadband Front End for MTW-OPAL and Multipetawatt All-OPCPA Systems" at International Conference on Ultra-Intense Lasers (ICUIL) held September 9-13, 2024, in Cozumel, Mexico.
5. Stepan Bulanov "Laser ion acceleration at PW-class laser facilities and beyond," SPIE Optics + Optoelectronics held April 7-10, 2025 in Prague, Czech Republic.

## 6.3 Other products or engagements

### *6.3.1 Project Documents*

Appendix 1 lists Project Peer Reviews completed during the reporting period. Review minutes are archived.

### *6.3.2 Theses*

Graduate and undergraduate students working on the NSF OPAL project have not produced any theses yet.

### *6.3.3 Summer school participation*

1. Ani Aprahamian at National Nuclear Target Development School on August 15-19, 2024, at Texas A&M (College Station, TX)
2. Antonino Di Piazza at Heidelberg, Germany on October 7, 2024
3. Eva Zurek at CMAP school for undergraduates held on June 2-6, 2025, in Rochester, NY
4. Ani Aprahamian at 2025 summer REU program at Notre Dame University

5. Ani Aprahamian at NP3M Summer School on June 9-13, 2025, at Indiana University
6. Ani Aprahamian at Exotic Beam summer school held on June 22-28, 2025, at LBNL

#### *6.3.4 Technical visits*

1. Elias Gerstmayr (QUB) to UR on September 5, 2024
2. RI-1 team at Apollon on October 11, 2024
3. RI-1 team at ELI Beamlines on October 14, 2024
4. Antonino Di Piazza at ELI Nuclear Physics on December 2, 2024
5. Antonino Di Piazza in Corsica, France on October 27, 2024
6. Jon Zuegel at LANL on November 12, 2025
7. Antonino Di Piazza at ZEUS facility on November 13, 2024
8. Jon Zuegel at LLNL on November 14, 2025
9. Jake Bromage at Rutherford Appleton Laboratory (RAL) on February 26, 2025
10. Antonino Di Piazza at Vulcan 20-20 Science Case (virtual) April 10, 2025
11. Jon Zuegel at Oxford University on April 28, 2025
12. Franklin Dollar at U. Michigan for ZEUS multi-PW experiments related to PAALS flagship in May 2025
13. Florida State Univ. (FSU) visit to UR/LLE on June 13, 2025

# 7. Participation data/demographics

Table 7.1 summarizes participation in the project by NSF OPAL Frontier Science Working Groups (FSWGs) and Work Breakdown Structure (WBS) elements. A survey sent to all FSWG and WBS team members asked them to self-report their level of effort contributing to the RI-1 project in their respective areas represented by full-time-equivalent (FTE) months of effort. A 1-FTE unit in Table 7.1 corresponds to one month of full-time effort. The survey responses were received from many but not all who have been involved. Additional data from charges to RI-1 project accounts in Year 2 efforts supplemented reports by the survey where gaps were identified. Y1 reporting was updated from the last annual report with additional data.

Table 7.1 – NSF OPAL level of participation (# of individuals, FTE-months) during the first year of the project (Y1) and the current reporting period Year 2 (Y2)

| | Frontier Science | | | | Facility Design + Prototyping Teams (incl. subawards) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **FSWG** | **Y1 #** | **Y1 #** | **Y1 FTE** | **Y2 FTE** | **WBS** | **Y1 #** | **Y2 #** | **Y1 FTE** | **Y2 FTE** | **WBS** | **Y1 #** | **Y2 #** | **Y1 FTE** | **Y2 FTE** |
| **PAALS** | 8 | 8 | 17 | 49 | **1.1** | 14 | 22 | 36 | 54 | **1.7** | 1 | 1 | 2 | 1 |
| **HFP/QED** | 25 | 3 | 26 | 4 | **1.2** | 1 | 3 | 2 | 7 | **1.8** | 1 | 9 | 1 | 2 |
| **LAPP** | 6 | 6 | 5 | 17 | **1.3** | 1 | 1 | 0 | 4 | **1.9** | | 2 | | 7 |
| **LDNP** | 4 | 2 | 3 | 2 | **1.4** | 3 | 3 | 9 | 6 | **2.1** | 13 | 28 | 31 | 37 |
| | | | | | **1.5** | 16 | 27 | 51 | 80 | **2.2** | 14 | 14 | 31 | 34 |
| | | | | | **1.6** | 9 | 19 | 19 | 53 | **2.3** | 2 | 2 | 13 | 13 |
| **FSWG Totals** | 43 | 19 | 51 | 72 | **WBS1 + WBS2 Totals** | | | | | | 75 | 133 | 195 | 299 |

PAALS: Particle Acceleration & Advanced Lights Sources
HFP/QED: High-Field Physics Quantum Electrodyn.
LAPP: Laboratory Astrophysics + Planetary Physics
LDNP: Laser Driven Nuclear Physics

WBS1.1: Project Mgt.
WBS1.2: Front-End Systems
WBS1.3: Large-aperture OPAs
WBS1.4: OPA Pump Systems
WBS1.5: Pulse Compression and Transport
WBS1.6: Experimental Systems

WBS1.7: Diagnostic Dev.
WBS1.8: Controls Systems
WBS1.9: IT Systems
WBS2.1: Actively Cooled Disk Amplifier (ACoDA)
WBS2.2: Extra-Large Gratings
WBS2.3: Large-aperture OPA Crystals

Due to the increased pace and volume of work in the RI-1 project, the overall number of participants increased from 118 in Year 1 to 152 in Year 2. Total effort increased from 246 FTE-months (20.5 FTE-years) in Year 1 to 372 FTE-months (31 FTE-years) in Year 2.

Estimating participation involved several limitations and considerations:

- The survey received inputs from many but not all those who have been involved, so the reported participation under counts the number of individuals and level of efforts. Those associated with but not funded by the project, notably members of the FSWGs, fall into this situation.
- FSWG efforts during Year 1 focused heavily on identifying experimental use cases that led to proposals for flagship experiments. FSWG involvement then slowed in Year 2 as the project focused on conceptual design.
- WBS 1.4 efforts supported by complementary programs, such as the MEC-U and FLUX projects, are not included in Table 7.1.

The RI-1 project held two updates streamed to the community on Zoom:

- an NSF OPAL Conceptual Design Update on October 31, 2024, with 188 registered participants (144 from North America, 40 from Europe, 4 from Asia) from 58 different institutions
- NSF OPAL Diagnostic Community Update on January 16, 2025, with 55 registered participants (41 from North America, 10 from Europe, 2 from Asia, 1 from South America) from 22 different institutions.

The RI-1 conceptual design review (CDR) was held on April 22-23, 2025, with participation by 224 registered members of the scientific community (165 from North America, 49 from Europe, 4 from Asia, 1 from South America, 5 blank) from 60 institutions noted in Table 7.2.

Table 7.2 – Institutions participating in NSF OPAL RI-1 Conceptual Design Review

| | | | |
|---|---|---|---|
| Amplitude Laser Inc. | Brookhaven NL | Coherent Inc | Cycle Lasers |
| ELI Beamlines | ELI-ERIC | ELI-NP | EvolvOptic |
| General Atomics | GSI | GIST | Helmholtz Inst. Jena |
| HZDR | Imperial College | L3Harris | LANL |
| Leonardo Electronics US | Light Conversion | LLNL | Princeton University |
| Prism Computational Sciences, Inc | Queen's U. Belfast | Sandia NLs | Starfuel |
| SUNY Buffalo | Sydor Technologies | Univ. Michigan | Univ. Notre Dame |
| Univ. Oxford | Univ. Rochester | UC Berkeley | UC Irvine |
| UKRI | U.S. National Science Foundation | Vilnius University | Wilkinson M Consulting |

The Friends NSF OPAL mailing list has 444 registrants.

*Early-career participants:*

Developing the workforce of the future stands as a key objective of the NSF OPAL RI-1 project, so the project engages early-career participants at several levels of education, training, and employment.

Postdoc (5): Sapan Karki (UR), Stefano Racioppi (UB), Heath Lefevre (UM), Arnold Schwemmlein (UR), JH Kim (Cornell)

Recent college graduates (4): Dominic LoMascolo (UR), Taylor Fowler (UR), Noah Carrier (UR), Jack Roche (PGL from Bridgewater State University, now pursuing MS at UMass Dartmouth)

Graduate students (8): Pedro Spingola (OSU), Xuanqi Li (UM), Smrithan Ravichandran (U. Maryland), Rhett Wampler (UR), Amanda Elliott (UR), Reshad Rahman (UR), Adrian Hosak (UR), Thomas de Vos (UR)

Undergraduate students (13): Alex Frye (OSU), Ashley Brodeur (RIT co-op), Amy Martinez (UCI), Sarine Yeghiayan (UCI), Connor O'Neil at PGL (Wentworth College), Maia Ross (UR), Abby Bonino (UR), Connor Boehly (UR), Emily Dill (UR), Nyaradzo 'Valery' Mararanje (UR), Jenny Zhao (UR), Karim Waly (UR), Benjamin Kamenetaky at PGL (UR)

High School (2): Prathiksha Mangalasubaskaran (Pittsford Mendon HS, rising UR freshman), Sean Della-Torre (McQuaid HS).

# 8. Changes/Problems

The NSF OPAL configuration changed from the original concept that included two, independent experimental areas (EA1 + EA2) to a single target bay. This more compact layout significantly reduces the estimated building construction cost.

The WBS 2.2 Grating subaward to PGL was paused while the project team reassessed the needed funding profile to complete the Nanoruler5 (NR5) design and to remove NR5 construction project scope since NR5 will not be needed to produce XL gratings at the completion of the RI-1 project. The associated budget will be redirected to (1) prototyping low-cost, lightweight mirrors and (2) improving the Laser Induced Damage Threshold (LIDT) of gratings and short-pulse transport Optics to enable smaller optics.

# 9. Financial Summary

[REDACTED]

# 10. Appendices Table of Contents

Appendix 1 – Facility Design Peer Reviews

| WBS | Peer Review Title | Date |
|---|---|---|
| 1.2 | Ultrafast Front-end (UFE) | 1/8/2025 |
| 1.2 | Non-collinear Optical Parametric Amplifier - nanosecond stage (NOPA-n) | 11/22/2024 |
| 1.2 | Radial Group Delay Compensator | 12/11/2024 |
| 1.3 | Beamline Design | 12/4/2024 |
| 1.5 | Double Plasma Mirror (and Debrelay) | 12/4/2024 |
| 1.5 | Transport & Diagnostics Table/Packages | 11/20/2024 |
| 1.5 | UV | 11/1/2024 |
| 1.5 | Grating Compression Chamber | 11/15/2024 |
| 1.6 | Facility Vacuum Systems | 12/11/2024 |
| 1.6 | Target Systems - Rapid Deployment System | 12/18/2024 |
| 1.6 | Flexible Platen Interface (FXPI) | 12/18/2024 |
| 1.6 | Experimental Area 1 | 1/15/2025 |
| 1.6 | Radiation Shielding | 1/8/2025 |
| 1.6 | Diagnostic Interfacing | 1/10/2025 |
| 1.8 | Hardware Timing System (HTS) | 11/13/2025 |

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