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

Optical
Parametric
Amplifier
Line

Flagship Experiment Selection Report

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Executive Summary

This document serves as a record of decision about the selection of flagship experiments (FSEs) that will guide the NSF OPAL midscale research infrastructure (RI-1) project that will design and prototype critical systems for a new, world-leading, high-power laser user facility at the University of Rochester.

NSF OPAL frontier science working groups [1] (FSWGs) identified eight potential NSF OPAL flagship experiments enabled by multi-petawatt lasers. Flagship experiments serve a dual role of (1) providing highly compelling long-term (decadal-scale) science goals for the facility and the community, and (2) defining the objective performance envelope of the planned capabilities that will be designed by the RI-1 project to deliver unique capabilities to the scientific user community.

The bulk of the operational capability of any future NSF OPAL facility will be composed of "mature" experimental capabilities, some of which may or may not necessarily contribute to achieving the selected flagship experiments. All eight flagship-experiments offered compelling, long-term science goals for a future NSF OPAL facility and the broad scientific community and push the limits of technology to realize compelling science goals, as intended, but the project team has determined that their combined scope exceeds the capacity of the RI-1 project to design and implement all of them in a future construction project. This led to developing and implementing a process to select NSF OPAL flagship experiments and other operational facility capabilities. The FSWGs identified a "champion" for each FSE to assemble a proposal team to prepare and submit proposals. This report summarizes the outcome of an external peer review panel (PRP) and feasibility review of these proposals that informed flagship experiment selections. Section 1 describes the peer review panel and feasibility review processes, while Section 2 summarizes their results. Section 3 analyzes the proposed flagship experiments and identifies them in two general categories. Four appendices provide supporting material, as noted in Sections 1 to 3.

- A **flagship experiment** provides a highly compelling long-term (decadal-scale) science goal for the facility and the community that defines the objective performance envelope of NSF OPAL and the scope of the RI-1 design project that is also deemed feasible. One proposal met these criteria fully.
  - <u>Stimulated Photon-Photon Scattering (HFP/QED2)</u>: This flagship proposes a ca significant demonstration of strong-field quantum electrodynamics (SF-QED). The co-timing/co-pointing requirements will drive NSF OPAL performance and require state-of-the-art systems to frequency double, split, and focus two outputs of a multi-10PW laser beam. This flagship experiment team will join the NSF OPAL construction project proposal team and have priority at leading experiments leading to a flagship experiment.

  Several of the flagship proposals met some but not all of the flagship experiment criteria and/or their proposed scope was not deemed fully feasible given the current or projected state of the art with enough detail for the RI-1 project to design them. The RI-1 project will partially fulfill three of the proposals with **NSF OPAL operational facility capabilities** that would lead to future flagship experiments once all of capabilities are fully realized.
  - <u>Ultrafast laboratory astrophysics and planetary physics (LAPP1)</u>: The LAPP scientific community spans a range of high-energy density (HED) sciences that is large and active in areas of both discovery and programmatic science that hold excellent prospects for high-

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[1] **PAALS** – particle acceleration and advanced light sources; **HFP/QED** – high-field physics/quantum electro-dynamics; **LAPP** – laboratory astrophysics and planetary physics; **LDNP** – laser-driven nuclear physics

impact results and advancing science critical to the nation. Frequency-doubled NSF OPAL pulses with ultrahigh temporal contrast, driven by HFP/QED2 requirements, find compelling applications in LAPP discovery and programmatic science. LAPP1 called for some laser-driven probe requirements that constitute flagship development efforts of their own, such as an inverse Compton source for probing HED conditions. The RI-1 project team will assess the feasibility of enabling (or at least not precluding) implementation of such a currently unproven probe in the future.

  — Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams (PAALS1): The proposed experiment stands at the forefront/convergence of plasma-based accelerators and optics at high intensities. It points to intriguing possibilities for electron acceleration using "flying-focus" technology for laser wakefield acceleration (LWFA), as well as important potential scientific applications for such electron beams. Uncertainties in how flying-focus technology might develop, plus the potentially significant expense and space envelope of 100+ GeV electron beams constitute significant risks that must be mitigated before committing to the design and construction of NSF OPAL to reach the proposed flagship performance. NSF OPAL will be designed to provide maximum flexibility for dedicated R&D efforts that could lead to the proposed flagship performance.

  — Tritium-induced nucleosynthesis (LDNP1): Laser-driven triton beams proposed in LDNP1 could address some potentially compelling NNSA programmatic questions that were not explicitly included in the proposal. NSF OPAL would require a dedicated target chamber and associated systems for handling tritium to avoid contaminating equipment used for other experiments. Implementing this capability in the NSF OPAL facility design depends on a mutual agreement of NSF and NNSA.

The RI-1 project team will design the NSF OPAL facility for the feasible elements identified by these proposals. The HFP/QED2, LAPP1, PAALS1, and LDNP1 (conditional) experimental teams will join the NSF OPAL construction project proposal team and have priority at leading experiments leading to future flagship experiments.

- **Future flagship experiments** addressed by four proposals could be pursued with future upgrades. A new facility, like NSF OPAL, should provide opportunities to address evolving science by providing extra capacity for future development.

  — Multi-messenger probing of ultra-intense/relativistic light-matter interactions (PAALS2): The PRP recognized this as curiosity-driven with very high discovery potential, but it did not identify an explicit science case. Developing the proposed experimental capabilities would drive significant technological innovation with high impact to the science community. These capabilities could be developed at another multi-beam facility that would inform future implementation at NSF OPAL.

  — Extreme Fields: Testing QED in uncharted strong field regimes (HFP/QED1): This experiment would explore new QED cascade physics that represent a definite goal of the strong-field QED science community. Initial stages could and most likely would need to occur at other laser facilities that offer dual high-intensity beamlines, like NSF ZEUS and ELI NP, or at a facility that collocates an ultraintense laser with a linear accelerator. New techniques, such as a proposed "plasma eyepiece" to control focusing, could be developed on NSF OPAL as a user-facility capability or at these other facilities. The proposed flagship experiment could then use the world-leading properties of the proposed NSF OPAL facility to extend performance and achieve new results in a “future flagship” experiment.

— Testing strong-field QED with the avalanche precursor (HFP/QED3): This experiment would employ the unique capabilities of a future NSF OPAL user facility with the highest intensity counter-propagating laser beams that would push the limits of NSF-OPAL performance and potentially lead to a very high impact result. Like the HFP/QED1 experiment, the required developments could and most likely would need to occur first at other facilities. It overlaps strongly with astrophysics, an area of physics that would excite the public.

— Neutron-Neutron Scattering (LDNP2): This experiment aims to address a controversial issue in the description of neutron-neutron scattering, where contradictory indirect measurements and theory fail to agree. This “future flagship” experiment would prove extremely challenging technically and requires more development that could advance using capabilities available at NSF OPAL and other ultraintense laser facilities. If successful, LDNP2 would advance nuclear physics strongly and demonstrate the utility of nuclear photonics while also developing ultrafast, pulsed-neutron sources that could find other applications.

The PAALS2, HFP/QED1, HFP/QED3, and LDNP2 proposals offer information that will inform RI-1 design efforts with the goal of accommodating the associated capabilities as much as possible.

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1. Peer Review Panel and Feasibility Review Processes

1.0 Introduction

The NSF OPAL RI-1 award supports the design of a new, world-leading, high-power laser user facility at the University of Rochester. This design project for the facility to be called NSF OPAL envisions two new powerful lasers to be located at the university's Laboratory for Laser Energetics (UR/LLE). NSF OPAL will employ a technique developed at UR/LLE for the generation of very powerful, ultrashort laser pulses that was recognized by the 2018 Nobel Prize in Physics. 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. Once completed, NSF OPAL will be the highest-power laser system in the world. The two laser beams combined will deliver approximately the same total power as incident on the Earth’s surface from the Sun, but focused into an area smaller than the cross-section of a human hair. The design effort will engage the U.S. industry to develop critical laser optics and will include hands-on training of a new generation of laser facility designers, builders, and users.

The NSF OPAL facility design award supports design of two 25-petawatt lasers using optical parametric chirped-pulse amplification, as well as associated experimental and diagnostics systems. The design will be guided by the most pressing scientific questions that can be answered using such a laser system in four areas of frontier research: 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). The frontier science working groups (FSWGs) involve a large group of scientists who have contributed significantly, many of them unfunded by the RI-1 project.

The main aims of the project are to: (1) design the NSF OPAL facility, including lasers, experimental systems and 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. This 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. The NSF OPAL frontier science working groups have also engaged a significant portion of their respective communities in preparing flagship experiment proposals outside of the RI-1 project funding, which demonstrates their commitment to the future possibilities of NSF OPAL.

NSF OPAL flagship experiments have a dual role of both (1) providing highly compelling long-term (decadal-scale) science goals for the facility and the community, and (2) defining the outer performance envelope of the planned capabilities that will be designed by the RI-1 project. The bulk of the operational capability of a future NSF OPAL facility will be composed of “mature” experimental capabilities to support user-defined experiments, some of which may or may not necessarily contribute to achieving the selected flagship experiments.

The NSF OPAL frontier science working groups (FSWGs) and the RI-1 project team identified eight NSF OPAL Flagship Experiments (FSEs), enabled by multi-petawatt lasers. Appendix A includes the submitted flagship proposals, as described below.

- PAALS1: Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams (Champion: Jessica Shaw, UR/LLE; 19 team members from 2 institutions)
- PAALS2: Multi-messenger probing of ultra-intense/relativistic light-matter interactions (Champions: Stepan Bulanov, Lieselotte Obst-Huebl, LBNL; 8 team members from 5 institutions)
- HFP/QED1: Extreme Fields: Testing QED in uncharted strong field regimes (Champion: Stuart PD Mangles, Imperial College London, UK; 21 team members from 12 institutions)
- HFP/QED2: Stimulated Photon-Photon Scattering (Champion: Hans Rinderknecht, UR/LLE; 7 team members from 5 institutions)
- HFP/QED3: Testing strong-field QED with the avalanche precursor (Champion: Gianluca Gregori, Oxford University; 10 team members from 5 institutions)
- LAPP1: Ultrafast laboratory astrophysics and planetary physics (Champion: Danae Polsin, UR/LLE; 10 team members from 6 institutions)
- LDNP1: Tritium-induced nucleosynthesis (Champion: Ani Aprahamian, University of Notre Dame; 10 team members from 7 institutions)
- LDNP2: Neutron-Neutron Scattering with Two High Shot-Rate Neutral Beams (Champion: Chad Forrest, UR/LLE; 9 team members from 5 institutions)

As intended, the NSF OPAL flagship experiments push the limits of technology to realize compelling science goals, but the project team has determined that the scope exceeds the capacity of the RI-1 project to design and implement all of them, so the project team proposed a process for further down selection. The RI-1 project charged its External Advisory Board (EAB) at its first meeting (EAB1) on April 17, 2024 to provide advice about its plans to down select and/or defer some of the proposed experiments to a "future flagship" status. The EAB1 report recommended:

1. "*Identify a Science Director/Coordinator, preferably external to LLE, who will rally the community, and be seen by NSF MPS, the LLE organization, and the national and international community as the spokesperson and champion for the broad scope of science addressed by the facility*.
2. "*Identify a Science Advisory Committee from the community to evaluate the many inputs to the prioritization process, and to rank the relative priority for the scientific cases for capabilities and experiments*.
3. "*The down selection process should take into account scientific metrics (see below), costs, and impact on the broader user program to optimize the scientific impact of the facility as a whole within the constraints of cost and resources. It should consider flagship experiments along with other experimental use cases*."

The project recognized the value of the first recommendation but decided that the flagship selection process needed to proceed immediately, so it deferred identifying a Science Director/Coordinator for now. The project team developed and implemented a peer review panel (PRP) and a feasibility review process described below to address the second and third recommendations. The FSWGs identified a "champion" for each FSE to assemble a proposal team to prepare and submit proposals.

1.1 Peer Review Panel (PRP) Process Description

The project team developed a proposal template to describe FSEs as concisely and completely as possible, including: the scientific merit, FSE team, the path to Conceptual Design Review (CDR), and the path to executing the flagship on NSF OPAL. FSE teams were encouraged to tap into the broader community to grow the NSF OPAL FSWGs for their proposal and to consult with the OPAL project team on paths to CDR and Flagship when preparing their proposal to ensure its feasibility. A successful FSE team will join the NSF OPAL construction project proposal team and have priority at leading experiments leading to the FSE if/when the NSF OPAL facility gets constructed.

The NSF OPAL Flagship Experiment PRP assessment criteria included five sections described in Appendix B and summarized here. Appendix B includes a screenshot of the PRP scoring sheet.

1. **Scientific Merit** – Does the proposal state a clear and compelling scientific question or hypothesis that the proposed flagship experiment will address?
2. **Flagship Experiment (FSE) team** – Does the proposal identify an appropriate champion and associated team to develop a conceptual design for the FSE that can be translated into conceptual designs for capabilities in the NSF OPAL facility?
3. **Path to Conceptual Design Review (CDR)** – Does the proposal include a credible and comprehensive plan for 'doing the experiment on paper' before CDR?
4. **Path to Flagship**– Does the proposal include a credible plan that will lead to performing the flagship experiment on NSF OPAL if/when it is constructed?
5. **Overall Summary** – In a few words, how does the PRP reviewer characterize the overall FSE proposal?

The NSF OPAL FSE proposal template included five sections:

- Cover page
- Introduction/Background – Briefly introduce the FSE and where it sits in the current field.
- Scientific Proposal – Address assessment criteria 1 in this section.
- Team and Resources – Address assessment criteria 2 in this section. Include an NSF formatted biosketch for each team member.
- Paths to CDR and Flagship – Address assessment criteria 3 + 4 in this section.

The project principal investigator/project director (PI/PD) coordinated the PRP process and selected the 13 PRP members in consultation with NSF. The PRP chair sent proposals to the PRP on June 3, 2024 and collected reviews, all of which were completed by June 17, 2024. The PRP chair collected review comments in a PRP Scoring Summary Sheet, shown in Appendix B that was distributed to the PRP members. With two exceptions, each reviewer reviewed four proposals. PRP members provided confidential reviews with scores and ordinal rankings, plus comments. Most of the PRP met via Zoom to discuss the scoring results on June 20. Section 2.1 summarizes the PRP points.

1.2 Feasibility Review Process Description

The RI-1 project team evaluated the feasibility of each proposal in parallel with and independent of the PRP reviews to expedite the process. Feasibility reviewers included the project manager (PM), project system engineer (SE), the Laser Science Team leader, and leaders of design project work breakdown structure (WBS) elements.

Each feasibility reviewer was asked to:

- score each FSE its impact on the design effort and its impact on a future construction project based on the following feasibility scoring basis table; and
- provide bulletized comments describing rough order-of-magnitude (ROM) estimates for the level of effort required to design and achieve the flagship experiment

Reviewers used the feasibility scoring basis shown in Table 1.2.1. Section 2.2 summarizes the feasibility review points.

Table 1.2.1 – Feasibility scoring basis

Score	Path to CDR Score Basis
1	Path to CDR understood and resources clearly identified
2	Path to CDR is reasonably well understood but some resources need to be identified or steps clarified
3	A plan has been provided, but is either missing resources or needs significant clarification
4	No plan has been provided by the proposal team

Score	Design Impact/Effort Level Score Basis
1	Technical requirements understood and experiment looks feasible based on current technology;
2	Technical requirements reasonably well understood but some R&D &/or significant new design required
3	Technical requirements understood but extensive R&D &/or significant new design required
4	Technical requirements not understood &/or looks infeasible based on future technology

1.3 Flagship Experiment Abstracts

PAALS1: Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams

Abstract: High-Energy Physics colliders provide a window into the basic building blocks of the universe. As the energy gain from conventional radiofrequency accelerator technology begins to plateau, advanced accelerator concepts become the only way to push particle energies to new levels where the boundaries in the understanding of the universe can be expanded. Dephasingless laser wakefield acceleration (LWFA) driven by an achromatic flying focus is an original concept that is a disruptive technology with the potential to transform the field of laser-plasma acceleration (LPA) and more broadly advanced accelerators. Conventional LWFA approaches can accelerate electrons to high energies, but the maximum energy is constrained by the low plasma densities required to limit dephasing between the laser pulse and accelerated electrons. The achromatic flying focus is a new spatiotemporal focusing system that provides the ability to propagate a high-intensity laser pulse over meters at any velocity while maintaining a small focal spot and a near-transform-limited pulse duration. By controlling the velocity of a focal spot propagating in a plasma, a wakefield can be driven at the speed of light, thus eliminating dephasing. Initial simulations of this “dephasingless” LWFA with no dephasing between the laser pulse and accelerated electrons suggests that a 20-fs, 500-J laser (NSF OPAL) would be capable of accelerating electrons to TeV-class energies in a one-meter stage. This flagship experiment seeks to successfully demonstrate such a TeV-class LPA.

PAALS2: Multi-Messenger Probing of Ultra-Intense/Relativistic Light-Matter Interactions

Abstract: Laser-matter interactions at relativistic intensities are at the forefront of plasma physics research nowadays. This is in part driven by the fast progress in laser technology, which enabled the design, construction, and operation of multi-PW laser facilities. This progress opened new avenues of research and a plethora of new phenomena to study, which require new tools to characterize and explore. We propose to study the interaction of a multi-10 PW laser pulse with a near critical density plasma by employing two plasma targets each irradiated by a multi-10 PW laser pulse. The first laser target interaction would produce copious amounts of high energy electrons, ions, and photons, which will be used to probe extreme electromagnetic fields and density waves generated by the second laser target interaction. These multiple messengers will arrive at the second target at various delays, due to their varying time of flight, providing multiple screenshots of the laser matter interaction. Thus, it would be the first multi-messenger study of relativistic light matter interaction, which will deliver a comprehensive suite of data describing from start to end the entire history of the interaction at unprecedented laser intensities.

HFP/QED1: Extreme Fields: Testing QED in Uncharted Strong-Field Regimes

Abstract: We propose to use the unique multi-beam capabilities of NSF-OPAL to collide high-energy electron beams with ultra-intense laser pulses and study how the fundamental force of electromagnetism behaves when the fields are extremely strong and can no longer be described using perturbation theory. By colliding ~10 GeV electrons from a laser wakefield accelerator driven by one multi-PW laser, with the intense fields at the focus of a second ~25 PW laser pulse, we will access an uncharted regime of quantum electrodynamics where the theoretical challenges, both technical and conceptual, mean that there is no consensus on the expected behavior. We will compare the key signatures of these collisions— the electron energy loss and the production of gamma photons and electron-positron pairs—against the predictions of the best current models and provide new insight into one of the fundamental forces of nature.

HFP/QED2: Stimulated Photon-Photon Scattering

Abstract: We propose to use the NSF OPAL facility to measure Stimulated Photon-Photon Scattering (SPPS), providing a first direct measurement of the nonlinearity of the QED vacuum. Stimulated Photon-Photon Scattering is a prediction of strong-field QED for the response of the vacuum to intense electromagnetic fields, in which virtual electron-positron pairs mediate scattering between photons. The scattering is a fourth-order QED process and has never been directly observed due to its low cross-section. The proposed experiments will test the hypothesis that the Euler-Heisenberg Lagrangian accurately predicts the nonlinear vacuum response to intense EM fields, and will begin to address the broader scientific question: *How can we harness the nonlinearity of the quantum vacuum?* Preliminary simulations predict NSF OPAL can produce a detectable signal of over 1000 scattered photons per shot with three input beams in either of two configurations. The Alpha-1 beam will be split and optionally frequency-doubled, then both beams will be co-focused with the Alpha-2 beam. By varying the relative power and, ultimately, focal geometry of the beams, we will rigorously assess the probability of stimulated photon-photon scattering, and explore the scattering, frequency shifting, and birefringent properties of the nonlinear QED vacuum.

HFP/QED3: Testing Strong-Field QED with the Avalanche Precursor

Abstract: The NFS OPAL facility will deliver extreme optical fields that will allow probing, for the first time, a fundamentally new regime of the electromagnetic radiation interaction with matter when the dynamics of electrons is dominated by quantum radiation reaction and light can be transformed into high-brilliance gamma radiation and even electron-positron pairs. Electrons injected into the mutual focus of two multi-PW counterpropagating laser pulses can be repeatedly accelerated by the extreme electric field to GeV-scale energies at a sub-cycle time, with a rapidly increasing probability rate to emit high-energy photons causing strong recoil. With 3D PIC-QED simulations, we show that in two laser pulses with a total power >40 PW, the energy transferred to high-energy photons exceeds that of electrons by an order of magnitude. At increasing power, a fraction of photons can also create secondary electron-positron pairs. This renders the precursor of avalanche-type (or selfsustained) QED cascades characterized by an exponential particle number growth. To achieve this, we propose to focus strongly two NSF OPAL Alpha-beams with the peak power in a (transparent for the laser) gas jet of heavy-atomic gas (e.g., Argon). The initial electrons will result from the ionization process. The study of outgoing photon radiation and electron spectral features will allow identifying the radiation-domination regime, whilst registering positrons will give strong evidence of a QED avalanche onset.

LAPP1: Ultrafast Laboratory Astrophysics and Planetary Physics

Abstract: The Laboratory Astrophysics and Planetary Physics (LAPP) Flagship capability aims to examine materials under intense pressure, 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. To understand the origin, nature, and evolution of these planets and astrophysical objects, it is necessary to understand the properties and evolution of high energy density matter. The LAPP Community seeks to combine three cutting-edge capabilities offered by NSF OPAL: dynamic compression, impulsive heating, and ultrafast probing. We present three stages of experiments leading to the flagship experiment: (1) the NSF-OPAL Alpha short-pulse beams will be activated at 1ω and 2ω to create laser-produced relativistic pair plasmas in a new intensity regime; (2) dense plasma spectroscopy experiments will be performed where the NFS-OPAL Alpha beams will be used to isochorically heat shock- and ramp-compressed targets to explore a wide range of temperatures and densities using high-resolution x-ray emission and absorption spectroscopy; (3) the OMEGA EP long-pulse UV beams will be activated to ramp-compress planetary materials (ex. SiO2, H2O, Fe) to conditions inside the cores of planets. This staged approach will lead to the flagship capability to shock and ramp-compress these planetary materials to terapascal pressures and use the femtosecond PW beams to create ultrafast probes for time-resolved x-ray and electron diffraction, radiography/phase contrast imaging, and x-ray emission and absorption spectroscopy to identify structural and electronic phase transitions and unravel their nonequilibrium dynamics. These experiments will answer key questions spanning the existence of exotic low temperature quantum phases to the high-temperature plasma opacity of stellar components at HED conditions.

LDNP1: Tritium-Induced Nucleosynthesis

Abstract: A controllable, high-yield triton beam is an invaluable tool for nuclear physics in studying the properties of light nuclei. One of the unresolved challenges in Nuclear Astrophysics is how nucleosynthesis proceeds beyond the A=5 and A=8 gaps for nucleosynthesis in core collapse supernovae, big bang nucleosynthesis, and even in neutron star mergers. The mass A=5 gap prohibits the production of substantial amounts of lithium and beryllium whereas the mass A=8 gap prohibits the production of heavier elements such as boron, carbon, and beyond. The answer lies in tritium reactions. Li reactions can perhaps explain why the ^{7}Li abundance is three times lower than predicted. The reactions of ^{7}Li(t,γ)^{10}Be and ^{7}Li(t,n)^{9}Be may hold the key. Tritium induced reactions may further explain the origin of neutrons and ^{12}C for nucleosynthesis to proceed beyond the lighter elements via the ^{9}Be(α,n)^{12}C reaction.

Di-neutron transfers onto ^{6}Li or ^{9}Be create neutron-rich nuclei that theorists only recently were able to model in ab-initio calculations. In addition, these reactions provide the opportunity to study di-neutron correlations during the transfer. Such light-ion reaction cross sections are also essential for nucleosynthesis models. A triton beam platform has been established on the OMEGA/OMEGA-EP facility that successfully measured neutrons produced by laser-accelerated tritons. Advances in activation detector development will make a series of lithium and beryllium reactions with tritium measurable to much higher precision with higher intensity beams. NSF OPAL will be uniquely positioned to continue these measurements for two reasons. First, the high shot rate will significantly improve statistics, especially with activation detectors. Second, a dedicated tritium target chamber will eliminate the current requirement for joint shots using the OMEGA-EP laser to produce the triton beams in the OMEGA target chamber that includes tritium handling systems.

LDNP2: Neutron-Neutron Scattering with Two High Shot-Rate Neutral Beams

Abstract: The neutron-neutron scattering (a_{nn}) length is a direct check on charge symmetry and charge independence of the nuclear force. Presently, this quantity has only been inferred from indirect measurements from breakup reactions with neutral and charged particles on deuterons; no direct measurement of this quantity has been observed. Knowledge of neutron-neutron scattering length would be of considerable value for nuclear and particle physics community. A proposed experimental platform is under development at the University of Rochester Laboratory for Laser Energetics (LLE) that will utilize neutrons generated from advanced ion acceleration processes to impose neutron-neutron scattering interactions. The proposed laser facility (NSF-OPAL) is positioned to fulfill these measurements for two specific reasons; 1) the twin 25 PW beams are essential to generate the high luminosity due to the large number of neutrons emitted in a very short pulse and small dimensions in the interaction region to induce and measure the scattering length from neutron-neutron elastic scattering and 2) the high shot rate, short duration of pulse eliminates many sources of background that plagued previous attempts, and is a requirement to generate statistical significance for a direct measurement of this elastic cross section.

2. Peer Review Panel (PRP) and Feasibility Review Results

2.1 Peer Review Panel (PRP)

Table 2.1 summarizes the PRP scoring and ordinal ranking. Higher values indicate better ratings for the four scoring categories (Scientific Merit, Flagship Experiment Team, Path to CDR and, Path to Flagship Experiment).

Three proposals stood out clearly with the top average scores that all exceeded the overall scoring average of 13.8 for all proposals, and their ordinal rankings matched their scoring ranks. These three proposals, in scoring and rank order, include LAPP1, HFP/QED2, and PAALS1. Table 2.1 highlights them in green.

The average scores for the other five proposals all fell below the overall scoring average, and their ordinal rankings did not consistently align with their scoring ranks. These proposals, in no particular scoring or rank order follow and include PAALS2, HFP/QED1, HFP/QED3, LDNP1, and LDNP2.

The following includes summary comments from the PRP Zoom meeting discussion, plus notable individual reviewer comments with light editing applied to avoid redundant points and to fix typographic and grammatical errors. Appendix C contains all Peer Review Panel (PRP) reviewer comments.

1. LAPP1: Ultrafast laboratory astrophysics and planetary physics

- Can work at various levels of success, which is good.
- Coupling (NSF OPAL) to OMEGA EP enables addressing EOS measurement relevant to planetary science, where a large community potentially exists. In addition, combining so many nanosecond and femtosecond lasers brings together many experimental possibilities, which increases significantly the discovery potential.
- The work will enable a broad range of astrophysically relevant experiments from pair plasmas through probing material structures to diamond precipitation.
- The scientific motivation for the LAPP1 effort is excellent.
- Strong team with international participation and age/gender diversity. [Combines several reviewer comments]
- Particular strengths are in the way the team plans to do cutting-edge science using subsystems before the full capabilities of OPAL are available for the FSE, and the broad potential for using the platform for similar experiments.
- The proposed setup is a must for NSF OPAL and the proposal makes a case for high discovery potential.

Table 2.1 – PRP scoring and ordinal ranking

Flagship ID (score range →)	Scientific Merit/Impact (1-5)	FSE Team (1-5)	Path to CDR (1-3)	Path to FSE (1-3)	Reviewer Subtotals	Reviewer Ordinal Ranking	Flagship Score Avg.	Flagship Score Stdev.	SCORING RANK	Ordinal Avg.	Ordinal RANK
Reviewer ID	**Overall scoring average and stdev. =**						**13.8**	**0.9**			
PAALS1	**Flying-Focus-Driven Laser-Plasma Accelerator**						**Range**	**2.3**			
F	3	5	3	3	14	2	**14.0**	**1.2**	**3**	**1.8**	**3**
G	4	4	---	---	---	2					
J	5	4	3	2	14	1					
L	5	5	3	3	16	1					
P	3	5	3	2	13	3					
K	4	4	3	2	13	2					
PAALS2	**Multi-messenger probing of ultra-intense/relativistic light-matter interactions**										
A	2	5	2	2	11	4	13.2	1.7	4	3.7	8
B	3	5	3	2	13	4					
C	3	5	3	3	14	2					
D	---	---	---	---	---	4					
G	2	3	---	---	---	4					
H	4	5	3	3	15	3					
I	4	5	3	3	15	None					
J	3	5	1	2	11	5					
HFP/QED1	**Extreme Fields: Testing QED in uncharted strong-field regimes**										
C	4	5	2	2	13	4	13.0	1.4	6	2.3	4
D	---	---	---	---	---	1					
G	3	4	---	---	---	3					
J	4	4	3	3	14	2					
K	5	5	2	2	14	1					
L	3	4	2	2	11	3					
HFP/QED2	**Stimulated photon-photon scattering**										
A	5	5	2.5	2.5	15	1	**14.8**	**1.2**	**2**	**1.5**	**2**
C	5	5	3	3	16	1					
E	5	5	2	3	15	1					
H	5	5	3	3	16	1					
P	4	5	2.5	2.5	14	2					
J	5	4	2	2	13	3					
HFP/QED3	**Testing strong-field QED with the avalanche precursor**										
C	3	5	3	2	13	3	13.2	2.2	4	2.7	5
E	4.5	4.5	2	3	14	3					
J	3	4	1	3	11	4					
L	4	4	2	3	13	2					
K	4	4	2	1	11	3					
P	5	4	3	3	17	1					
LAPP1	**Ultrafast laboratory astrophysics and planetary physics**										
A	5	5	1.5	2.5	14	2	**15.3**	**1.0**	**1**	**1.4**	**1**
B	5	5	3	3	16	1					
D	---	---	---	---	---	2					
F	5	5	3	2	15	1					
G	5	5	---	---	---	1					
I	5	5	3	3	16	None					
LDNP1	**Tritium-Induced Nucleosynthesis**										
B	4	5	2	2	13	3	12.8	2.0	8	3.7	7
E	4	5	3	1	13	4					
F	5	3	3	2	13	3					
H	4	2	1	2	9	4					
K	3	4	2	1	14	4					
L	4	5	3	3	15	4					
LDNP2	**Neutron-Neutron Scattering**										
A	4	5	2.5	2.5	14	3	13.0	2.0	6	2.9	6
B	5	5	3	2	15	2					
D	---	---	---	---	---	3					
E	5	5	3	2	15	2					
F	5	3	1	1	10	4					
P	2	3	2	3	12	4					
H	5	3	2	2	12	2					

2. HFP/QED2: Stimulated Photon-Photon Scattering

- Well-thought-out proposal.
- QED is well-known physics, but this experiment clearly drives NSF OPAL technical capabilities.
- The proposal clearly states that it wants to move science to the next level by exploring fourth-order QED processes in photon-photon scattering. High-impact results will be of two kinds: proof of principle, as soon as signal will be detected, and precision measurement by checking QED theory against results in the perturbative regime (correction terms).
- Until now, all proposed experiments I know of are limited to two-beam experiments. In addition, the experiment is photon-hungry so NFS OPAL is in a good position to make a strong impact. The proposal makes an outstanding case for exploitation of NFS OPAL capabilities compared to competition.
- Proposal neglects to describe important backgrounds that may hamper experiment, particularly scattering from itinerant electrons which are always likely to be present at densities of 1e9 or so, as the cross section for Thomson scattering from electrons is extremely high.
- This is science I say is the reason to aim for intensities of 10^{29} W/cm^2. One of the questions I get asked is what happens in the focused beam before reaching the highest intensity at the focus. The proposed experiment would help answer this question. It is a path to photon-photon scattering without the need for reaching the Schwinger limit.
- Excellent team. Good student involvement.
- They have put together an international team that has studied the various aspects of this project.
- Second harmonic generation is very challenging. Test planned for MTW-OPAL. How much related research is needed to develop this capability? What additional costs for NSF OPAL?
- Beams overlapping in time and space will push the envelope, developing capability will push the field.
- Weakness is expecting 60% (SHG) conversion of a 20fs pulse. I don't know of any frequency doubling of ultrashort pulses with this level of conversion.
- They propose to investigate the process as a function of power but as they are expecting few photons even at the highest power, this may be a big ask to have much of a power variation that has a signal above the background.
- Very good proposal that makes a unique scientific case for use of NFS OPAL. However, it shifts a lot of the difficulty and work on the laser (frequency doubling plus stability and its detection). A clear delimitation of the responsibility between experimental team and facility should happen at an early stage to manage expectations.
- One of the flagship experiments for the EuXFEL is in the same scientific space, so it would be helpful to understand whether or not their success is going to undercut the novelty of this experiment.

3. PAALS1: Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams

- It's a thought-through proposal for developing a TeV-electron beam tool, which overall seems very reasonable. The discussion of the path toward CDR and FSE is excellent with a well-defined timeline (by far the best one of the four proposals reviewed). The risk associated with this proposed effort is quite high though.
- Test of novel flying focus idea will be uniquely done at NSF OPAL.
- At the forefront/convergence of plasma-based accelerators and optics (at high intensities); it is uniquely grounded on leading expertise of the team; The team is mostly local but has the links to expand worldwide; world-leading team, including the next generation of leaders; Steps for CDR are clear and rely on expanding numerical tools (low risk); Main challenge (plasma source) has been identified. Potential for being a truly unique and flagship science result.
- Good candidate for developing elsewhere before NSF OPAL is available to demonstrate full potential of the flying focus approach.
- Whether TeV is likely is hard to know from the proposal, but they do have a path forward to make it happen. They will need the power of the NSF-OPAL laser to achieve it. The broad bandwidth of OPAL gives more control over the process to fine tune the speed of the flying focus.
- This is the team that invented the flying focus so is the only team that should be carrying it out. [One PRP reviewer noted during the PRP Zoom meeting, “All three of the top-scoring flagships have (too?) strong involvement by folks at LLE. Need to consider involving more participants from the broader community.”]
- Although the team is mostly from LLE, they do collaborate with the other large laser facilities and so can test the ideas on the multi-PW scale lasers already up and working.
- ILC comparison is inappropriate, because it requires not merely comparing the energy gradient, but also comparing the total peak and the average current.

4. PAALS2: Multi-messenger probing of ultra-intense/relativistic light-matter interactions

- The proposed experiment is rather a kind of investigation tool than a big flagship one. However, such an experimental tool would be one of the most important ones in the future OPAL facility. The risks of implementation are moderate.
- The proposed setup contains a lot of “cool” ideas and puts together new technologies like NCD targets, LC plasma mirrors and detectors, which are all at the forefront of development. This proposal comes from experts on these fields. While this setup can be classified as having a very high discovery potential and curiosity-driven, the proposal does not have a science case to it. Because the proposal does not formulate its goal in terms of a precise scientific question, its impact will be low and likely to interest only a modest subset of the community. From a technological standpoint, the experiment will bring a lot of technological innovation of high impact to the community.
- The proposal does not make a case as of why NFS OPAL can uniquely answer a scientific question (partly because of the lack thereof). I do not understand the need for a multi-10-petwatt laser. I see a risk that such ideas could be implemented at other competing multi-

beam facilities with lesser performance like ELI or Apollon, which are already in or near operation.

- Very well written proposal with a competent, young team that includes international participation and age/gender diversity. [Combines several reviewer comments]
- Part of this proposal is the use of AI and ML for the beam alignment and stabilization. This work will need to be done for the use of NSF-OPAL. This work is already being carried out at BELLA, so OPAL can benefit from this work.
- NCD (near-critical density) target development will be required. The proposal is for gas jets. These will need to be well characterized if the resulting, photons and particles are to be used as multiple messengers.
- It is not clear about the timing between the pump pulse and the multiple messengers. It is not clear how the messengers go through the plasma mirror. If the two beams spatially overlap then the plasma mirror cannot simultaneously allow the reflection of one beam and the transmission of the other and this would limit the messaging on the short time scale.
- Find the proposal to be unclear. The proposal focuses on multi-messenger probing of rapidly evolving ultra-intense/relativistic matter, while not clearly articulating why such extreme transient plasmas are interesting or what the platform could be used to study. There is a clear path of what has to be done to enable to the FSE, which does include key capability developments such as plasma mirrors for laser coupling and near critical density, repeatable gaseous targets. The team is strong with significant early career involvement.
- The scientific case is somewhat weak, but this experiment can potentially provide useful diagnostics for other studies. This proposal is ranked high because it can lead to the development of novel particle sources.

5. HFP/QED1: Extreme Fields: Testing QED in uncharted strong-field regimes

- The concept is exciting, but it is not clear that this specific experiment will deliver conclusive measurements. Is the energy spread from LWFA going to be an issue? This looks like an experiment that should be done at a facility collocated with a linear accelerator.
- Best of the bunch – new physics, proposal well-fleshed out with details of experimental methods/diagnostics. Definitely a goal of the strong-field QED community; maybe will (appropriately) be done first at ELI NP.
- This is an excellent proposal for a flagship experiment. The proposed work would be high impact and would utilize the unique properties of the proposed NSF OPAL facility.
- Proposal addresses relevant question in SF-QED (but parameters to be achieved still far from main goal – probing the properties of QED close to the Ritus-Narozhny Conjecture).
- Other facilities are also pursuing similar goals, and not clear what would be unique on the parameter range or configuration to be explored. Similar experiments will also be pursued in many other facilities (lower risk but lower degree of uniqueness).
- This is the one proposal that I read that could really benefit from the success of the flying focus accelerator. The premise of the proposal is that with the laser acceleration that has been achieved to date (and so electron energies of 10GeV), they can see the onset of SFQED with peak intensities above what has been achieved but would be possible with the NSF-

OPAL. If they had access to even higher electron energies, then with the expected focused intensity of the NSF-OPAL, they should be well into the SFQED regime and make this proposal even more exciting to perform

- The international team assembled for this proposal has significant expertise across all aspects of the proposed research plan.
- The team is suggesting investigating new avenues for laser acceleration including a plasma eye piece.
- This collaboration has already done a number of preliminary experiments on lower power facilities and the path to a future NSF OPAL experiment utilizes their experience in this area.
- Significant overlap with other flagship proposals.

6. HFP/QED3: Testing strong-field QED with the avalanche precursor
   - The fact that other flagship laser facilities plan to do something similar had to be directly addressed in the proposal. Is it possible for someone else to observe the precursor before the proposed flagship experiment? The scientific impact is also less clear than that for the other proposals.
   - The one question I have about this work is it will require the full power of NSF-OPAL to be seen and requires that a standing wave be set up between the counterpropagating fields. The theory done for this work undoubtedly used Fourier Transform pulses and so both propagating fields have identical wavelength across both pulses. The transform limit is almost impossible to achieve in reality with ultrashort pulses. What is the limit on the two beams having identical central frequencies? There was no discussion about how much this might reduce the observed particles. There was some discussion about whether not having exact 180° between the beams could cause a problem.
   - This is a very good proposal that relies on the unique capabilities of the OPAL project.
   - This proposal will strongly focus two NSF OPAL beams with a gas jet of argon and would be a very high impact result, if successful.
   - Excellent team but needs to include more student participation (recognizes the need). Need more team members and will have to apply for funding for these students and post-docs.
   - Little more on diagnostics would be useful but expect there are “lessons to be learned “on other facilities (ZEUS, ELI, etc.).
   - They will apply to perform to develop the experiment. This is the kind of experiment that will be hard to prep for as a null result is expected, and many stringent requirements are made. There were no specific initial experiments discussed.
   - This experiment will push the limits of NSF-OPAL the most of the experiments that I reviewed. This experiment has overlap with astrophysics which is the area of physics most conducive to public engagement. This experiment could help excite the public to the work being done in this field with extreme laser pulses.
   - This is an excellent proposal and would be a good flagship experiment. The technical challenges for enabling this experiment at NSF OPAL are significant and so I would classify this experiment are very risky.

- The QED cascade is new physics. This team is strongest in theory and simulation. Even some of the experimentalists are first-rate theorists; but the converse is not true, and so experimental expertise, particularly in detectors, needs to be strengthened. The plan to involve preliminary and ancillary work on other facilities like ZEUS is a strong positive.

7. LDNP1: Tritium-induced nucleosynthesis
   - The questions to be addressed are important and the results could have high scientific impact.
   - The scientific motivation for this proposed effort is exciting and it is more realistic than the proposed n-n scattering proposal. It also builds on work that has already been accomplished at MTW and EP.
   - Triton beams would be unique and cannot be done elsewhere, interesting physics.
   - Natural follow up to existing program at OMEGA and OMEGA-EP. Low risk and opportunity to access unique regime of relevance for tritium-induced nucleosynthesis.
   - Laser-based generation of a tritium beam would be a ground-breaking achievement; however, the tritium beam itself is a further tool for nuclear sciences. It could be regarded rather as a necessary tool (service) of the OPAL facility, than a flagship experiment itself.
   - Experiment seems to be on track to be performed, independently of being considered flagship (or not); high degree of maturity; ranked it lower than the others because it seems this experiment will occur independently of any specific design effort at the facility (and the science case looks incremental).
   - Advantage of NSF-OPAL is shot rate and statistics to help deconvolve cross-sections given non-monoenergetic TNSA beams.
   - The proposal is a good one and describes a series of experiments that would be high impact. The main criticism of this work is that it does not rely exclusively on the unique capabilities of NSF OPAL. It should be possible to do these experiments using conventional technologies – and indeed there may be advantages to using other technologies.
   - Justification for NSF OPAL based on rep rate, rather than physics, is a weakness.
   - While the scientific merit of having tunable triton beams is made clear (address fundamental nucleosynthesis and nuclear structure questions), it is less obvious that the unique laser capabilities of OPAL are really required for this work. It would have been nice to see some more discussion about how the unique OPAL intensity might help optimize triton acceleration. Also, the TPIE detector proposed for use in the OPAL experiments uses passive detectors (IP, CR-39) and is not suited for rep rate. Tritium target production is also currently tedious and not rep-rate compatible.
   - The proposing team is excellent and comes from several institutions with significant experience in this research.
   - The team consists of an excellent set of researchers, but once again the list is lacking some important people for this type of effort.
   - The discussion about the path forward toward CDR and execution of the FSE could also have been better.
   - The path to flagship experiments is good and the plan to improve target designs and test detectors is reasonable.

8. LDNP2: Neutron-Neutron Scattering

- The proposal proposes to address a controversial issue in the description of neutron-neutron scattering, where contradictory indirect measurements and theory fail to agree. If successful, this experiment will impact nuclear physics and illustrate the strength of nuclear photonics. In addition, the development of pulsed neutrons sources could find other applications.
- The proposal bases its expectations on a tertiary neutron beam generated from deuteron-deuteron fusion (from laser-accelerated deuterons) with a particle number of 10^{14} neutrons at an energy of 1 MeV. This represents an energy of 16 J, or a ~3% conversion efficiency for 500 J (laser to neutrons). This is overly optimistic. [Three reasons given]
- This proposal has a clear, strong scientific goal, and lays out a reasonable path to achieving it in terms of preparatory experiments at other facilities and target and detector development efforts required. Achieving the scientific goal … would be a monumental achievement.
- Developing the neutron beam platform on OPAL will likely benefit several related and high-profile experiments in addition to the specific flagship experiment. The only reason this proposal is ranked slightly lower than LAPP1 is because LAPP1 uniquely enables cutting-edge science along the path to FSE.
- Agree that lower energy neutrons would be more suitable for scattering expt, but how to achieve well-collimated low energy beams?
- Bit of a long shot but would be interesting result if achieved. Downgraded only because of difficulty in assessing the difficulty.
- The motivation for the neutron-neutron (n-n) scattering proposal is exciting from a scientific point of view, but it’s an extremely challenging project. This is evidenced by the fact that the n-n scattering length has never been measured before even though researchers have tried for more than 4 decades. In addition, with predicted yields of order 1e6 under ideal conditions (which are highly uncertain), not many, if any, signal events will be detected by a highly-collimated nTOF positioned several meters away. A discussion about signal and background levels in the nTOF data should have been made and would ne required to get to adequate yield levels. The team consists of an excellent set of researchers, but the list is lacking some important people for this type of effort. The discussion of the path toward CDR and FSE is also not clear and a timeline doesn’t exist.
- This is colliding two neutron beams with each other, to measure some simple low energy strong-interaction physics (charge symmetry and charge independence.) Need to measure the neutron-neutron scattering length. No general discussion of the significance of violations of this symmetry. Experiment is to extend well-studied methods of ion beam acceleration from laser-driven surfaces to neutral beams via (d,n) or similar reactions. Proposal estimates number of scatters but doesn't go on to estimate the scattering length precision, nor what precision is required for a good test of charge independence.
- On the basis of current predictions (MatRadExt 7 (2022) 024401), the neutron yield per pulse is expected to be at least one order of magnitude lower than the required 10^14 neutron / shot. On the basis of the demonstrated neutron yield (Nat. Com.13, (2022) 170), one can foresee only 10^12 neutron / shot.
- Preliminary expts to increase neutron yield are important for risk reduction for NSF-OPAL
- Good proposal and broad participation – would have liked to see more student mentioned.

2.2 Feasibility Review

Table 2.2 – Feasibility reviewer scoring

Flagship ID	Path to CDR * see basis (1-4)	Impact/Effort * see basis (1-4)	Feasibility Reviewer Subtotals
PAALS1	**Flying-Focus-Driven Laser-Plasma Accelerator**		
S	2	3	5
T			0
U			0
V	1	3	4
W	1	3	4
X	2	3	5
Y	1	2.5	3.5
Z	1	2	3
PAALS2	**Multi-messenger probing of ultra-intense/ relativistic light-matter interactions**		
S	2	3	5
T			0
U			0
V	3	3	6
W	3	3	6
X	1	2	3
Y	2.5	3	5.5
Z	3	2	5
HFP/QED1	**Extreme Fields: Testing QED in uncharted strong-field regimes**		
S	2	3	5
T			0
U			0
V	2	4	6
W	3	3	6
X	3	3	6
Y	1.5	3	4.5
Z	2	3	5
HFP/QED2	**Stimulated photon-photon scattering**		
S	2	3	5
T			0
U			0
V	1	3	4
W	1	3	4
X	2	3	5
Y	2	3	5
Z	1	3	4

Flagship ID	Path to CDR * see basis (1-4)	Impact/Effort * see basis (1-4)	Feasibility Reviewer Subtotals
HFP/QED3	**Testing strong-field QED with the avalanche precursor**		
S	3	4	7
T			0
U			0
V	2	3	5
W	3	1	4
X	2	2	4
Y	3	3	6
Z	2	4	6
LAPP1	**Ultrafast laboratory astrophysics and planetary physics**		
S	2	3	5
T			0
U			0
V	4	3	7
W	4	3	7
X	2	4	6
Y	3.5	3	6.5
Z	3	3	6
LDNP1	**Tritium-Induced Nucleosynthesis**		
S	3	3	6
T			0
U			0
V	3	3	6
W	3	2	5
X	2	1	3
Y	2.5	3	5.5
Z	3	4	7
LDNP2	**Neutron-Neutron Scattering**		
S	3	4	7
T			0
U			0
V	3	1	4
W	3	2	5
X	3	1	4
Y	2	2	4
Z	3	4	7

Table 2.3 – Average proposal feasibility scores

		Average Path to CDR	**Average Impact**	**Average Total**
PAALS1	TeV-class Electron Acceleration	1.33	2.75	3.06
PAALS2	HED Ion Acceleration	2.42	2.67	3.81
HFP/QED1	Fully Non-perturbative Regime of Strong-field QED	2.25	3.17	4.06
HFP/QED2	Stimulated photon-photon scattering	1.50	3.00	3.38
HFP/QED3	QED cascade precursor	2.50	2.83	4.00
LAPP1	Ultrafast laboratory astrophysics and planetary physics	3.08	3.17	4.69
LDNP1	Tritium-Induced Nucleosynthesis	2.75	2.67	4.06
LDNP2	Neutron-Neutron Scattering	2.83	2.33	3.88

Table 2.2 summarizes the feasibility review scoring and Table 2.3 summarizes the average feasibility scores for the flagship experiment proposals. PAALS1 and HFP/QED2 consistently scored best, while LAPP1 scored least well due to challenges realizing advanced laser-driven probe beams identified in the proposal. According to Table 1.2.1, lower values indicate less uncertainty or less design impact/effort (good) versus higher values reflect more uncertainty or more design impact/effort (bad).

The following summarizes comments from the feasibility review in the same order as Sec. 2.1 with light editing applied to avoid redundant points and to fix typographic and grammatical errors. Appendix D contains all feasibility reviewer comments.

1. LAPP1: Ultrafast laboratory astrophysics and planetary physics
    - The path to CDR for the primary flagship experiment was not well defined.
    - A secondary flagship included (development of a Compton source) for which no plan was discussed or presented. Serious concerns about the feasibility of the development of a relevant Compton source have been expressed during the Project Requirements Workshop.
    - An upgrade of the OMEGA EP facility to support 30ns beam is critical to the success of this proposal; the performance of the OMEGA-EP system is outside of the sphere of the OPAL effort. Additionally, it has been determined by the EP system science team that the pulse length increase per beam will be capped at 20ns.
    - The proposal states "> 10^{24} W/cm^2, once realized, would open up new parameter regimes." This is beyond what is expected for NSF OPAL, even at 'objective performance' levels.
    - Assumes frequency doubling of both Alpha beams.
    - Transporting an electron beam (along with many other types of secondary sources?) into TA1 will add significant complication and expense to the project.
    - Providing a clear line of sight (LOS) between EA-1 to EA-2 imposes significant constraints on the overall facility design and is a costly requirement (have to fit long f/# beam, electron source, conditioning optics, dump and shielding in line with EA-1).
    - Targets are likely massive. There is currently no well-understood debris management plan.
    - Target chamber schematic shows 4 UV beams on both sides of tank. Plan is for four on one side and optional rerouting of only two to the opposite side.
    - Femtosecond co-timing to OMEGA EP beams (i.e., shock breakout) is not currently feasible.

2. HFP/QED2: Stimulated Photon-Photon Scattering
    - The path to CDR was clearly communicated and required resources were identified.
    - The success of this experiment relies on the development of a high-efficiency doubling technique for high-power, broadband, very large beams. This technology does not exist at present and will require significant development
    - The need to split a beam into two and focus each, from a different optic/direction, to a fraction of a spot size and timed to a fraction of a pulse length would be extremely challenging.
    - The proposal mentions the need for low-energy timing shots, but does not include a proposal on how to execute this activity.
    - Varying the relative beam power of Alpha 1 and 2 should be straightforward. Varying the power of the split Alpha 1 beams would be challenging in the one-color case. In the three-color case, not clear if crystal detuning could be used as crystal are so thin.

- Background signal is a big concern, as they state, motivating three-color approach and an ultra-low vacuum level (10^{-8} torr).
- There are ideas about how to achieve local UHV, although these have not been investigated in depth. Requiring the entire chamber to maintain UHV would be costly.
- Beam delivery infrastructure looks feasible. Getting it to fit may require rethinking the current EA1 layout.
- Are beam dumps required after beams pass through interaction area? Any diagnosis of these beams?

3. PAALS1: Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams
    - Overall, the path to CDR was clearly laid out and needed resources identified. The review panel had concerns about the cost of this effort as well as the significant technology development required.
    - Team is well rounded, has expertise and experience in theory and experimental aspects of the project.
    - Path to CDR milestone / deliverables clearly communicated.
    - The footprint of this system will be very large requiring space for the f/7 optical focus, gas jet system, electron beam formatting, and large spectrometer. Additionally, the optical and diagnostic components will all be large, unique, expensive, and will require significant development.
    - Rating of 3 for 'Impact' is due to the very large footprint required to house electron transport line and TeV-Class spectrometer. Considerations must be taken to ensure space is adequate for FSE but also fits on LLE property.
    - The proposal includes a plan for echelon development at the MTW OPAL scale, but it does not include a plan for the scaling up of this technology to the OPAL scale and fluences.
    - If round beams are required for MTW-OPAL experiments, energy out of GCC will be less than 7.5 J. Similarly, a round beam from NSF OPAL will not reach 500 J, but ~380 J (based on inscribed circle of same fluence).
    - Final beam dump/termination will likely be something more complex than a mass of concrete.
    - LLE does not have in-house expertise in large scale electron beam transport and diagnosis, but this is a well-understood field. External resources would have to be brought in if we pursue this FSE.
    - Requirements for plasma source and diagnostic details (spectrometer size, interferometer source, focal spot monitor) stated as "done", but unclear what these are. Could impact top-level design if design team assumptions are incorrect.
    - Resources: Has separate funding identified outside of NSF-OPAL project for R&D work

4. PAALS2: Multi-messenger probing of ultra-intense/relativistic light-matter interactions
    - The path to CDR was not well defined and lacked clear details.
    - The proposal requests continuously varying ellipticity between linear and circular for both beams. The current baseline is to have a binary option of linear or circular on a single beam. This would be a significant and costly change to the system design and layout.
    - The request for an optical probe picked off from the main beam is new and would be a significant change to the design.

- what is expected distance between the two focal planes, given the stated need for varying time-of-arrival for multi-messenger probing. Also, Fig. 1 appears to show some particle-beam conditioning before passing through the beam combiner and on to the second 'Snowplow' target.
- AI/ML to assist with co-pointing/timing of beams would build on BELLA experience.
- scaling LC plasma mirrors raises concerns about LC film and debris.
- needs variable polarization ellipticity using quarter-waveplate rotation, which is not consistent with the full-scale RPR approach (linear or circular, not arbitrary elliptical)
- very high temporal contrast of 10^{-15} stated but over what temporal range not given.
- details parameter sweeps (v. helpful) but no mention of varying energy on target. Are all experiments at maximum energy available for configuration (e.g., with DPM, etc.)?
- significant experimental complexity, but justifies much of the system layouts and configurations that others will learn to use.
- some description of experiments that they can perform to better understand, but no real outline of the work needed to be done and who will be doing it.
- 1ns of delay is quite a lot.
- LC plasma mirror and target (e.g. liquid jet) development seem to be the biggest development challenge.
- diagnostics seem mostly conventional other than rep rate. Path to develop and scale up at other facilities identified.
- curved LC PM development and renewable plasma targets would be generally very useful.

5. HFP/QED1: Extreme Fields: Testing QED in uncharted strong-field regimes

- Proposal has a reasonably well-defined, well-structured plan
- The path to CDR not well defined. There are a lot of work packages identified, but not a clear plan for execution and who would be responsible.
- The proposed layout with two alphas in EA2, one to drive a LWFA, represents a significant deviation from the planned facility layouts. This would require a significant change to the EA2 concept. [Probably best accomplished in EA1, if possible]
- It would be a significant expense (and likely require that this experiment be the ONLY TA2 experiment) to implement the proposed geometry.
- not clear that the stated e-beam energy is realistic. During the Project Requirements Workshop and proposal process it has been indicated that going over 10 GeV would require advanced techniques such as those in the TeV-class proposal"
- "must consider using second 'alpha beam' to drive the wakefield accelerator" not consistent with EA1 as requires e-beam conditioning or EA2 as requires both Alpha beams
- Need a way to co-time/co-point as part of WP3, ideally at reduced power, but not clear if concepts have been developed that can be used to co-time/co-point photons and electrons (e.g., no references given for past attempts or concepts).
- large focal spot (100 um) requires a novel plasma eyepiece approach at full energy.
- LLE has little to no experience with electron transport at scale.
- timing of e-beam and colliding laser is <10fs.
- What is co-pointing requirement with a ~25um electron beam spot size (if only 10um as stated, is co-pointing system required)? Co-timing to 10fs IS required.
- Electron beamline details are still unresolved (5m up to 10's of meters)

- High intensity focal spot information is required

6. HFP/QED3: Testing strong-field QED with the avalanche precursor

- The proposed path to CDR is not consistent with the planned project schedule; one reviewer suggests that the activities and timelines are more in line with DOE Critical Decision milestones rather than NSF CDR.
- There are significant concerns about the feasibility of fielding this experiment on NSF OPAL. There are concerns that the precursor signal is too weak for realistic OPAL parameters. The proposal requests around 30PW with a 1um spot size, which exceeds the expected performance of the facility. The experiment may likely require true counter-propagating signals, and while this MAY be feasible with laser plasma mirrors, the use of the plasma mirrors would further derate the on-target power.
- Concerned that the signal is too weak for realistic laser parameters that include actual focusability (Strehl values), even to see a 'precursor'.
- Caption for Fig. 1 states 'radiation regime is reached around 30 PW and 1 um'. Does the 30 PW correspond to total or single-beam power? Similarly, text below states total laser power > 25 PW is the threshold level for f/1 focusing at diffraction limit, which is beyond current focusing concepts & expectations.
- CDR timeframe significantly exceeds planned time to OPAL CDR
- Very strict polarization requirements.
- Gas Jet system currently exists, but would benefit from an upgrade.
- Co-timing and co-pointing will be challenging, but are in line with planned performance.

7. LDNP1: Tritium-induced nucleosynthesis

- very few details on the path to CDR nor clearly identified resources for specific activities.
- Technical requirements largely missing
- The addition of tritium and cryo systems will add a significant amount of additional design and implementation costs.
- Highly collimated line of sight for the neutron beam requires a space claim for shielding on what is likely a highly desired line of sight for other future campaigns.
- Details on the facility needs were also very thin
- difficult to gauge the team’s preparedness and plans (partially because this is a science area that I am least familiar with)
- The path to CDR does not include modeling or other computational efforts
- Strictly speaking no facility requirements were provided and the impact should be a 4, but based on extensive conversations with the team the needs are understood.
- Not mentioned is the issue of tritium containment in beam transport. This problem must be understood before this FSE can be supported.
- IF Omega Tritium Facilities/Recovery cannot be used for NSF-OPAL, a new facility will have to be built.
- This FSE fits well into the existing facility concept - a Tritium Target Chamber is a 'module' that can be added on in the future, as long as there is a space claim made during building design.
- The flagship will require diagnostic capabilities that are currently exist, are prototyped, or are in development.
- The flagship does not list any beam requirements that appear taxing

- may require a unique geometry for detectors that may impact the facility design and ConOps.
- Cryo experiments is a significant impact to design as there are no other needs for cryo identified.
- Tritium would have impact on con-ops beyond the just the target chamber and could force users to be radiation workers, or have areas that are hands off except to rad worker technical staff.
- cryogenic targets mentioned on timeline but not mentioned elsewhere

8. LDNP2: Neutron-Neutron Scattering with Two High Shot-Rate Neutral Beams

- very few details on the path to CDR nor clearly identified resources for specific activities.
- highly collimated line of sight for the neutron beam requires a space claim for shielding on what is likely a highly desired line of sight for other future campaigns.
- concerned that no codes exist to model these effects and confirm that we could be in the right regime. Could be an expensive mistake if find out NSF OPAL cannot reach the necessary regime after incorporating a range of 'best guess' approaches specific to this Flagship.
- strictly speaking no facility requirements were provided and the impact should be a 4, but based on extensive conversations with the team the needs are understood.
- most experimental system and diagnostic needs are well-understood and already exist.
- rapid deployment of four individual target components is a solvable problem, but will require development.
- includes items required to progress design, but does not actually spell out a path to CDR.
- cryo foils mentioned in the timing diagram, but not elsewhere.
- Neutron beam dumps will be significant in size given the angle and fluxes proposed.
- Campaign geometry unclear, cartoon on page 3 shows TNSA generation near chamber wall which may be incompatible with conceptual system design requiring significant change in concept to support. Text states this will occur within a few cms of foils. If neutral beam generation occurs within conceptual beam pointing/focusing volume this would not be a concern.

3. Analysis of flagship experiments

3.0 Introduction

All eight flagship-experiment (FSE) proposals offered compelling, long-term science goals for a future NSF OPAL facility and a broad range of the scientific community. The top three PRP scoring proposals (LAPP1, HFP/QED2, and PAALS1) require laser, target, and experimental diagnostic capabilities that cover many, but not all, of the needs identified in other proposals, as reflected in Table 3.1. These capabilities include:

- Two 25-PW Alpha beams and one 1- or 2-PW Beta beam (only available with one Alpha beam)
- Frequency doubling the Alpha beams (not included in the original RI-1 proposal)
- OMEGA EP UV/ns beams transported to Experimental Area 1 (EA1)
- Femtosecond timing/synchronization and micron pointing stability

The top three PRP-scoring proposals require capabilities specific only to them, including:

- Custom optics: achromatic flying focus (AFF) optics for PAALS1, and a full-aperture 2ω beam splitter and focusing for HFP/QED2,
- Ultrahigh vacuum (UHV) for HFP/QED2,
- Single-photon detector (more accurately a photon counting detector) for HFP/QED2.
- Meter-scale plasma source and interferometry, and >10 GeV electron spectrometer for PAALS1
- Ultrafast x-ray probe beams based on inverse Compton scattering (ICS) and/or betatron radiation for LAPP1, and
- Time-integrated and time-resolved x-ray diagnostics for LAPP1 (many available already in the Omega Laser Facility).

The lower scoring FSE proposals (PAALS2, HFP/QED3, LDNP1, LDNP2) require capabilities not covered by the top three proposals, including:

- PAALS2: curved (focusing) LC mirrors, and near-critical density (NCD) targets,
- HFP/QED3: f/1.4 off-axis parabola
- LDNP1: tritium handling, planar cryogenic targets, plus Thomson parabola, neutron time of flight (nTOF), and phoswich detectors, and
- LDNP2: Thomson parabola and neutron time of flight (nTOF) detectors.

Sections 3.1 to 3.2 analyze the proposed flagship experiments and identifies them in two categories:

- flagship experiments that will define the scope of the NSF OPAL RI-1 project and a subsequent NSF construction project proposal, and NSF OPAL operational capabilities that would lead to future flagship experiments once all needed capabilities are realized. The RI-1 project team will design the NSF OPAL facility for the feasible elements identified by these proposals. The associated experimental teams will join the NSF OPAL construction project proposal team and have priority at leading experiments leading to future flagship experiments.
- future flagship experiments that could be pursued with future upgrades. These proposals offer information that will inform RI-1 design efforts with the goal of accommodating the associated capabilities as much as possible.

Table 3.1 – NSF OPAL facility capabilities required for proposed flagship experiments

		Laser Capabilities						Target Capabilities									
FSE Tag	**FSE Title**	**Beta Beam (2PW)**	**Alpha1 Beam (25PW)**	**Alpha2 Beam (25PW)**	**Custom Optics**	**Alpha1 to Alpha2 fs synch.**	**OMEGA EP UV/ns Beams**	**Plasma Source (column)**	**LC plasma mirror (curved)**	**LC plasma mirror (HP?)**	**Liquid jet targets**	**LWFA gas target(s) to produce e-beam**	**Gas jet**	**Ultra-High Vacuum (1e-8 Torr)**	**Foils / EOS pkgs / Foams / Pucks**	**Tritium Handling**	**Planar Cryogenic Foils**
PAALS1	**TeV-class Electron Acceleration**	**X**	**f/7**		**AFF**			**X**									
PAALS2	Multi-messenger probing of Ultraintense/ Relativistic Light-Matter Interactions		f/2	f/2	Plasma eyepiece	X			X	X	X						
HFP/QED1	Fully Non-perturbative Regime of Strong-field QED	X	f/long	f/2		X						X					
HFP/QED2	**Stimulated Photon-Photon Scattering**		**f/2**	**f/2**	**2ω split**	**X**								**X**			
HFP/QED3	QED Cascade Precursor		f/2	f/1.4		X							X		X		
LAPP1	**Ultrafast Laboratory Astrophysics and Planetary Physics**		**1ω or 2ω**				**X**					**X** **ICS &/or betatron**	**X**		**X**		
LDNP1	Tritium-Induced Nucleosynthesis	X	1ω												X	X	X
LDNP2	Neutron-Neutron Scattering		1ω	2ω		X									X		

Color code: red = 1w; blue = 2w; purple = 3w

Table 3.1 – NSF OPAL facility capabilities required for proposed flagship experiments (continued)

		Focal Spot Diagnostic	Plasma Interferometry	Electron Spectrometer	>100 GeV Electron Spect.	Optical probe(s)	EPPS* particle spectrometer	Gamma spectrometer	X-ray Imaging/Radiography	XRPHC / XRSC / XRFC	XAS / EXAFS / XANES	X-ray diffractometry	Single-photon detection (3w)	nTOF Detectors	Phoswich Detector	TPIE (Ion Spectrometer)	PIC Simulations (OSIRIS)	Realistic beam simulations?	Sensitivity/Optimization	Residual gas scattering?	QED & QED+ predictions	AI / ML capabilities
FSE Tag	**FSE Title**	**Diagnostic Capabilities**															**Theory/Simulation**					
PAALS1	**TeV-class Electron Acceleration**	**X**	**X**	**X**	**X**	**X**											**X**					**??**
PAALS2	Multi-messenger probing of Ultraintense/ Relativistic Light-Matter Interactions	X				X	X	X	X								X					X
HFP/QED1	Fully Non-perturbative Regime of Strong-field QED	X		X				X									X	X			X	X
HFP/QED2	**Stimulated Photon-Photon Scattering**	**X**											**X**					**X**	**X**	**X**		
HFP/QED3	QED Cascade Precursor	X					X	X	X	X							X	X				
LAPP1	**Ultrafast Laboratory Astrophysics and Planetary Physics**	**X**					**X**	**X**	**X**	**X**	**X**	**X**						**X**				
LDNP1	Tritium-Induced Nucleosynthesis	X												X	X	X						
LDNP2	Neutron-Neutron Scattering	X												X		X						

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3.1 Flagship Experiment and User-Facility Capabilities

The proposed HFP/QED2 flagship experiment met fully the criteria for a flagship experiment and it was deemed feasible. Three proposed flagship experiments (LAPP1, PAALS1, LDNP1) met some but not all of the flagship experiment criteria and/or their proposed scope was not deemed fully feasible given the current or projected state of the art or did not provide enough detail for the RI-1 project to design them. The capabilities noted below will support important "mature" user-facility experiments and/or they could lead to future flagship experiments. All four of these flagship experiment teams will join the NSF OPAL construction project proposal team and have priority at leading experiments that could lead to future flagship experiments.

HFP/QED2: Stimulated Photon-Photon Scattering

HFP/QED2 proposes a very challenging experiment that would directly demonstrate the nonlinearity of the vacuum, if successful. The co-timing/co-pointing requirements will drive NSF OPAL performance and require state-of-the-art systems.

The awarded RI-1 proposal did not include frequency doubling the NSF OPAL Alpha beams but this capability has been identified as an important one found at only a few facilities worldwide and none at the performance levels (energy and pulse width) possible at NSF OPAL. LAPP1 requires this capability. Splitting the full-aperture 2ω (or even 1ω) compressed-pulse beam poses a challenge that will be addressed during the RI-1 design project. R&D to develop the required photon-counting detector could be covered by separate funding while the RI-1 project covers its operational implementation in NSF OPAL. The required ultrahigh vacuum presents a challenge to mitigate background that the flagship team will need to address in coordination with the RI-1 project team.

LAPP1: Ultrafast laboratory astrophysics and planetary physics

The LAPP scientific community spans a range of high-energy density (HED) sciences that is large and active in areas of both discovery and programmatic science that hold excellent prospects for high-impact results and advance science critical to the nation. This is evident by the breadth and depth of collaborators in the flagship proposal. LAPP/HED science also finds significant support across multiple U.S. federal agencies, including NSF, NNSA, and the DOE Office of Science, as well as abroad.

The proposal includes numerous capabilities that already exist at the Omega Laser Facility or that can be developed/adapted for NSF OPAL with relatively modest effort. This includes offering dynamic compression with drive beams on both sides of a planar target, an OMEGA EP capability requested by the Omega Laser User Group (OLUG). Realizing this capability in OMEGA EP has posed significant challenges so it has not been implemented, but this capability would be relatively straightforward to design into NSF OPAL. The number of LAPP1 experimental diagnostics designed for NSF OPAL can be managed to deliver the most critical ones while providing RI-1 and construction scope flexibility.

Implementing frequency doubling of NSF OPAL Alpha beams would offer a significant feature. Frequency-doubled, ultrashort laser pulses with ultrahigh temporal contrast find some compelling NNSA programmatic applications that were not explicitly included in the LAPP1 proposal. Since HFP/QED2 also requires this capability, the RI-1 project scope will include it. R&D for the MTW and MTW OPAL lasers already included in the FY24-FY28 LLE-NNSA cooperative agreement will inform the RI-1 project design efforts in this area.

The LAPP1 proposal identified the need for ultrafast x-ray probe beams based on inverse Compton scattering (ICS) and/or betatron radiation that would have a large impact on the cost and complexity of NSF OPAL. Betatron radiation is a relatively mature technology that could be implemented on NSF OPAL, but experimentally demonstrated performance to date does not provide the spectral brightness needed for experiments. Experimental capabilities in experimental areas EA1 and EA2 will enable developing betatron sources that might advance the state of this technology to the needed performance over time, but this needed R&D introduces risk and too much uncertainty at this point. Coupling betatron sources generated in EA2 to LAPP experiments in EA1 would constrain significantly and possibly even preclude NSF OPAL facility designs, so including this capability in the NSF OPAL facility design will serve as a stretch goal but not a requirement.

Understanding exactly how to use the NSF-OPAL beams to generate monoenergetic, narrow-bandwidth, low-divergence electrons and x rays represent flagship experiments in their own right. R&D to develop these electron and ICS x-ray sources will require years of dedicated R&D to mature before applying them to NSF OPAL experiments. For instance, an ICS x-ray source could be developed but it would require a significant complementary program to develop such a capability that could be implemented at NSF OPAL and/or NNSA facilities. This R&D effort could benefit from flying-focus R&D covered by PAALS1 advances, since theoretical studies predict significantly improved performance (narrowband and collimated output beams) from schemes using this concept [2]. The RI-1 project will not include ICS source R&D explicitly but it will attempt to make provisions that enable (or do not preclude) implementing it later.

PAALS1: Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams

As noted by a PRP comment, the proposed PAALS1 experiment stands “at the forefront/convergence of plasma-based accelerators and optics (at high intensities).” The proposal points to intriguing possibilities for electron acceleration using flying-focus technology for laser wakefield acceleration (LWFA), as well as important potential scientific applications for such electron beams.

Flying-focus schemes require significant development to reach the ultimate potential performance. The first two phases of the proposed path to flagship would use the MTW-OPAL laser (7.5J) and the NSF OPAL Beta beam (30J), respectively. As noted in the proposal, significant advances could use lasers available before the construction of NSF OPAL (e.g., ZEUS, CoReLS, or the L3 laser at ELI Beamlines) if the team is ready for scaling experiments. An NSF OPAL Alpha beam would provide the ultimate capabilities to exercise mature flying-focus technology if/when it is ready.

Uncertainties in how flying-focus technology might develop, plus the potentially significant expense and space envelope of systems needed to produce, characterize, apply, and provide radiation shielding for 100+ GeV electron beams, constitute significant risks that must be mitigated before committing to the design and construction of NSF OPAL to reach the flagship performance. The RI-1 project scope will include provisions for developing flying-focus LWFA in Experimental Area 2 (EA2) that will be designed to provide maximum flexibility for dedicated R&D efforts like this. EA2 could be expanded/extended in the future to accommodate advanced capabilities beyond those needed when using the Beta beam or early stages using an Alpha beam. This would likely require new building construction or renovation that cannot be justified or even specified with needed accuracy before completing initial phases of research on NSF OPAL.

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[2] D. Ramsey, B. Malaca, A. Di Piazza, M. Formanek, P. Franke, D. H. Froula, M. Pardal, T. T. Simpson, J. Vieira, K. Weichman, and J. P. Palastro, “Nonlinear Thomson scattering with ponderomotive control,” Phys. Rev. E 105, 065201 – Published 6 June 2022; https://doi.org/10.1103/PhysRevE.105.065201.

LDNP1: Tritium-induced nucleosynthesis (provisional)

The LDNP1 proposal scored and ranked relatively poorly in the PRP process and it requires a tritium-handling capability not required by any other proposed flagship experiments. The LDNP1 proposal likely suffered unintended consequences from the implementation of the PRP process, as PRP reviewers only reviewed four proposals each assigned in such a way as to provide overlapping reviews with the goal of normalizing scores. This appears to have put the LDNP proposals from the relatively new and small "nuclear photonics" scientific community at a disadvantage relative to the other three FSWG areas that historically have garnered significant attention. PRP reviewers found the questions to be addressed important with results that could have high scientific impact, and the capabilities relatively well understood and low risk to implement.

The laser-driven triton beams proposed in LDNP1 could address some potentially compelling NNSA programmatic questions that were not explicitly included in the proposal because needed discussions could not be arranged in time. If these needs prove important, existing tritium handling capabilities in the OMEGA facility might be extended to NSF OPAL or new dedicated capabilities developed. In either case, NSF OPAL would likely require a dedicated target chamber and associated systems to avoid contaminating equipment used for other experiments. Implementing this capability in the NSF OPAL facility design depends on a mutual agreement of NSF and NNSA.

The summary diagram at the end of the proposal notes the need for "cryogenic planar foils" that the LDNP1 proposal did not describe. Cryogenic target systems increase substantially the design and operational complexity of a facility. The RI-1 project scope will not include cryogenic target systems but the project team will attempt to make provisions that enable (or do not preclude) implementing it later.

3.2 Future Flagship Experiments

Four proposed experiments (PAALS2, HFP/QED1, HFP/QED2, LDNP2) identified experiments that would address important, long-term science goals but they all require significant advances before implementing them on NSF OPAL, and/or they could use capabilities made available by the experiments described in Section 3.1. These proposals offer information that will inform RI-1 design efforts with the goal of accommodating the associated capabilities as much as possible.

PAALS2: Multi-messenger probing of ultra-intense/relativistic light-matter interactions

PAALS2 proposes an experiment that the PRP recognized as curiosity-driven with very high discovery potential, but it failed to identify an explicit science case. It found the proposed experiment to be more an investigation tool that could be important for NSF OPAL than a flagship experiment. The risks associated with implementing such a tool were deemed moderate. From a technological standpoint, developing this experimental tool will bring significant technological innovation of high impact to the community. These capabilities could be developed at another multi-beam laser facility already operating, like ELI NP, that would inform future implementation at NSF OPAL.

HFP/QED1: Extreme Fields: Testing QED in uncharted strong field regimes

The HFP/QED1 proposal described exploring new QED cascade physics that represent a definite goal of the strong-field QED science community. This could be explored on NSF OPAL following a path to developing the needed experimental methods and diagnostics well-fleshed out in the proposal. This development could and most likely would need to occur first at other facilities that offer dual high-intensity laser beamlines, like NSF ZEUS and ELI NP, or at a facility that collocates an ultraintense laser with a linear accelerator. New techniques, such as the proposed "plasma eyepiece" to control focusing, could be developed on NSF OPAL as a user-facility capability and/or at these other facilities. The proposed flagship experiment could then use the leading properties of the proposed NSF OPAL facility to extend performance and achieve new results in a "future flagship" experiment informed by these preparatory efforts. These developments promise excellent opportunities for scientific and technical collaborations funded by multiple sponsors.

HFP/QED3: Testing strong-field QED with the avalanche precursor

The HFP/QED3 proposal relies on the unique capabilities of a future NSF OPAL user facility that would achieve the highest intensities in counter-propagating laser beams and push the limits of NSF-OPAL performance. The proposed experiment would lead to a very high impact result, if successful. Like the HFP/QED1 experiment, the required developments could and most likely would need to occur first at other facilities, like NSF ZEUS and ELI NP, that offer dual high-intensity laser beamlines. The excellent team could exercise broad experimental collaborations to develop detectors and experimental methods that include more students and postdocs to build on lessons learned at the other facilities leading to a "future flagship" experiment on NSF OPAL. This experiment overlaps strongly with astrophysics, an area of physics that could help excite the public.

LDNP2: Neutron-Neutron Scattering

The LDNP2 proposal aims to address a controversial issue in the description of neutron-neutron scattering, where contradictory indirect measurements and theory fail to agree. The proposal stated a clear, strong scientific goal. It lays out a reasonable path to achieving with target and detector development efforts, as well as preparatory experiments that could be performed at other facilities. The "future flagship" experiment would prove extremely challenging. If successful, it would advance nuclear physics strongly and demonstrate the utility of nuclear photonics while also developing ultrafast, pulsed-neutron sources that could find other applications.

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Appendix B – NSF OPAL Flagship Experiment PRP Assessment Criteria

Appendix C – Peer Review Panel (PRP) Comments (not included)

Appendix D – Feasibility Review Comments (not included)

Appendix A – NSF OPAL Flagship Proposals

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A2 – PAALS2: Multi-Messenger Probing of Ultra-Intense/Relativistic Light-Matter Interactions

A3 – HFP/QED1: Extreme Fields: Testing QED in Uncharted Strong-Field Regimes

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NSF OPAL Flagship Proposal Cover Page

Proposal Deadline: Friday, May 31, 2024

Title of Proposed Experiment: Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams

Flagship Experiment Champion:
Name: Jessica L. Shaw
Institution: University of Rochester's Laboratory for Laser Energetics (UR LLE)
Email: jshaw05@lle.rochester.edu
Telephone: +1 (585) 273-5174

Flagship Team:

Name	Affiliation	Tentative Role	Email
Jessica L. Shaw	UR LLE	Champion | Experiment (Early Career)	[redacted]
Dustin Froula	UR LLE	Co-PI | Experiment	[redacted]
John Palastro	UR LLE	Co-PI | Theory/Computation	[redacted]
Jeremy Pigeon	UR LLE	Experiment (Early Career)	[redacted]
Charlie Arrowsmith	UR LLE	Experiment (Post Doc)	[redacted]
Manfred Ambat	UR LLE	Experiment (Grad Student)	[redacted]
Hunter Markland	UR LLE	Experiment (Grad Student)	[redacted]
Isabelle LaBelle	UR LLE	Experiment (Grad Student)	[redacted]
Isabelle Settle	UR LLE	Experiment (Undergraduate)	[redacted]
Kyle Miller	UR LLE	Theory/Computation (Early Career)	[redacted]
Warren Mori	UCLA	Theory/Computation	[redacted]
Amanda Elliott	UR LLE	Theory/Computation (Grad Stud.)	[redacted]
Lavonne Mack	UR LLE	Theory/Computation (Grad Stud.)	[redacted]
Robert Boni	UR LLE	Optical Engineering	[redacted]
Amy Rigatti	UR LLE	Optical Engineering	[redacted]
Joanna Rosenbluth	UR LLE	Optical Engineering (Undergrad.)	[redacted]
Sara MacNally	UR LLE	Optic Fabrication	[redacted]
Marcela Mireles Ramirez	UR LLE	Optic Fabrication	[redacted]
John Spaulding	UR LLE	Optic Fabrication	[redacted]

Abstract:

High-Energy Physics colliders provide a window into the basic building blocks of the universe. As the energy gain from conventional radiofrequency accelerator technology begins to plateau, advanced accelerator concepts become the only way to push particle energies to new levels where the boundaries in the understanding of the universe can be expanded. Dephasingless laser wakefield acceleration (LWFA) driven by an achromatic flying focus is an original concept that is a disruptive technology with the potential to transform the field of laser-plasma acceleration (LPA) and more broadly advanced accelerators. Conventional LWFA approaches can accelerate electrons to high energies, but the maximum energy is

constrained by the low plasma densities required to limit dephasing between the laser pulse and accelerated electrons. The achromatic flying focus is a new spatiotemporal focusing system that provides the ability to propagate a high-intensity laser pulse over meters at any velocity while maintaining a small focal spot and a near-transform-limited pulse duration. By controlling the velocity of a focal spot propagating in a plasma, a wakefield can be driven at the speed of light, thus eliminating dephasing. Initial simulations of this "dephasingless" LWFA with no dephasing between the laser pulse and accelerated electrons suggests that a 20-fs, 500-J laser (NSF OPAL) would be capable of accelerating electrons to TeV-class energies in a one-meter stage. This flagship experiment seeks to successfully demonstrate such a TeV-class LPA.

Figure 1: Photo of flagship team. From left to right: Manfred Ambat, Hunter Markland, Isabelle LaBelle, Lavonne Mack, Jessica Shaw, John Palastro, Dustin Froula, Amanda Elliott, Robert Boni, Isabelle Settle, Marcela Mireles Ramirez, and Sara MacNally. Missing from photo: Jeremy Pigeon, Charles Arrowsmith, Kyle Miller, Warren Mori, Amy Rigatti, Joanna Rosenbluth, and John Spaulding.

Introduction/Background

In 1979, Tajima and Dawson published the seminal *Laser Electron Accelerator* manuscript that opened the field of laser-plasma acceleration and the potential for TeV electron beams [1]. About a decade later, the first electrons from a plasma accelerator were measured [2, 3], and in 2004, the Dream Beam publications demonstrated quasi-monoenergetic MeV electron beams accelerated in millimeter-long plasmas [4-6]. Although many more advancements are needed to achieve the quality electron beams required for High-Energy Physics (HEP) studies, the recent 7.8 GeV [7] and 10 GeV [8] results are reaching the pinnacle of the current advanced accelerator concepts, where 100 separate 10-GeV laser wakefield accelerator (LWFA) stages are envisioned to produce the next generation TeV linear collider [9]. Extending conventional LWFA stages beyond 10 GeV requires lowering the plasma density and extending the laser pulse durations while maintaining relativistic intensities (challenging the available laser energies in current systems).

A novel LWFA concept based on the recently demonstrated "flying focus" technology [10] offers a new paradigm in laser-plasma acceleration that could advance the dream of a TeV linear accelerator using a single-stage system without guiding structures [11]. This achromatic flying focus enables a small- diameter (<20 μm diam.), ultrashort-duration (<30 fs) laser pulse to propagate through meters of plasma at the speed of light. The concept decouples the plasma conditions from the acceleration length, removes the need for a plasma guiding structure, and provides a novel injection scheme for monoenergetic electron beams. This dephasingless LWFA (DLWFA) is ideal for modern laser systems like NSF-OPAL that are pushing the power frontiers by reducing the laser's pulse duration. In contrast to conventional LWFA, reducing the pulse duration allows for operating at higher plasma densities (larger accelerating gradients) and requires less laser energy to achieve relativistic intensities.

The achromatic flying focus uses spherical aberration to create an extended focal region and a radial echelon to control the time at which rings of power reach their respective foci. This allows the pulse duration to remain short and the focal velocity to be decoupled from the plasma conditions. This combination allows a short, high-intensity laser pulse to drive a wakefield at any velocity. Conventional LWFA approaches can accelerate electrons to high energies, but the maximum energy from a single stage is constrained by the low plasma densities required to limit dephasing between the laser pulse and accelerated electrons. When driving the wakefield at the speed of light, electrons cannot over take the accelerating field, leading to a dephasingless accelerator. Decoupling the velocity of the wakefield from the plasma density and removing the need to guide the laser over long distances removes two significant constraints in conventional LWFA and enables a dephasingless LWFA that could provide electron beam energies limited only by the available laser energy in a single stage. Relieving these constraints will also allow the laser-plasma accelerator to be optimized in original ways, opening new opportunities for improving electron beam quality (e.g., energy spread, peak current, transverse emittance, etc.…). Initial scaling with no dephasing between the laser pulse and accelerated electrons suggests that a 20-fs, 500-J laser pulse would be capable of accelerating electrons to TeV-class energies with a single 1-meter stage. This remarkable performance compares with the proposed International Linear Collider that will be between 30- and 50-km long (if constructed) at an estimated cost of $6.7 billion (in 2007 US dollars, excluding R&D, prototyping, land acquisition, underground easement costs, detectors, contingencies, and inflation), per its Reference Design Report [12].

Scientific Proposal

This proposal introduces an original concept of a disruptive technology with the potential to transform the field of laser-plasma acceleration and, more broadly, advanced accelerators. Specifically, this proposal addresses two fundamental science questions:

- *What ultimately limits the electron beam energy for laser wakefield accelerators driven by multi-petawatt laser pulses?*
- *Can high-density plasmas be used to accelerate electrons beyond 10 GeV?*
- *What role does radiation reaction play in limiting the production of TeV-class electron beams?*

The ultimate goal of this flagship experiment is to demonstrate TeV-class electron energies from a single plasma stage using an achromatic flying focus driven by the NSF OPAL Alpha beam. Such a demonstration will make significant progress towards answering the fundamental science questions posed above.

Additionally, the results of this flagship could provide a step-wise change in the direction of the field of advanced accelerators, which could eventually be a gamechanger for HEP. A successful TeV-class flagship could shift laser drivers to modern, high-power laser architectures since optimizing the accelerator for energy gain requires short laser pulses and high laser energies. Additionally, demonstrating TeV-class energies in a single stage can shift the focus of the LWFA field away from needing to stage hundreds of 10-GeV stages to reach TeV energies, which could make TeV linear colliders a real possibility.

The outcome of the proposed research fits well within the stated goals of the NSF Mission and the NSF Vision. As described, the proposed research promotes the progress of science and helps the US prevent technological surprise. The proposed research also meets the NSF Vision to capitalize on new concepts in science and provide global leadership in advancing research and education.

The team has high confidence that a DLWFA driven by NSF OPAL will lead to paradigm-changing electron energies from a single stage. Although this field is still quite new, the anticipated experimental results are well predicated by the computational work, and the current simulations predict TeV-class electron beams. Furthermore, our team has received more than $1.5M through CY2026 from the Office of Science [13] to develop the science and technologies for dephasingless LWFAs. This funding provides the foundation for our team's research and development, while NSF OPAL could be the transformative technology that enables the next grand challenge in laser-plasma acceleration.

Because DLWFA is predicted to provide electron beam energies limited only by the available laser energy, the research is ideally suited for the highest-energy laser that exhibits an ultrashort pulse duration. Because the NSF OPAL design calls for 500 J in 20 fs, which is more laser energy than is available anywhere with an ultrashort pulse duration, it is uniquely suited to demonstrate a TeV-Class DLWFA. Note that the Vulcan 20-20 upgrade design [14] calls for 400 J in 20 fs, so this research could also be completed there if proper experimental space was allocated. Other existing laser facilities with the required ultrashort pulse duration (<30 fs), such as ZUES and L3 @ ELI Beamlines, do not offer such energies. Therefore, these facilities are useful stepping stones to the flagship experiment, but ultimately are not expected to be able to produce TeV-Class electron beams.

Team and Resources

The team assembled for the TeV-class DLWFA flagship comprises a committed and competent group of experimentalists, theorists, and optical engineers for all phases of the project. The core team has been working towards DLWFA since the initial flying focus concept in 2017 [10], which was patented in 2020 [15]. The team is championed by early career experimentalist Jessica Shaw, who is active in the NSF OPAL project, including the design of the facility-provided secondary sources. She and the team of experimentalists have a strong track record of obtaining funding for DLWFA research, securing experimental time on laser systems, and publishing results. The theory/computation team has pioneered the concept of flying focus in simulations. They have 29 publications that explore the potentials of flying focus, and they are intimately involved with the experimental team in the demonstration of concepts. The optical engineering and fabrication team leads the field in the design and fabrication of the requisite optics, including developing and demonstrating two methods to fabricate the first viable flying-focus optics [16]. The optical engineering/fabrication team also includes members who are field leaders in large-aperture optical fabrication, which will be essential for the 80^2-cm^2 NSF OPAL laser beams.

This team represents the broad plasma-based accelerator community, which consists of ~100 institutions spread across Europe, North America, and Asia. The team maintains a balance of established leaders (Froula, Palastro, Boni, Rigatti, Mori) and emerging leaders in the field, including 5 early-career scientists, 1 postdoc, 5 graduate students, and 2 undergraduates. Women and underrepresented groups in STEM are strongly represented in the team. Many of the stepping-stone experiments to the flagship, including the facilities on which those stepping stones will be conducted, are ideal for graduate-level research and will lead to 5+ Ph.D. dissertations. Over the lifespan of the project, the team will continue to recruit postdocs, graduate students, and undergraduates, and in so doing will seek the full participation of women and underrepresented groups.

Technical Design Work

In this section, the design and technical work required to reach the TeV-class flagship experiment is outlined. Projects that could be part of graduate research are marked with "*", and projects for which the team will apply for additional grants to support the work are marked by "‡".

Theory/Computational Path

To date, the proposal team has implemented the ability to model flying-focus pulses into the particle-in-cell (PIC) code OSIRIS [17]. OSIRIS was used to demonstrate that a DLWFA driven with an achromatic flying focus using a 6.2-J drive pulse can accelerate 25 pC of charge over 20 dephasing lengths to a maximum energy gain of 2.1 GeV [18]. Extrapolating these computationally limited simulations to a 500-J, 20-fs-long laser pulse suggests electron energies of 125 GeV in a single, less-than-one-meter-long stage [18].

The ultimate goal for the TeV-class flagship is to complete a full-scale simulation with a 500-J pulse‡. These simulations are prohibitively expensive with current PIC capabilities due to their nearly 1-meter plasma length and the large transverse width required to properly model the flying focus drive laser. To enable such simulations, the next step for the team is to implement flying focus pulses in the quasi-static code QPAD [19], where the focal trajectory and performance can be studied for meter-scale DLWFA*. The QPAD results will also be verified against OSIRIS for sub-scale runs*. In parallel, the capability to model flying-focus pulses in the Lorentz-boosted frame, which shrinks the overall computation load by a factor of ~40, will be added to OSIRIS. By combining the boosted frame with injectors from a radial boundary, it may also be possible to simulate the full, 1-m stage in OSIRIS. The team estimates that the QPAD work the preliminary sub-scale OSIRIS validation will be completed by March 2025 for CDR.

Optic Development

The TeV-class DLWFA flagship team has developed the technologies required to fabricate the axiparabolas and echelons that produce an achromatic flying focus. Those optics are currently installed for the first DLWFA experiments on MTW OPAL. The major technical gap that exists for the optic development is the extension of the fabrication technologies to the apertures required for NSF OPAL. The team sees manageable risk with this gap; the techniques have been demonstrated to be viable. The optical fabrication members of our flagship team, who have been instrumental in the fabrication of flying focus optics to date, also have extensive experience in producing large-aperture optics for systems such as the NIF.

Although the flagship team has working concepts, we are also continuously developing new, novel concepts to produce flying focus pulses that would also allow for DLWFA*‡. These concepts are often conceptualized by graduate students and become the core of their PhD research. New concepts include a dynamic flying focus that is based on a deformable mirror and spatial light modulator [20]. This concept would allow programable velocity for active feedback and machine learning. As these concepts mature, they may further simplify the production of flying focus optics.

Target Development

The TeV-class DLWFA flagship will use a meter-scale plasma source as its target*‡. Similar long plasma sources (up to 10 m) were developed and are in use at the FACET experiment at SLAC [21, 22] and the AWAKE experiment at CERN [23]. Large-aperture plasmas are part of normal operation for CO_2 lasers [24]. The primary challenge for the plasma source for the TeV-class DLWFA flagship is that the plasma source needs to have both a large aperture and a length of ~1 meter. Developing such a source is a primary risk for this flagship proposal. The team is currently working on developing concepts to produce such a plasma source. The demonstration of a scaled-down version of this source is currently underway on the MTW OPAL facility by graduate student M. V. Ambat. Ultimately, if the full-scale plasma source is not achieved, the sub-scale plasma source would limit the ultimate energy gain of the electrons.

Diagnostic Development

At its core, the TeV-class DLWFA flagship experiment only requires one measurement: the electron energy‡. Simulations predict 25 pC of electron charge with energies up to 125 GeV, so there should be adequate signal such that signal-to-noise is not a concern. The ideal and most-established electron energy measurement would employ a magnetic electron spectrometer. Electron spectrometers out to 80 GeV have already been demonstrated at SLAC. For this flagship, that capability would ideally be extended to 125 GeV, although meaningful measurements could be made even if the spectrometer only had 30-GeV capability. The primary risks in the design of this spectrometer are the cost and the space required to resolve the highest electron energies. In the case that the available space or budget is limited, the team is developing alternative concepts*‡ to measure electron energies of this magnitude, such as methods based on stopping distances in materials, plasma wakefield acceleration, nuclear physics, Cherenkov emission, or the produced betatron spectrum.

This flagship would also benefit from two supporting diagnostics: an interferometer to characterize the plasma source and a focal spot monitor to characterize the focal volume. Both of these diagnostics have a small footprint and have already been demonstrated on DLWFA experiments on the MTW OPAL laser. A third novel diagnostic currently being developed uses the Cherenkov emission angle emitted from the flying focus propagating through gas to characterize it trajectory [25]. This diagnostic could provide an in-situ verification of the trajectory and be used for active feedback to optimize the trajectory using the programable flying focus concepts.

Path to CDR

Table 1 below summarizes the path to CDR, which is scheduled in March 2025.

Table 1: Summary of Path to CDR with planned completion dates

Milestone	Planned Completion Date
Theory/Computation	
Implement Achromatic Flying Focus Pulses in QPAD‡	January 2025
Implement Achromatic Flying Focus Pulses in Lorentz-Boosted OSIRIS‡	March 2025
Verify QPAD validity using OSIRIS to 10 cm*‡	March 2025
Full-scale simulation in QPAD*‡	March 2025
Laser Development	
Requirements for Laser	Done
Requirements for Experimental Geometry	Done
Optic Development	
Technique for Fabrication of Axiparabolas/Echelons	Done
Target Development	
Requirements for Plasma Source	Done
Concepts for Producing Plasma Sources*	March 2025
Diagnostic Development	
Requirements for Electron Spectrometer	Done
Requirements for Minor Diagnostics	Done

Experimental Concept of Operations

After initial alignment of the system, the TeV-class flagship experiment could operate in either a single-shot mode or a high-repetition-rate mode. A higher repetition-rate will facilitate optimizing the DLWFA and collecting parameter scans, but fundamentally, once the system is optimized, a single shot is enough to demonstrate TeV-class electron beams. As no targets need to be changed between shots, the repetition-rate at which this experiment can run is only limited by the laser system. To optimize the DLWFA, the team will need to ramp up the laser energy and potentially tune the flatness of the laser spatial profile. The plasma parameters, such as the gas mixture, gas backing pressure, source length, and source position, may also need to be tuned. No secondary sources are required for this flagship.

Path to Flagship

The ultimate goal of the flagship experiment is to demonstrate TeV-class electron energies from DLWFA in a single stage using the NSF OPAL Alpha Beam. This section describes the path to the flagship experiment, and that entire path is summarized in the diagram on the attached slide. Technical work to achieve that path is summarized at the end of this section. Work that could comprise PhD research is marked with a "*", and work for which the team will apply for additional funding outside the NSF OPAL funding is marked with "‡".

CW Demonstration of an Achromatic Flying Focus

In preparation for a flagship experiment, the team has been laying out a path to systematically demonstrate all technologies and experimental concepts. This path started with the all-optical demonstration of an achromatic flying focus using an ultrabroadband CW laser, which demonstrated the key features that could enable the system to be used for DLWFA. This work [16], which was led by early career scientist J. Pigeon, demonstrated that a controllable ultrabroadband flying focus with a nearly transform- and diffraction-limited moving focus can be created over a centimeter-scale—an extended focal region more than 50 Rayleigh ranges in length. This work additionally verified that the team could fabricate the necessary optics to produce an achromatic flying focus.

DLWFA on MTW OPAL (7.5 J Demonstration)

Current experiments are working to demonstrate a DLWFA for the first time using MTW OPAL [26]. This research is funded by the DOE [13] through FY26. This demonstration using the 20-fs, 7.5-J system will comprise the PhD research of at least two graduate students*—M. Ambat and I. LaBelle, both of whom are part of this flagship team. Recently, M. Ambat demonstrated an extended focal volume produced by an achromatic flying focus driven by an short pulse laser at high power. Continuing into summer 2024, M. Ambat will complete a series of campaigns demonstrating the plasma source and looking for the first demonstration of DLWFA. Starting in Fall 2024, a postdoc has been hired to help lead the efforts to optimize the DLWFA and study the fundamentals of particle trapping. In this campaign, the trajectory of the flying focus will be optimized to trap a narrow-energy-spread electron beam and accelerate it to over 1 cm. This work will study the physical tradeoffs between energy again, total accelerated charge, and beam quality. The findings will be compared against theory and to inform the next design and experimental steps.

Additionally, during this phase, the team will test other achromatic flying focus concepts, such as the dynamic flying focus based on a deformable mirror-spatial light modulator [20] or other programmable achromatic flying focus, as they mature.

Flying Focus Light on NSF OPAL (30 J Demonstration)

To bridge the gap between 7.5 J and 500 J, the team plans to execute the first flying-focus experiments on NSF OPAL using the round Beta beam (30 J)*‡. Leading into these experiments, 30-J simulations will be conducted by early career scientist K. Miller, and appropriate optics will be designed and fabricated at LLE. Any new physics uncovered by these simulations will be used to steer the experimental campaign plan. A plasma source scaled to the 30 J energy will be deployed*‡. This plasma source, which will be scaled up from the 7.5-J design to match the system, will incorporate all lessons learned from the 7.5-J campaign and will be fully characterized before experiment. The campaign plan will target the same goals as the 7.5-J demonstration and the eventual 500-J demonstration: measure the extended focal volume, energy ramp up, acceleration optimization, and trapping control. The exact goals will be informed based on lessons learned from the 7.5-J experiments and simulation work. This campaign will also serve to commission the round Beta beam capability and the apodizer requirements for the achromatic flying focus optics.

If the team is ready for 30-J experiments before the Beta beam is available at NSF OPAL, the study could also be completed on other user facilities with tens of joules and ultrashort laser pulses (CoReLS @ 80 J/<20 fs or L3 @ Eli Beamlines @ 30 J/ <30 fs or ZEUS @ 75 J/25 fs)*‡. The team has a good record of securing experimental time at user facilities.

Flagship: Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage, TeV-Class Electron Beams

The ultimate goal of the flagship experiment is to demonstrate TeV-class electron energies from a single plasma stage using a flying focus driven by the NSF OPAL Alpha beam. The campaign plan will target the same goals as the 7.5-J and 30-J demonstrations: measure the extended focal volume, energy ramp up, acceleration optimization, and trapping control. The exact details of the plan will be informed based on lessons learned from the 7.5- and 30-J experiments and simulation work. If TeV-class electron beams are successfully demonstrated, the flagship can be extended to investigate the role that radiation reaction plays at these electron energies [27], but that is outside the scope of this proposal. One risk here is that NSF OPAL is not able to provide the full 500 J. This flagship can still be completed at reduced energies but at the cost of the maximum electron energy that we can produce. Regardless, the result would still have a significant impact on the field.

Technical Work Milestones during Path to Flagship

In parallel, the team continues technical preparations for the flagship experiment and the 7.5- and 30-J stepping-stone experiments to flagship. Although the full description of technical work was outlined above, Table 2 summarizes the milestones along the Path to Flagship and their estimated completion dates.

Table 2: Summary of technical work along Path to Flagship and planned completion dates

Milestone	Planned Completion Date
Theory/Computation	
Simulation of 7.5-J Experiment: DLWFA on MTW OPAL	Done
Simulation of 30-J Experiment: Flying Focus Light on NSF OPAL*‡	FY 26
Optic Development	
Design/Fabrication of Axiparabola/Echelon for 7.5-J Experiments	Done
Design of Axiparabola/Echelon for 30-J Experiments*‡	FY 27
Fabrication of Axiparabola/Echelon for 30-J Experiments‡	FY 27
Design of Axiparabola/Echelon for NSF OPAL‡	FY 29
Fabrication of Axiparabola/Echelon for NSF OPAL‡	FY 30
Continue Advancing Designs, Including Dynamic*‡	Ongoing
Target Development	
Plasma Source for 7.5-J Experiments*‡	In Progress
Plasma Source for 30-J Experiments*‡	FY 27
Plasma Source for NSF OPAL*‡	FY 30
Diagnostic Development	
Electron Spectrometer for 7.5-J Experiment*‡	Done
Design/Build Electron Spectrometer for 30-J Experiment*‡	FY 27
Design Electron Spectrometer for NSF OPAL*‡	March 2026
Mature Alternate Concepts to Electron Spectrometer	Ongoing
Build Electron Spectrometer for NSF OPAL*‡	FY 30
Minor Diagnostics for 7.5-J & 30-J Experiments*‡	Done
Design/Build Minor Diagnostics for NSF OPAL*‡	FY 30

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Flying-Focus-Driven Laser-Plasma Accelerator for Single-Stage TeV-Class Electron Beams

Champion: J.L. Shaw (UR LLE)

Flagship Campaign →

Estimated timeline: FY24 ……………………… FY39

DOE funded through FY 26

Flagship Campaign	Timeline	Simulation Capabilities			Laser Capabilities			Target Capabilities	Diagnostic Capabilities				
		AFF in OSIRIS	AFF in QPAD	AFF in Lorentz Boosted OSIRIS	AFF Optics	Beta	Alpha	Plasma Source	Focal Spot Diagnostic	Interferometer	Electron Spectrometer	>100 GeV Spectrometer	
CW Demonstration of Achromatic Flying Focus	Done	●			●				●				
Simulations for DLWFA on MTW OPAL	Done	●											
DLWFA on MTW OPAL (7.5 J Demonstration)	FY24 – FY26				●			●	●	●	●		
Simulations for Flying Focus Light on NSF OPAL	FY26		●	●									
Flying Focus Light on NSF OPAL (30 J Demonstration)	FY27 – FY29				●	●		●	●	●	●		First Day
Simulations for Flagship	FY24 – FY25		●	●									
Flagship: TeV-Class DLWFA	FY32 – FY36				●		●	●	●	●	●	●	Mature

Community Leadership and Involvement

Simulation Team

Miller† (UR/LLE)
Palastro (UR/LLE)
Mori (UCLA)
Elliot (UR/LLE)
Mack (UR/LLE)

Experiment Team

Shaw† (UR/LLE)
Froula
Arrowsmith† (UR/LLE)
Pigeon† (UR/LLE)
Ambat* (UR/LLE)
LaBelle* (UR/LLE)
Markland* (UR/LLE)

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*Graduate Student
†Early Career

NSF OPAL Flagship Proposal Cover Page

Proposal Deadline: Friday, May 31, 2024

Title of Proposed Experiment: Multi-messenger probing of ultra-intense/relativistic light-matter interactions

Flagship Experiment Champion:

Name: Stepan Bulanov, Lieselotte Obst-Huebl

Institution: Lawrence Berkeley National Laboratory

Email: sbulanov@lbl.gov, lobsthuebl@lbl.gov

Telephone: +1 (510) 486-5939, +1 (510) 486-6632

Flagship Experiment Team:

Name	Affiliation	Tentative Role	Email
Stepan Bulanov	Lawrence Berkeley National Laboratory	Principal Investigator, theory and simulation	[redacted]
Lieselotte Obst-Huebl	Lawrence Berkeley National Laboratory	Principal Investigator, experiment	[redacted]
Davide Terzani	Lawrence Berkeley National Laboratory	Co-Investigator, theory and simulation	[redacted]
Axel Huebl	Lawrence Berkeley National Laboratory	Co-Investigator, theory and simulation	[redacted]
Louise Willingale	University of Michigan	Co-Investigator, experiment	[redacted]
Franklin Dollar	University of California Irvine	Co-Investigator, experiment	[redacted]
Douglass Schumacher	The Ohio State University	Co-Investigator, experiment	[redacted]
Mingsheng Wei	Laboratory of Laser Energetics/University of Rochester	Co-Investigator, experiment, liaison LLE	[redacted]

Abstract

Laser-matter interactions at relativistic intensities are at the forefront of plasma physics research nowadays. This is in part driven by the fast progress in laser technology, which enabled the design, construction, and operation of multi-PW laser facilities. This progress opened new avenues of research and a plethora of new phenomena to study, which require new tools to characterize and explore. We propose to study the interaction of a multi-10 PW laser pulse with a near critical density plasma by employing two plasma targets each irradiated by a multi-10 PW laser pulse. The first laser target interaction would produce copious amounts of high energy electrons, ions, and photons, which will be used to probe extreme electromagnetic fields and density waves generated by the second laser target interaction. These multiple messengers will arrive at the second target at various delays, due to their varying time of flight, providing multiple screenshots of the laser matter interaction. Thus, it would be the first multi-messenger study of relativistic light matter interaction, which will deliver a comprehensive suite of data describing from start to end the entire history of the interaction at unprecedented laser intensities.

Introduction/Background

Laser-matter interaction at relativistic intensities is the subject of numerous studies dating back more than half a century [1-4]. Research of these interactions has come a long way from a basic understanding of the fundamental physics of plasma waves to the study of different plasma instabilities, particle acceleration, magnetic reconnection, and the generation of sources of high frequency radiation. Pivotal discoveries with considerable societal impact include EUV lithography for the production of integrated circuits for the semiconductor industry, compact laser particle accelerators (LPA) and light sources, and the demonstration of fusion gain at the National Ignition Facility. These successes have been in part driven by the fast progress in laser technology, which allowed the use of ultra-short, ultra-intense, high-power laser pulses for experiments on laser matter interactions. Moreover, this progress, especially in terms of laser power and intensity, has opened new avenues for research, giving rise to the regimes of light-matter interaction not accessible before. As the available light intensity increases, a plethora of new phenomena for study become available, as well as enabling novel groundbreaking applications. Areas of fundamental discovery include, for example, understanding the creation of the heaviest elements in the universe, the generation of ultra-strong magnetic fields, creating plasma conditions modeling those typical in space or in different astrophysical object environments, or testing the models describing strong field quantum electrodynamics.

New tools are needed to characterize and explore these interactions. A critical difficulty in investigating such phenomena lies in their taking place on largely variable time scales that cannot all be captured with a single diagnostic. For example, a laser pedestal could be intense enough to ionize and pre-expand a target several nanoseconds in advance of reaching the peak intensity. Once surpassing a certain threshold intensity, the plasma electrons are accelerated to relativistic velocities in as little as a few femtoseconds. Their interaction with the laser pulse, propagation, and recirculation throughout the target could take place within 10s of femtoseconds, including rapidly producing extremely strong electromagnetic charge separation fields. These fields can be present 100s of femtoseconds before declining, and leaving the plasma to expand over the course of picoseconds to nanoseconds. Diagnostic techniques so far used to study these processes are either time integrated and, hence, not able to resolve the transient nature of the interaction, or take snapshots of the interaction with a single species probe at selected time steps. Numerical simulations of these systems rely on assumptions and need benchmarking. Here we propose the first multi-messenger study of relativistic light matter interactions to deliver a comprehensive suite of data describing from start to end the entire history of these interactions at unprecedented laser intensities.

Recently there was a lot of interest in studying high-intensity, high-power laser interactions with near critical density (NCD) targets [5-9]. These targets have such a low density that when turned into plasma it is near the threshold of transparency for the laser light. As the laser pulse intensity increases, these targets become increasingly transparent for the laser radiation. This makes the laser pulse interaction with NCD targets of interest due to a number of reasons. First, the laser pulse can be completely depleted, achieving almost 100% laser energy conversion into plasma electrons and ions. Second, energization of electrons and ions and their collective motion leads to the generation of extreme electro-magnetic (EM) fields in plasma, whose strength might approach mega-Tesla and peta-eV/m according to different analytical and computer simulation estimates. Third, plasma density modulations are excited that move with different velocities and in different directions, also giving rise to a number of instabilities. Straightforward applications of such interactions are the acceleration of electrons and ions, as well as the generation of high energy photons. These applications are based on the intense laser pulse volumetric interaction with the NCD plasma in the regime of relativistic transparency. Though the current understanding of these phenomena allows us to qualitatively and somewhat quantitatively characterize this interaction, the lack of experimental data on the evolution of target and laser properties significantly limits our understanding of such an interaction. Since the interaction of intense laser pulses with NCD plasmas produces copious amounts of accelerated ions and electrons, as well as high energy photons, it can be used as a source for the multi-messenger radiography. Here the unique capabilities of the future NSF OPAL facility come into play. The ability to deliver two high intensity laser pulses in the target chamber allows to set up an experiment where one pulse will generate different probes, which would characterize the interaction of a second pulse with a plasma target. These probes, interacting with extreme fields and density modulations inside the NCD target irradiated by a multi-10 PW laser pulse, will generate different signals by being accelerated, decelerated, scattered, producing radiation, or even decaying into electron-positron pairs (as high energy photons can do in strong EM fields). Thus, this scheme can be referred to as the *multi-messenger probing of ultra-intense/relativistic light-matter interactions*.

Scientific Proposal

Here we propose to employ multi-messenger (MM) probing of ultra-intense laser interactions with a relativistically transparent plasma target. In order to do that, the unique capabilities of the NSF OPAL facility should be used.

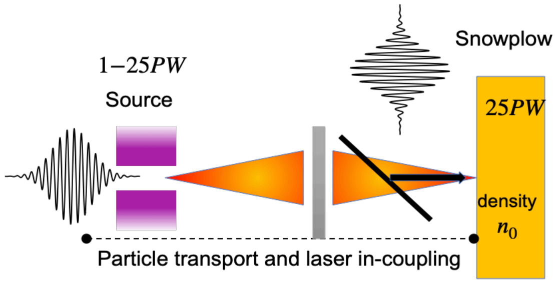

Figure 1: The FSE setup, including two 25 PW laser pulses irradiating two NCD targets. The source target produces electrons, ions, and photons, which are transported to the second target to achieve MM probing of ultra-intense laser interaction with a plasma target.

The flagship experiment (FSE) setup is sketched in Fig. 1. There are two targets, each irradiated by a high intensity laser. The first one serves as a source of high energy ions, electrons, and photons. Here, in particular, a near critical density target (NCD) is chosen, which enables ion acceleration via the magnetic vortex acceleration (MVA) mechanism [10-12]. In the MVA regime, an intense laser pulse makes a channel in the plasma target. As the laser propagates in this self-generated channel, it drives a strong electron current in its wake and generates a strong magnetic field, which is intensified as the current pinches. As the laser leaves the target rear, strong longitudinal accelerating and transverse focusing electric fields for ions are formed, producing a high energy, well collimated ion beam. It is well known that MVA also produces copious amounts of electrons, accelerated to relativistic energies. These electrons and the extreme fields generated inside the NCD plasma target give rise to the production of high energy photons, especially for laser powers exceeding the PW-level [5]. The protons and heavier ions, electrons, and photons will be used to probe extreme EM fields and density waves in the second NCD target irradiated by a 25 PW laser pulse. These multiple messengers will arrive at the second target at various delays, due to their varying time of flight, providing multiple screenshots of the laser matter interaction in the second NCD target.

Additionally, their varying charge state (and, in the case of photons, lack of an electrical charge) will provide complementary mapping of fields and densities. Their magnetic momentum (spin polarization) can also be manipulated to provide an additional modality for field mapping.

Preliminary computer simulations of ultra-high intensity/relativistic laser plasma interactions with NCD targets show a rich landscape of interesting effects unfolding in the plasma. Our simulations indicate that complex extreme EM fields produced in a 10 PW-NCD interaction can be probed with laser accelerated protons of a broad energy spread injected into these fields at different times during the field evolution. (see Fig. 2)[1]. In this figure the proton energy gain dependence on the initial energy and a delay between the proton bunch and the laser pulse is shown for a 10 PW, 30 fs laser pulse, focused down to w_0=4 μm on an NCD target of 50 μm thickness and with a density equal to the critical plasma density. Since the extreme EM fields in the plasma evolve and move together with density modulations this results in a quite complicated pattern of final proton energies, which can be used to decode this evolution. The straightforward result that can be deduced from Fig. 2 is the existence of 10's to 100's TeV/m longitudinal electric fields moving at a speed which is a fraction of the speed of light. This conclusion is due to the acceleration of several hundred MeV protons up to 2.5 GeV with the acceleration showing strong dependence on initial proton energy and delay. In our FSE scheme, this only constitutes one messenger, and will be complemented by electron, photon, and positron probe messengers from varying time points, as well as spatial mappings via radiography. This will provide the most complete picture of these extreme interactions ever recorded in experiments. We note that an additional outcome of the FSE will be the first demonstration of the staged acceleration of protons [9] to the relativistic energies.

Unpublished material redacted

Paths to CDR and Flagship

We will develop the science and technology (S&T) needed to execute this FSE at NSF OPAL. We describe the current technology as well as technical gaps and how we intend to address these in the following section titled "Science & Technology development for FSE". Many of these developments can be pursued in a modular fashion at existing NSF facilities such as ZEUS. We provide sections on "Experimental concept of operations", as well on our proposed "Timeline to CDR and FSE". This is followed by a section on "Potential risks and mitigation".

Science & Technology development for FSE

Virtual twin: Diagnostics of multi-messenger signatures based on theory and numerical simulations. The design of the experimental layout and components, as well as the expected experimental

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[1] These results are based upon work supported by the Defense Advanced Research Projects Agency via Northrop Grumman Corporation.

signatures will be informed by highly parallel particle-in-cell simulations conducted with the open community simulation codes of the Beam, Plasma & Accelerator Simulation Toolkit (BLAST), especially the exascale code WarpX [13, 14] developed at LBNL. Our preliminary simulations will be extended to full 3D simulations to study in detail the rich science enabled by NSF OPAL. This will include (but not be limited to) the study of scaling the laser focal spot, pulse length, temporal contrast and direction of electric field polarization on both plasma stages. Due to the extremely high laser power, the laser pulse length and focal spot size can be increased and the temporal contrast improved (e.g., with plasma mirrors or nonlinear doubling crystals) while still generating relativistic electrons and extreme fields upon interaction with the plasma targets. Results from our simulations will guide the Conceptual Design ("experiment on paper") and will serve to respond to key questions raised in the Conceptual Design Review (CDR).

The full interaction from start to end, including the laser plasma interaction and messenger creation, messenger transport including propagation through the plasma mirror, the second laser plasma interaction, and the detection of messenger signatures will be implemented into a fully self-consistent, start to end simulation using WarpX. Serving as a "virtual twin", this simulation will provide essential guidance for the design and strategic positioning of messenger detectors. The observed signatures will be used to develop theoretical scaling laws and train machine learning models that are able to extrapolate from data sets that are potentially sparse (limited computation and experimental time limits the amount of available data).

MM-detect: Detection of multi-messenger signatures with novel diagnostics. The multi-messenger probes will be generated in the first laser plasma interaction, propagate through the plasma mirror, and then probe the second laser plasma interaction. The thus manipulated messenger probes will be diagnosed with detectors that are capable of operating at high shot repetition rates. These detectors will include proton, ion, electron, positron, and gamma spectrometers and radiography panels. Active detector materials such as scintillators, phosphor screens, YAG and diamond crystals, multi-channel plates, etc. Additional low power optical probes with tunable delay might be employed to investigate the onset of relativistic transparency. These beams can be split off of the alpha 1 and 2 beams in the main target chamber and routed over a motorized delay line. All diagnostics can be designed, assembled and commissioned at other laser facilities in advance of the FSE.

Co-align: Laser alignment and stabilization supported by AI/ML. We will implement active alignment and stabilization of the laser pointing using motorized tip/tilt mirror mounts. This will enable alignment of the two laser beams with respect to each other and onto the plasma targets with 1 to 10 micrometer precision. Both temporal and wavefront stabilization with active control of a motorized delay stage and deformable mirror are also envisioned to lock the temporal synchronization of the two laser pulses to <10 fs precision as well as stabilizing the focus quality. This technology development is currently underway at the BELLA PW 2nd beamline (2 x 0.5 PW) [15] and will be scaled up for NSF OPAL laser power. The technology development will have broad impact not only for other NSF OPAL experiments but also for high precision applications of high power laser systems with societal benefits such as LPAs for cancer therapy and laser plasma interactions for inertial fusion energy (IFE).

PM Coupling: Plasma mirrors for laser coupling. We will use liquid crystal (LC) plasma mirrors (PM) developed in an NSF OPAL sub award (PI D. Schumacher), to couple in and align the 2nd laser beam to drive fields in the 2nd plasma. We will make use of the unique LC quality (optical surface quality) and thin film interference property to tune the laser focus and contrast on the 2nd plasma. The maximum laser energy reflected off of a LC PM is 12 J [16] and the LC PM subaward project investigates the scaling to higher laser energies. We will investigate the concept of producing curved LC PMs with focal lengths that can be changed on-demand to allow for active tuning of the focal spot size on the 2nd plasma target. This development will also address other pressing questions in science and technology, such as that of final optics for high energy/high power laser systems for LPAs and IFE power plants. Those optics are typically a fundamentally challenging component from a technological and financial standpoint, due to the large laser fluence they need to withstand.

NCD-target: Development of tailored density, renewable plasma targets. To create a dense plasma, one typically uses a solid target; these are generally non-replenishable and require frequent replacement which prevents long term operation. Upon ionization from a high laser, the overdense plasma is typically preceded by an exponentially decaying density profile which is detrimental to many applications. Gases, on the other hand, offer the route to cheap and replenishable sources, and some research and development has taken place to create overdense plasmas with supersonic gas flows and shock waves. We will develop targets based on gas jets and other replenishable target technology such as continuously flowing liquid jets that feature a density profile that can be tailored on demand. This will allow for precisely controlled scans of the velocity and lateral distribution of electromagnetic fields created in the 2nd plasma target. This development will also benefit other critical science questions, such as that of final laser optics in LPAs and IFE power plants as mentioned above.

Experimental concept of operations

The table below summarizes key aspects of operating this FSE:

System variables to be changed/scanned during campaigns	● Pulse length Alpha 1 & 2: 25→200 fs (e.g., by adding 2nd order spectral phase with Dazzler or pulse compressor grating separation) ● Spot size Alpha 2: 2→10 um (adjustable focus location, will be varied with LC PM) ● Polarization Alpha 1 & 2: linear to circular in variable steps (λ/4 wave plate rotation) ● Temporal contrast Alpha 1 & 2: 10^{-15} or 10^{-10} (binary, by adding or removing plasma mirror assemblies or nonlinear crystals) ● Co-timing of Alpha 1 & 2: Change relative delay up to 1 ns
Number of shots needed for meaningful statistical analysis	For each parameter above (except temporal contrast): 15 settings, 10 shots per setting, i.e., 150 shots. Allow for multidimensional parameter scanning and vary temporal contrast, too: total of 3000 shots.
Would tuning of secondary sources be required?	The first plasma stage will serve as a multi-messenger "secondary source" and will be tuned as part of the FSE.
Any other potential campaign variables?	A number of target and diagnostic technologies may be used and would involve flexible changes to the target chamber setup.

Timeline to CDR and FSE

The S&T steps and experimental concepts of operation to realize this FSE were described in previous sections. A timeline-and-capabilities-matrix is provided in the schematic titled "Timeline_to_flagship.pdf". It outlines milestones on the way to executing the FSE, including in the time before NSF OPAL availability, on the first day of operations, after some operation and maturity, and finally, at the time of the FSE execution. The *Virtual twin* milestone will provide the basis for the 'experiment on paper', including clear requirements for the targetry (*NCD target*) and diagnostics (*MM-detect*). Targets and diagnostics will be designed and tested at systems of reduced scale, such as BELLA and ZEUS. First day experiments will implement and test these diagnostics in the NSF OPAL chamber. Starting the first day and leading into maturity, the two alpha beams will be synchronized (*Co-align*) in the target chamber and the plasma mirror operation will be tested with alpha 2 (*PM coupling*). All components will come together for the FSE execution, the results of which will be used to benchmark and refine the theoretical description so far mainly informed by the Virtual twin.

Potential risks and mitigation

From a technical perspective, the coupling between the two plasma stages poses a significant challenge regarding the laser synchronization and stability among other things. This is an active area of research, for example at the BELLA Center for the staged laser wakefield acceleration of electrons using two synchronized laser pulses. Other institutions using multi-beam setups have made and continue to make considerable progress in this field. Techniques will be fielded and tested at reduced scale in advance of first day operations of NSF OPAL.

From an operations perspective, risk mitigation is achieved by a layered approach with multiple parallel milestone projects that can be completed independent from each other. Similarly, the use of both existing and new facilities and equipment provides redundancy and fall-back paths that increase the probability of success. There is a risk that the team will not be able to secure sufficient additional funding to execute the milestone projects. However, ongoing and already funded efforts in LPAs, laser photon production, plasma mirror development, simulation development and other topics at LBNL, UMich, UCI and other institutions will continue to produce results that will further our FSE. In the case of hiring shortages of qualified personnel to execute the research, the work will be executed by existing personnel at LBNL, UMich, and UCI. All work executed in the framework of this project will adhere to DOE and NSF rules regarding personnel and equipment safety and all involved institutions have excellent safety track records. Therefore, disruptive incidents are not anticipated.

Team and Resources

The team is ideally situated to execute this proposed research. It consists of a diverse group of researchers of varying career stages and institutions. Stepan Bulanov and Lieselotte Obst-Huebl from LBNL serve as co-principal investigators, reflecting the need for team leads for the theory/simulation thrust, in addition to the experimental realization of this flagship experiment. Both will represent and advocate for the FSE as champions. S. S. Bulanov will work with Davide Terzani and Axel Huebl from LBNL on theoretical and computational work to support the experimental conceptual design of the FSE. Bulanov has been a key contributor to the field of laser matter interactions and laser proton acceleration. D. Terzani has performed the WarpX simulations presented in this proposal and A. Huebl is a principal developer of the exascale code WarpX that is developed at LBNL. Both have substantial expertise in designing particle-in-cell simulations of laser matter interactions. L. Obst-Huebl will work with Louise Willingale from the Umich, Franklin Dollar from the UCI, Douglass Schumacher from OSU, and Mingsheng Wei from LLE/UR on the technical implementation and execution of the FSE. They will apply their extensive expertise from designing and performing experiments on multiple high power laser facilities around the globe, including the design and commissioning of new experimental facilities at BELLA and ZEUS, plasma diagnostic tools and exotic target technologies, and their solid understanding of high power laser architecture and pulse characterization. The theory/simulation and experimental effort for this FSE also involves benchmarking simulation codes and testing new experimental technologies at existing laser facilities such as BELLA, ZEUS, ELI, etc. Proposals for computation time at supercomputers, e.g., at NERSC, Oak Ridge National Laboratory, and the Texas Advanced Computing Center, as well as beam time at BELLA, ZEUS, ELI, and suitable LaserNetUS facilities will be prepared by the whole team, including additional subject matter experts from the respective facilities.

Obst-Huebl, Terzani, and Huebl are all early career researchers. Additionally, 50% of the team members are from groups that are underrepresented in STEM fields. Obst-Huebl, Dollar and Willingale are members of the PAALS working group and have reviewed the community input formulated in the MP3 report [1]. All team members were selected for this FSE working group for their expertise in laser secondary particle sources and their visibility as members of the community, active in conference committees, advisory boards, and panels. The team intends to acquire additional funding to execute the research proposed here. Thanks to the diverse institutional makeup of the team, several funding sources can be envisioned. Those include and are not limited to, the Department of Energy Office of Science (DOE-SC), the National Science Foundation (NSF), the Defense Advanced Research Projects Agency (DARPA), and others. Contingent on available funds, the team intends to bring in postdocs and students to work on the FSE. The team is committed to their education and career development. Junior team members will be encouraged to present their results on this project at community workshops and conferences.

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PAALS-MM

Multi-messenger probing of ultra-intense/relativistic light-matter interactions

FSWG Leads/PI: Stepan Bulanov (LBNL), Lieselotte Obst-Huebl (LBNL)

Flagship Campaign

Estimated timeline: FY24 …………………………. FY39

Graduate and Early Career PIs

		Science Capabilities	Diagnostic Capabilities		Laser Capabilities		Target Capabilities	
		Theoretical description	i, e, e+, γ spectrometers	Radiography	Alpha 1, 2 synchronization & stabilization	Optical probe	LC PM high power operation	Jet/liquid targets
EUC 1 - Virtual twin Terzani, Bulanov, Huebl (LBNL)	FYnn_1 – FYmm_1	●	●	●		●	●	●
EUC 2 – NCD target Obst-Huebl (LBNL), Dollar (UCI)	FYnn_2 – FYmm_2	●						●
EUC 3 - MM-detect Obst-Huebl (LBNL), Willingale (UMich)	FYnn_3 – FYmm_3	●	●	●		●		
EUC 4 – Co-align Obst-Huebl, Huebl (LBNL)	FYnn_4 – FYmm_4				●	●	●	
EUC 5 – PM coupling Obst-Huebl (LBNL), Dollar (UCI)	FYnn_5 – FYmm_5	●			●		●	
Flagship: MM prob. Of ultra-intense LM interactions S. Bulanov & L. Obst-Huebl (LBNL)	FYnn_{FS} – FYmm_{FS}	●	●	●	●	●	●	●

Before NSF OPAL

First Day

Mature

Flagship

NSF OPAL Flagship Proposal Cover Page

Proposal Deadline: Friday, May 31, 2024

Title of Proposed Experiment: Extreme Fields: Testing QED in uncharted strong field regimes

Flagship Experiment Champion:

Name: Prof Stuart PD Mangles
Institution: Imperial College London, UK
Email: stuart.mangles@imperial.ac.uk
Telephone: +44 20 759 49643

Flagship Experiment Team:

Name	**Affiliation**	**Role**	**Email**
Stuart Mangles	JAI, Imperial College London, UK	Experiment	[redacted]
Tom Blackburn	University of Gothenburg, Sweden	Theory	[redacted]
Stepan Bulanov	LBNL, USA	Theory	[redacted]
Antonino Di Piazza	University of Rochester, USA	Theory	[redacted]
Elias Gerstmayr	Queen's University Belfast, UK	Experiment	[redacted]
Arkady Gonoskov	University of Gothenburg, Sweden	Experiment	[redacted]
Tom Heinzl	University of Plymouth, UK	Theory	[redacted]
Anton Ilderton	University of Edinburgh, UK	Theory	[redacted]
Brendan Kettle	Imperial College London, UK	Experiment	[redacted]
Ben King	University of Plymouth, UK	Theory	[redacted]
Eva Los	JAI Imperial College London, UK	Experiment	[redacted]
Sebastian Meuren	Ecole Polytechnique, France	Experiment	[redacted]
Chang Hee Nam	GIST, Korea	Experiment	[redacted]
John Palastro	University of Rochester, USA	Experiment	[redacted]
Chris Ridgers	University of York, UK	Theory	[redacted]
Hans Rinderknecht	University of Rochester, USA	Experiment	[redacted]
Gianluca Sarri	Queen's University Belfast, UK	Experiment	[redacted]
Jess Shaw	University of Rochester, USA	Experiment	[redacted]
Matthew Streeter	Queen's University Belfast, UK	Experiment	[redacted]
Alec Thomas	University of Michigan, USA	Theory	[redacted]
Ulrik Uggerhoj	Aarhus University, Denmark	Experiment	[redacted]

Extreme Fields: Testing QED in uncharted strong field regimes

Abstract:

We propose to use the unique multi-beam capabilities of NSF-OPAL to collide high-energy electron beams with ultra-intense laser pulses and study how the fundamental force of electromagnetism behaves when the fields are extremely strong and can no longer be described using perturbation theory. By colliding ~10 GeV electrons from a laser wakefield accelerator driven by one multi-PW laser, with the intense fields at the focus of a second ~25 PW laser pulse, we will access an uncharted regime of quantum electrodynamics where the theoretical challenges, both technical and conceptual, mean that there is no consensus on the expected behavior. We will compare the key signatures of these collisions—the electron energy loss and the production of gamma photons and electron-positron pairs—against the predictions of the best current models and provide new insight into one of the fundamental forces of nature.

Introduction/Background:

Quantum Electrodynamics (QED) is the most precisely tested theory in the Standard Model. For example, calculations of the fine structure constant, α and experiments match to 1 part in a billion. QED has been so successful because it is based on *perturbation theory, i.e.,* an expansion in the small parameter $\alpha \approx 1/137$. However, when the number of particles taking part in an interaction becomes large, perturbative methods can fail. To solve this, SFQED splits the EM field into two parts: a strong classical background, and a quantized probe field. This treats the background to all orders and includes quantum fluctuations of both light and matter perturbatively. However, if the background field strength is increased even further, the interaction with the probe field also ceases to be perturbative. Higher orders of interaction, (i.e. those including absorption and re-emission of photons and electron-position loops) become as likely as lower orders of interaction; perhaps even the identification of individual electrons or photons becomes impossible. No existing theory describes this regime. NSF-OPAL will allow us to access parameters where these higher order interactions become significant. The first experimental investigation of this unexplored regime of electromagnetism will provide new insight into the fundamental force of electromagnetism. Figure 1 illustrates the regimes of QED and where this proposed flagship experiment will operate.

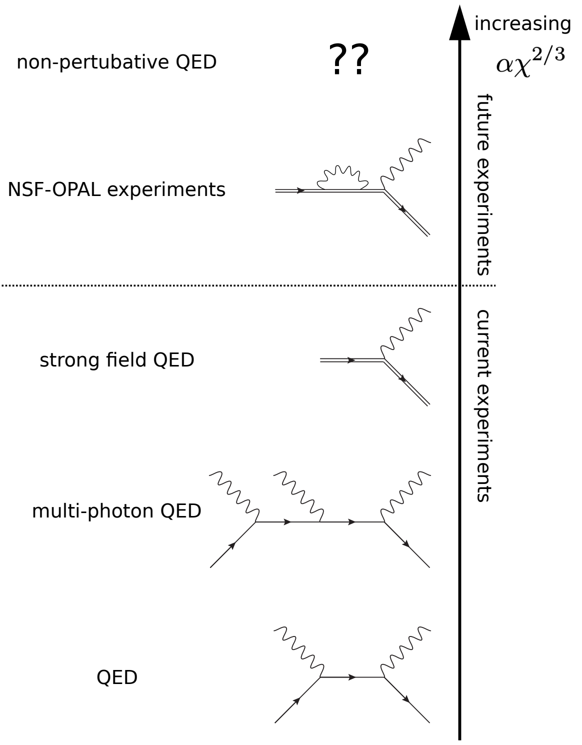

Figure 1: Regimes of QED in strong fields characterized by increasing $\alpha\chi^{2/3}$. NSF-OPAL will open access to an uncharted region.

The argument that electromagnetism could become fully-non perturbative, known as the ***Ritus-Narozhny Conjecture,*** suggests that the effective expansion parameter for SFQED is $\alpha\chi^{2/3}$, where χ is the quantum nonlinearity parameter, [Narozhny1980]. If this move to a fully non-perturbative regime is correct we expect the non-perturbative nature of electromagnetism to manifest when $\alpha\chi^{2/3} \sim 1$ (or $\chi \approx 1600$), with measurable departures from SFQED expected at $\alpha\chi^{2/3} \sim 0.1$ ($\chi \approx 50$). In the collision between an electron with energy, E and a laser of intensity I, the quantum nonlinearity

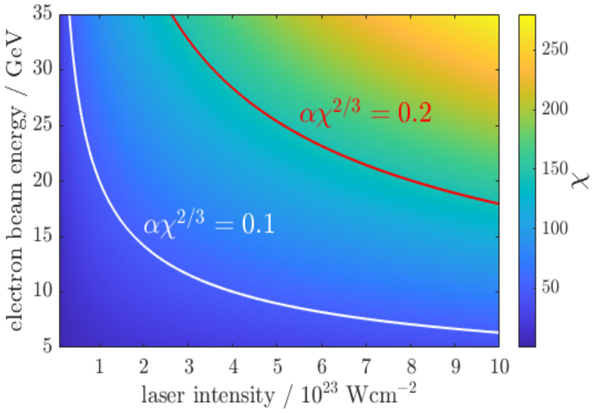

Figure 2: Variation of χ with laser intensity and electron beam energy. Contours show where $\alpha\chi^{2/3} = 0.1$ ***(white) and*** 0.2 ***(red).***

parameter (which is also the ratio of the electric field to the Schwinger field in the electron's rest frame) can be expressed as $\chi \approx 1600[E/200\,GeV][I/10^{24} W\,cm^{-2}]^{1/2}$.

Figure 2 shows the maximum value of χ reached in collisions as a function of laser intensity and electron beam energy. A 25 PW laser focused to a spot size of 3 µm (fwhm intensity, *f*/3 focusing optic) will exceed an intensity of 10^{23} Wcm^{-2}, reaching 10^{24} Wcm^{-2} when very tightly focused (*f*/1.4 focusing).

Empirical scaling based on existing results from laser wakefield accelerators (see figure 3 and table 1) predicts that a 500 J, 190 fs laser focused to 100 µm will produce electrons up to 28 GeV in an accelerator just 20 cm long.

Collisions involving a 25 PW laser focused to 10^{24} Wcm^{-2} with a 28 GeV electron beam could reach a maximum $\alpha\chi^{2/3} = 0.24$. Previous [Cole2018, Poder2018, Wistisen2019] and planned [Meuren2019, Abramowicz2021] experiments can only access $\alpha\chi^{2/3} < 0.01$ and cannot test contributions of higher-order loops to SFQED. NSF-OPAL will be able to carry out the first exploration of very high χ quantum electrodynamics.

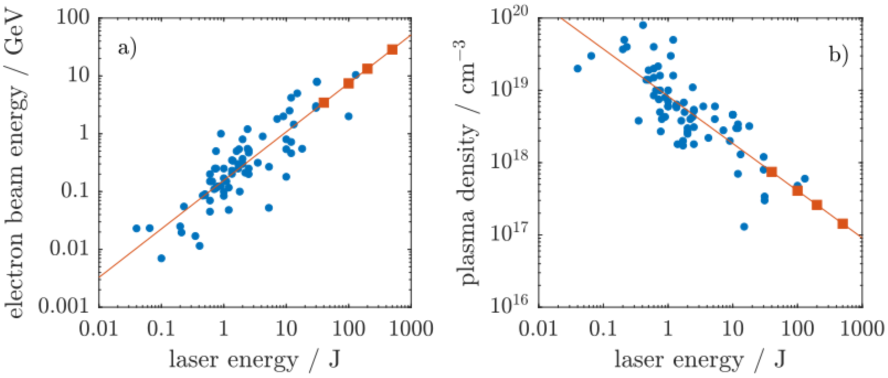

Figure 3: Empirical scaling of Laser Wakefield Accelerators with drive laser energy. a) variation of electron beam energy with laser power, b) variation of plasma density with laser power These show that a 500 J drive could produce 28 GeV electrons in a density of 1.4× 10^{17} cm^{-3} in a length of 20 cm. Data from [Mangles2016]

Scientific Proposal

A sketch of the layout for our proposed flagship experiment is shown in figure 4. One multi-PW beam is focused with a long focal length into a gas cell. This produces high-energy electrons via the laser wakefield acceleration mechanism. (See table 1 for expected parameters for different scenarios). These electrons are transported by a magnet beam line. The key experimental diagnostics will measure the products of the laser-electron collisions. The three principal diagnostics are:

1. Electron spectrometer: to measure energy loss and stochastic broadening
2. High-energy gamma diagnostic: to measure energy and angular spectrum of gamma photons
3. High-energy positron spectrometer: to measure energy spectrum of positrons.

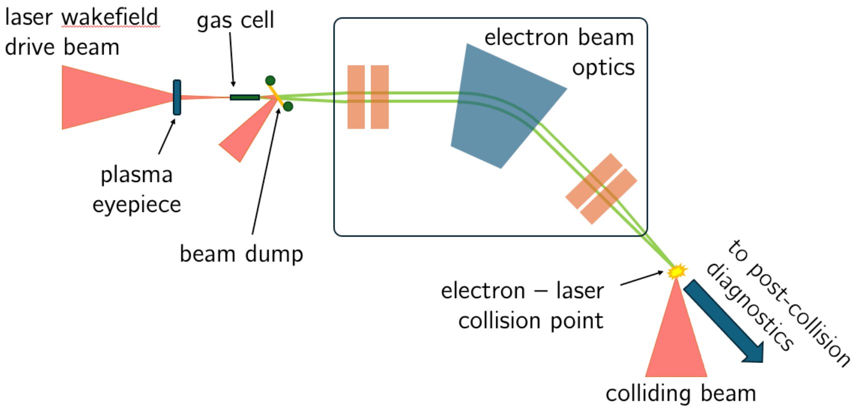

Figure 4: Schematic of the proposed experiment: One beam drives laser wakefield accelerator producing ~10 GeV electrons. A magnetic transport system selects a 1% energy spread portion of the electron beam and focusses it at the focus of a 25 PW beam. A suite of diagnostics (not shown) measure the products of the collision.

The following sections describe the work packages that are required for the experiments as well as our strategy to develop an "experiment on paper" capable of providing new insight into the fundamental behavior quantum electrodynamics in extreme fields.

WP1: Laser Wakefield Accelerator

The empirical scaling laws shown above are based on results from a wide range of laser wakefield experiments [Mangles2016]. The majority of these use the simplest experimental technique: self-guided self-injection, where a single laser pulse is focused into a uniform density gas target. The resulting plasma wave guides the laser pulse over extended distances and traps and accelerates electrons from the plasma itself.

laser wakefield driver energy /J	**plasma density / 10^{17} cm^{-3}**	**plasma length /cm**	**beam energy / GeV**	$\alpha\chi^{2/3}$ **f/3 focusing**	$\alpha\chi^{2/3}$ **f/1.4 focusing**
40	7.4	3.4	3.4	0.03	0.06
500	1.4	20.0	28.7	0.14	0.24

Table 1: Parameters of laser wakefield accelerator and achievable $\alpha\chi^{2/3}$ for two scenarios based on NSF-OPAL expected parameters. In both cases the pulse duration and focal spot are optimized for wake generation

Current plans at NSF-OPAL envision using the "beta beam" to drive the laser wakefield accelerator which is limited to ~30 J per pulse. Achieving the highest ~10 GeV energies on NSF-OPAL, needed to access high χ, may require the use of a high energy >100 J drive beam operating at pulse durations ~100 fs and focused to spot sizes ~100 µm: we must consider using the second "alpha beam" to drive the wakefield accelerator. The main constraint here will be the length of the focusing optic which can become prohibitively long. A promising solution to this problem is the "plasma eyepiece" [Zeng2020] which uses relativistic self-focusing inside a low-density plasma sheet (supplied by a gas jet) to increase the spot size and *f/*number of a more tightly focused laser. We will perform simulations and scaled experiments at lower power laser facilities to develop this elegant solution. Experiments involving a guiding structure tend to out-perform those using self-guiding, although at an increase in target and experiment complexity. We will also explore the use of suitable guiding structures, including HOFI channels [Shalloo2018] and capillary discharges [Butler2002] to select the best target options. An important part of the design process for this proposal will be a detailed modelling using particle-in-cell simulations and experiments at existing facilities to test targets and to determine the expected accelerator parameters.

WP2: Electron Transport

These experiments will need stable, narrow energy spread electron beams to allow small (10%) departures from current SFQED predictions to be observed. It is well known that it is a major challenge to produce such beams with laser wakefield accelerators. Rather than try to overcome this challenge, our strategy is instead to use conventional electron optics to transport a narrow (1%) energy spread component of the electron beam to a secondary interaction point. We will also explore the option of using the same beamline to perform gamma-photon–laser collisions by converting the electron beam via bremsstrahlung. This allows us to access different processes in high field QED involving only photons (e.g. photon splitting and the non-linear Breit Wheeler with real photons).

We will work with the John Adams Institute for Accelerator Science (JAI) and collaborators to design a suitable beamline. This will likely be based on quadrupoles to collimate the electron beam, dipole magnets to deflect the beam and perform energy selection followed by quadrupoles to focus the beam at the collision point. We aim to focus the beam to $\approx$25 μm rms radius. For a broad energy spread 10 nC beam produced by a high-energy self-guided LWFA, the energy selection and geometric difference in the beam size means approximately 2×10^6 electrons (0.3 pC) per shot will interact with the high intensity laser. If based on high-gradient permanent quadrupoles the beam transport system could be relatively compact (~5 m) but if tunability is determined to be important during the design process and electromagnets are used, the length of the beam line could become 10s of meters.

WP3: Collision point

To reach the highest χ the colliding laser will be focused to a much smaller spot size (1-3 μm fwhm) than the electron bunch (25 μm rms). Only a small fraction (1%) of the electrons delivered to the collision point will experience a strong collision field. Shot-to-shot variation in the electron beam can be monitored using the unaffected portion of the beam.

Important considerations in the design process will include: reduction and monitoring of the spatial and temporal jitter between the electron beam and colliding laser (which will need to surpass the 10 μm/10 fs level at the collision point); characterization of the intensity at focus (an existing NSF-OPAL sub-award); consideration and mitigation of energy loss by electrons in the rising edge of the laser pulse (which may require use of plasma mirrors [Dromey2004] or skewed laser pulses [Bradley2021]).

WP4: Electron spectrometer

Electrons in the collision radiate gamma-rays and hence experience energy loss and significant spectral broadening (due to stochasticity in the photon emission and spatiotemporal gradients in the laser intensity).

We will work with the JAI to design a broadband electron magnetic dipole spectrometer for 1–30 GeV electrons to characterize this energy loss and constrain models. The spectrometer will require significant lengths after the collision point (~10s meters) to deflect very high energy electrons. Key issues in the design will be ensuring sufficient resolution over the broad range and ensuring compatibility with gamma diagnostics.

WP5: Gamma-ray diagnostics

The angular distribution and spectrum of the emitted radiation carries valuable information on the electron dynamics in the field and allows one to reveal key signatures of strong-field quantum electrodynamics. Several diagnostics have been developed and experimentally tested for this type of experiments, including radiation-hard gamma-ray profilers, pair spectrometers, and long scintillator stacks [Behm2018, Fleck2020, Naranjo2021, Kettle2021, Cavanagh2023, Abramowicz2023]. We will design and develop a gamma-ray profiler based on a sapphire strip detector and a pair spectrometer to simultaneously measure, on-shot, the yield, spectrum, and angular distribution of the photon beams emitted at the interaction point.

WP6: Positron spectrometer

Gamma-photons produced in the collision can go on to interact with the laser field, producing electron-positron pairs via the non-linear Breit-Wheeler process: an iconic process in SFQED. The energy spectrum of these pairs (including the effect of cascades where the pairs also interact with the laser field) provide a sensitive diagnostic of SFQED and beyond. Our team has extensive experience in the design and implementation of this type of detectors for SFQED experiments [Kettle2021, Salgado2022]. We will develop and design a positron spectrometer. Key issues in the design will be the use of sufficiently sensitive detectors in the high noise environment.

WP7: SFQED predictions
Throughout the experimental design process, we will use the SFQED code Ptarmigan [Blackburn2023] to provide quantitative predictions of the number (and spectrum) of pairs, photons.

Preliminary 3D calculations for a collision between 25 µm rms radius, 10.0±0.1 GeV electron beam with a focused laser (3 µm 1/e^2 intensity radius) at various intensities are shown in figure 5. These show that ~10^6 positrons/photons will be produced per picocoulomb of electron beam charge.

Ptarmigan uses current methods for QED calculations in strong fields (SFQED) and is a useful benchmark for our proposed experiments; as no method currently exists to calculate the effect of higher-order loops in SFQED, the scale of the expected effect is shown as an indication only, assuming the loop contribution is $\Delta \approx \alpha\chi^{2/3}$.

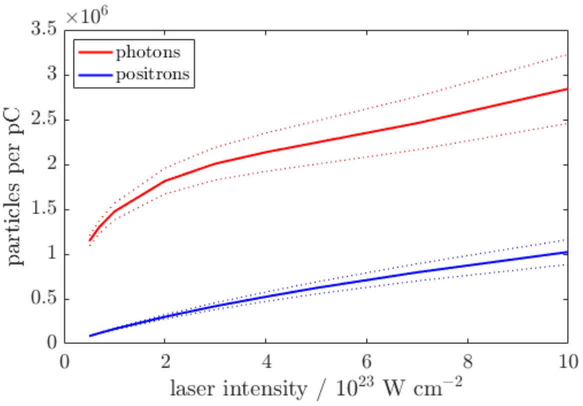

Figure 5: Predictions using SFQED for collision of 10 GeV electron beam with various intensity lasers. Red: number of photons > 100 MeV, and Blue: number of positrons, produced per pC of electron charge each collision. The dashed lines indicate the potential magnitude of the departure from current SFQED

Ptarmigan simulations will be used extensively in the experiment design process, including addressing experimental aspects such as spatiotemporal jitter between the beams and realistic pulse shapes (including skewness to reduce energy loss before electrons reach the peak intensity).

WP8: Beyond SFQED predictions
To provide accurate, testable predictions of higher-order processes in SFQED we must develop the necessary theoretical tools and investigate their phenomenology. Despite recent progress [DiPiazza2020], there remains a significant amount of work required to transform literature results at one loop into testable predictions.

The route is clear: one-loop vertex, polarization and self-energy corrections must be added to the tree-level ‘amplitudes’ describing processes of interest. Once these loop corrections, and a renormalization program, is complete, we will update existing simulation codes to include them in SFQED. These codes will then be used to provide testable predictions of experimental observables for the NSF-OPAL experiment.

We also aim to identify new, efficient methods of calculation and, ideally, of resummation, of higher order corrections. This will be essential for making progress beyond one loop. Some progress has already been made in this area [Mironov2020] and we will look to extend this.

WP9: Analysis
Our ability to interpret the novel physics we propose to investigate hinges on our understanding of the collision conditions, as the SFQED effects we aim to explore are strongly dependent on the laser intensity and electron beam properties at the collision. Uncertainties in these will be significant in the analysis.

We will address this by using a Bayesian inference approach, which provides a robust method for accounting for experimental uncertainties and is a natural approach for combining data from multiple diagnostics. We have recently demonstrated implementations of Bayesian inference for SFQED [Oloffson2023, Los2023].

Bayesian inference is also well-suited to model selection questions. Enabling meaningful questions such as “is model A a better description of the experiment than model B?” to be answered quantitatively.

This will allow us to test SFQED predictions made with and without loop corrections and allow us to properly explore this uncharted regime of quantum electrodynamics.

WP10: Signal-to-noise modellings
This experiment will require measuring relatively small signals in a very noisy environment. As well as detailed models of each diagnostic, it will be necessary to develop full start-to-end beamline simulations in MCMC codes such as Geant4 to optimize the design of the beamline in terms of signal-to-noise ratios. We have experience implementing these for laser-wakefield experiments [Ketttle2021] and have adapted Geant4 to include SFQED laser-electron collisions [Watt2020] and once available will be able to implement the corrections due to higher order effects.

Team and Resources

The international team assembled for this proposal has significant expertise across all work packages.

We have extensive experience of designing, preforming and analyzing experiments in laser wakefield acceleration, and strong-field QED experiments involving colliding beams.

Our team includes leading theoretical physicists specializing in SFQED from multiple schools who have diverse approaches to the difficult theoretical challenges. This diversity will be a key strength in developing the new theoretical capabilities needed to understand QED at very high χ.

Many of the work packages will make excellent projects for PhD students funded by our respective national and institutional programs. Involving early career researchers will help to train and secure the future user base of NSF-OPAL.

If this proposal is selected as one of the NSF-OPAL flagship experiments, developing it to a full “experiment on-paper” will require significant resource. We will support this through applications to our respective national funding bodies and relevant bi-lateral and multi-lateral schemes.

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HFP/QED

Fully non-perturbative regime of strong-field QED

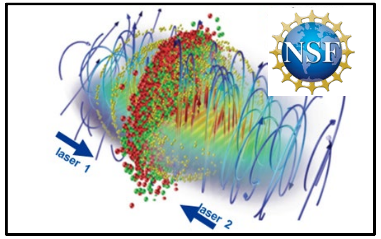
FSWG Lead/Co-PI: A. Di Piazza (UR and LLE)
Champion: S. Mangles (Imperial College, London)

Graduate and Early Career PIs

Flagship Campaign

Estimated timeline: FY24 ……………………… FY39

		Science Capabilities		Laser Capabilities			Target Capabilities		Diagnostic Capabilities			
		QED predictions for NSF OPAL	QED predictions beyond SFQED	Beta beam	Alpha (long focal length)	Alpha (short focal length)	LWFA gas target	LWFA focusing beam line	Electron spectrometer	Gamma diagnostics	Pair spectrometer	
EUC 1 LWFA: Kettle, Streeter	FY24 – FY33 (assuming starting experiments in FY32)			●	●		●		●			First Day
EUC 2 Quantum radiation reaction: Los, Gerstmayr	FY24 – FY36	●		●	●	●	●	●	●	●	●	Mature
Flagship: Stuart Mangles	FY24 – FY39	●	●	●	●	●	●	●	●	●	●	Flagship



FSWG Logo

Community Leadership and Involvement

Imperial College London
UR LLE
University of Gothenburg
University of Rochester
The University of Edinburgh
University of Plymouth
Queen's University Belfast
École Polytechnique
Berkeley Lab
University of York
The University of Michigan 1817
GIST
Aarhus University

Target Teams			Diagnostic Teams								
Team 1 (Inst.)	Team 2 (Inst.)	Team 3 (Inst.)	Team 1 (Inst.)	Team 2 (Inst.)	Team 3 (Inst.)	Team 4 (Inst.)	Team 5 (Inst.)	Team 6 (Inst.)	Team 7 (Inst.)	Team 8 (Inst.)	Team 9 (Inst.)

Undergrad, Graduate and Early Career STEM Opportunities

Appendix A4 – HFP/QED2

NSF OPAL Flagship Proposal Cover Page

Proposal Deadline: Friday, May 31, 2024

Title of Proposed Experiment:	**Stimulated Photon-Photon Scattering**

Flagship Experiment Champion:

Name: Given + Family Name	**Hans Rinderknecht**
Institution:	University of Rochester, Laboratory for Laser Energetics
Email:	hrin@lle.rochester.edu
Telephone:	216-402-5991

Flagship Experiment Team: add/delete rows, as appropriate

Name	Affiliation	Tentative Role	Email
Antonino Di Piazza	U. Rochester	Theory lead	[redacted]
Ildar Begishev	UR/LLE	2ω conversion lead	[redacted]
Seung-Whan Bahk	UR/LLE	2ω conversion theory	[redacted]
Felix Karbstein	Helmholtz Institute Jena, DE	Theory collaborator	[redacted]
Ben King	U. Plymouth, UK	Theory collaborator	[redacted]
Jörg Schreiber	LMU Munich, DE	Experimental collaborator	[redacted]
Matt Zepf	Helmholtz Institute Jena, DE	Experimental collaborator	[redacted]

Abstract: ~1,500 Character Limit (incl. spaces)

We propose to use the NSF OPAL facility to measure Stimulated Photon-Photon Scattering (SPPS), providing a first direct measurement of the nonlinearity of the QED vacuum. Stimulated Photon-Photon Scattering is a prediction of strong-field QED for the response of the vacuum to intense electromagnetic fields, in which virtual electron-positron pairs mediate scattering between photons. The scattering is a fourth-order QED process and has never been directly observed due to its low cross-section. The proposed experiments will test the hypothesis that the Euler-Heisenberg Lagrangian accurately predicts the nonlinear vacuum response to intense EM fields, and will begin to address the broader scientific question: *How can we harness the nonlinearity of the quantum vacuum?* Preliminary simulations predict NSF OPAL can produce a detectable signal of over 1000 scattered photons per shot with three input beams in either of two configurations. The Alpha-1 beam will be split and optionally frequency-doubled, then both beams will be co-focused with the Alpha-2 beam. By varying the relative power and, ultimately, focal geometry of the beams, we will rigorously assess the probability of stimulated photon-photon scattering, and explore the scattering, frequency-shifting, and birefringent properties of the nonlinear QED vacuum.

I. Introduction/Background – *briefly introduce FSE and where it sits in the current field.*

Quantum electrodynamics (QED) predicts that electromagnetic (EM) fields may interact in vacuum, with the interaction mediated by virtual pairs of charged particles and antiparticles. This so-called 'vacuum nonlinearity' is a purely quantum effect: the classical Maxwell's equations in vacuum are strictly linear. The idea that the existence of particle/antiparticle fields gives rise to nonlinear effects in the propagation of EM fields in vacuum was formulated in Refs. [1,2], where the quantum Lagrangian density of a slowly-varying EM field was determined including the quantum effects of the electron-positron "vacuum fluctuations." This is the renowned Euler-Heisenberg Lagrangian density, which was re-computed later in Ref. [3]

The space (time) scale characterizing the rapidity of variation of the electromagnetic field is determined by the reduced Compton wavelength (Compton time) $\lambda_C = \hbar/mc \approx 3.9\times10^{-11}$ cm ($\lambda_C/c = \hbar/mc^2 \approx 1.3\times10^{-21}$ sec)[1-3], with m indicating the electron mass. Since it is a relativistically-invariant quantity, it depends only on the two Lorentz invariants [4]: $F = -(1/2)(E^2 - B^2)$ and $G = -(\boldsymbol{E}\bullet\boldsymbol{B})$. The fact that the Euler-Heisenberg Lagrangian density depends nonlinearly on F and G implies that the resulting equations of motion of the EM field are nonlinear as well.

The importance of these nonlinear terms is determined by the strength of the EM field relative to the so-called critical electric and magnetic fields of QED: $E_{cr} = m^2c^3/\hbar|e| \approx 1.3\times10^{16}$ V/cm, and $B_{cr} = m^2c^3/\hbar|e| \approx 4.4\times10^{13}$ G. The critical fields exceed by orders of magnitude the most intense EM fields ever produced in the laboratory by high-power lasers: the world-record for laser intensity is presently about 1.1×10^{23} W/cm^2 [5], which corresponds to an electric field amplitude of approximately 6.4×10^{12} V/cm. This explains why vacuum-polarization effects are typically very small and challenging to measure.

Several experiments have been proposed to observe various consequences of vacuum nonlinearity. These include: vacuum-polarization effects and the related process of photon-photon scattering, the cross section of which was computed in Refs. [6-9] (see also Ref. [10]); birefringence and dichroic effects in the propagation of an EM wave through a strong laser field [11-34]; harmonic generation and photon splitting in intense laser fields [35-41]; vacuum Bragg scattering and Cherenkov radiation [42-45]; and vacuum polarization effects in plasmas [46-49]. Photon-photon scattering and related experimental proposals were analyzed, among others, in Refs. [50-57]. The above list of works is not exhaustive; we refer the reader to the reviews (Refs. [58-63]) for a more complete list of proposals. Recently, it has been claimed that vacuum birefringence was observed in the presence of the strong magnetic field surrounding a neutron star;[64] however, those conclusions have been criticized.[65]

The lowest-order nonlinear vacuum interaction between photons requires a closed fermion loop with four vertices, making it highly suppressed with respect to, e.g., electron-photon scattering. For optical photons ($\hbar\omega \approx 1$ eV), the scattering cross-section is calculated to be $\sigma_{\gamma\gamma} = [7.265\times10^{-66}\text{ cm}^2]\,(\hbar\omega/\text{eV})^6$.[66] The highest power laser system as of this writing [67] produces on the order of 10^{21} photons: if concentrating two such beams into a diffraction-limited f/1 focus, the number of scattered photons remains negligibly low ($N^2\sigma_{\gamma\gamma}/\pi R^2 \approx 2\times10^{-8}$).[68] While upper-bound results exist in the literature,[69] no realistic attempt to measure direct photon-photon scattering has been made to date.

We propose to use the unprecedented 2× 25 PW laser power of the NSF OPAL facility to measure photon-photon scattering for the first time, using the stimulated photon-photon scattering (SPPS) concept. In this design, which was first proposed in Ref. [50], three laser beams collide, one of which acts as a "stimulating" beam along which one of the two scattered photons is emitted. The SPPS process is analogous to non-linear 4-wave mixing in the quantum vacuum, and has the advantage that the scattered photon signal propagates in a known direction that is distinct from the incident lasers.[22,51,70] We predict NSF OPAL to produce a signal exceeding 1000 scattered photons per shot: this is high enough to avoid reliance on statistical methods to interpret the result, and to permit a detailed study of the SPPS interaction over a range of parameters. **If successful, this Flagship experiment will provide a direct measurement of nonlinear effects in the quantum vacuum.** These results will confirm a century-old prediction of quantum field theory. In addition, the results can constrain predictions of the mass and the coupling with photons of hypothetical particles, such as axions.[71] Axions were originally proposed to solve the so-called "strong CP" problem but are also possible candidates for dark matter. Constraints are available based on astrophysical processes but they depend, for example, on our model of the Sun.[71] Measurement of the QED process in three-beam interactions would provide an independent lab-based bound on New Physics such as axions and axion-like particles.[72] The high number of photons scattered per shot via the QED process would potentially allow for lab-based bounds that are even stronger than the current record bounds from cavity experiments such as PVLAS.[73]

II. Scientific Proposal – *Please address assessment criteria 1 in this section.*

The scattering of two real photons must simultaneously conserve momentum and energy: $\vec{k}_1 + \vec{k}_2 = \vec{k}_3 + \vec{k}_4;\ \omega_1 + \omega_2 = \omega_3 + \omega_4,$ where $\vec{k}, \omega$ are the wave-vector and frequency of the initial (1,2) and scattered (3,4) photons, respectively. For stimulated scattering, the frequencies and wave vectors of the three input beams (1, 2, 3) enforce a particular solution for the measured scattered photon (4). Additionally, the relative polarization of the input beams can modify scattering, with certain selections eliminating scattering almost completely.

For experiments at NSF OPAL, we have identified two families of experimental designs that are predicted to produce measurable scattered photon signals. In "one-color" designs, the three input beams share the same frequency ($\omega_1 = \omega_2 = \omega_3 = \omega$) and the scattered photon also has the same frequency. In "three-color" designs, two of the three beams are frequency doubled ($\omega_1 = \omega_2 = 2\omega$) and the stimulating beam is at the fundamental ($\omega_3 = \omega$), such that the scattered photon is at the third harmonic ($\omega_4 = 3\omega$). With these choices, the conservation laws result in the following constraints on the scattering geometry:

"One-color" solutions:	"Three-color" solutions:
$\vec{k}_1 = \omega[\cos\phi,\ \sin\phi,\ 0]$	$\vec{k}_1 = 2\omega[\cos\phi,\ \sin\phi,\ 0]$
$\vec{k}_2 = \omega[\cos\phi,\ -\sin\phi,\ 0]$	$\vec{k}_2 = 2\omega[\cos\phi,\ -\sin\phi,\ 0]$
$\vec{k}_3 = \omega[\cos\phi,\ 0,\ \sin\phi]$	$\vec{k}_3 = \omega[\sin\theta,\ 0,\ \cos\theta]$
$\vec{k}_4 = \omega[\cos\phi,\ 0,\ -\sin\phi]$	$\vec{k}_4 = 3\omega\left[\tfrac{1}{3}(4\cos\phi - \sin\theta),\ 0,\ -\tfrac{1}{3}\cos\theta\right]$

Here, ϕ is the half-angle between beams 1 and 2, and θ is the angle between beam 3 and the z-axis satisfying: $\theta = \arcsin(2\cos\phi - [1/\cos\phi])$. Example layouts are shown in Figure 1.

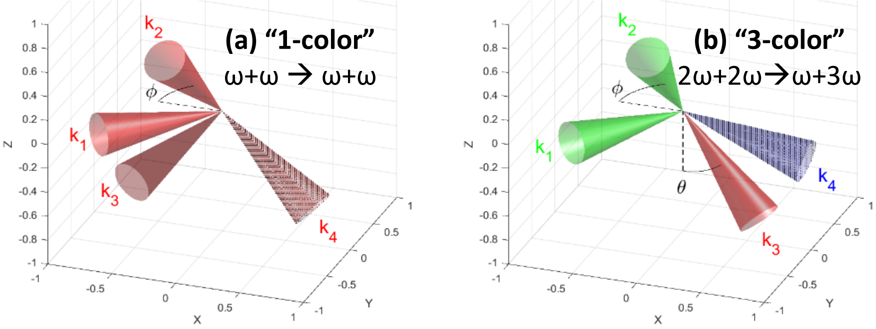


Figure 1: Layout for (a) one-color and (b) three-color scattering designs. Incident lasers (1, 2, 3) are shown focusing to the interaction point; scattered photons (beam 4, dashed) are shown exiting the interaction.

Because the center-of-momentum photon frequency scales as $(\sin \phi)$, the scattering cross-section scales rapidly with angle as $\sigma_{\gamma\gamma} \propto (\sin \phi)^6$. In general, scattering is maximized with maximally-opposing beams: for the one-color family, $\phi = 90^\circ$; for the three-color family, $\phi = 60^\circ$, $\theta = -90^\circ$. In these maximal solutions, all three incident beams lie in a plane, and the scattered photons travels directly opposite beam 3, which complicates detection. However, most of the benefit of increased scattering probability is attained with near-planar solutions. For the three-color solution, if the laser focusing optic subtends an angle less than 28° ($f/\# \geq 2$), the cones of beams 3 and 4 will not overlap for values of $\phi < 57.1^\circ$ ($\theta > -49^\circ$).

Our preliminary predictions for NSF OPAL are shown in Figure 2. We calculated scattering using a paraxial Gaussian beam model with f/2 focusing, 20 fs FWHM pulses, and optimal polarization choices. For the one-color solution, $\phi = 75^\circ$ and peak powers of [10, 10, 25] PW were assumed for beams [1, 2, 3], respectively, accounting for the loss of power due to splitting the Alpha-1 beam. A total signal of ~1960 photons with energy 1.38 ± 0.06 eV was calculated to scatter into a 20°-half-angle cone around the beam-4 vector. For the three-color solution, $\phi = 57^\circ$ ($\theta = 48.3^\circ$), and peak powers of [7.5, 7.5, 25] PW were assumed, accounting for the additional loss of power due to frequency doubling of Alpha-1. A total signal of ~3900 photons with energy 4.13 ± 0.07 eV was calculated into a 12°-half-angle cone. These signal levels are high enough to robustly measure stimulated photon-photon scattering in a single shot, and allow detailed characterization of scattering probability under various input conditions. The proposed experiments will test the hypothesis that the Euler-Heisenberg Lagrangian accurately predicts the nonlinear vacuum response to intense EM fields, and will begin to address the broader scientific question: *How can we harness the nonlinearity of the quantum vacuum?*

NSF OPAL offers a critical capability to perform this experiment, as it will deliver 5× the laser power of present facilities. The signal for SPPS scales with the product of intensity of the

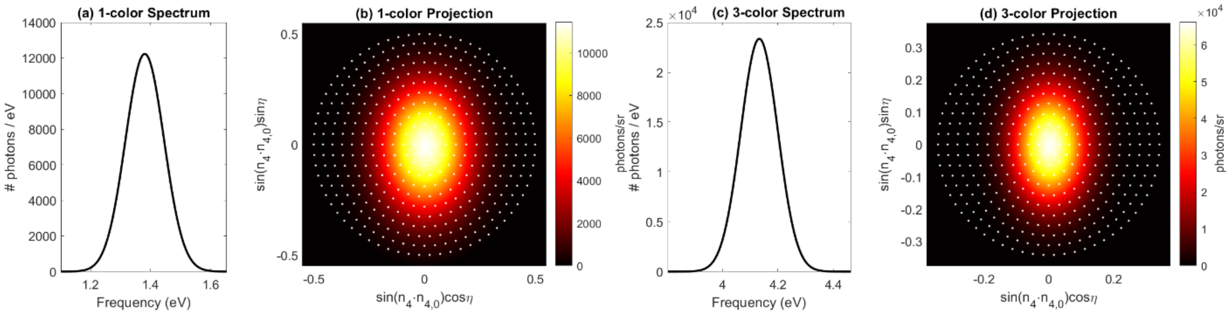


Figure 2: Calculation for (a,b) one-color solution with $\phi = 75^\circ$; (c,d) three-color solution with $\phi = 57^\circ$: (a,c) spectrum; (b,d) spatial projection of scattered photons. Spatial profile is elongated toward ±z.

three beams, so the signal at NSF OPAL will exceed the next-best capability by an estimated ~125×. This significantly increases the likelihood of a successful and significant result, and moves the experiment from the domain of "observation proof" to robust statistical testing of the Euler-Heisenberg Lagrangian hypothesis.

III. Team and Resources – *Please address assessment criteria 2 in this section. Include an NSF formatted biosketch for each team member.*

Our research team includes members from throughout the community who have the requisite expertise to design and successfully perform the stimulated photon-photon scattering experiment using NSF OPAL. **Dr. Hans Rinderknecht** (UR/LLE; champion) has fifteen years of experience designing diagnostics and laser-plasma physics experiments for the OMEGA and OMEGA-EP laser system. He will lead the experimental design team, with collaborators **Dr. Jörg Schreiber** (LMU Munich) and **Dr. Matt Zepf** (U. Jena). **Dr. Antonino Di Piazza** (U. Rochester; theory lead), **Dr. Felix Karbstein** (U. Jena), and **Dr. Ben King** (U. Plymouth) have decades of experience studying the theory of nonlinear EM interactions with the quantum vacuum. Their computational tools will be used to assess the performance of various experimental designs relevant to NSF OPAL. **Dr. Ildar Begishev** (UR/LLE; 2ω conversion lead) and **Dr. Seung-Whan Bahk** (UR/LLE) have contributed to development of critical technologies for MTW-OPAL and NSF OPAL.

Dr. Rinderknecht will mentor two students on this project during the summer of 2024. Emily Dill (UG, U. Rochester) will numerically assess the sensitivity of the SPPS signal to realistic aspects of the NSF OPAL laser system. Kadiatou Sow (UG, U. Rochester) will perform initial research and design for the required single-photon-counting detector. A graduate student will be recruited in fall of 2024 to build and qualify the prototype diagnostic on the MTW-OPAL laser at LLE by measuring scattered light from the residual vacuum chamber gas. These experiments will additionally validate the required vacuum level to successfully record SPPS signals.

IV. Paths to CDR and Flagship – *Please address assessment criteria 3 + 4 in this section*

At present, the theory of SPPS is well established in the literature. We have developed a code to calculate, for arbitrary time- and space-dependent EM fields, the spectrally- and spatially-dependent scattering signal. This code has been validated against previous results, and has been used to identify an NSF OPAL point design for both the one-color and the three-color approaches. We have performed preliminary simulations using a more realistic model of the focused square, flat-profile laser pulses that will be delivered by NSF OPAL. In these simulations, the one-color scattering was reduced by 0.7× ($N \approx 1360$ photons), and the three-color scattering was increased by 1.3× ($N \approx 4970$ photons); additionally, the spatial pattern of the scattered light was altered. During 2024, we will use this simulation tool in consultation with the laser team to address requirements for co-timing, co-pointing and polarization of the three laser pulses. We will also compare with our collaborators' codes [74] to validate and confirm the results.

The results of this study will establish requirements for the detection system. The detector must be capable of robustly measuring $N \approx 1000$ scattered photons in a narrow energy band (1ω or 3ω), while rejecting the background of photons produced by the NSF OPAL lasers. To accomplish this, the detector must be isolated spatially, temporally, and spectrally as much as possible from the background. In addition, the detector should measure polarization of the scattered signal, which is sensitive to vacuum birefringence.[75] These requirements will inform the selection of a detector technology. We anticipate the measurement will be more challenging in the one-color design, as the signal has the same frequency as the lasers. Thomson or Compton scattering of light from residual gas in the vacuum chamber will also produce background. On the basis of prior work,[76] we estimate that a vacuum below 10^{-8} torr is required to reduce this source of background to below the scattering signal. Collimation of the detection angle and shielding the detector field-of-view will reject photons from outside the scattering volume.

Initial research into detector designs during the summer of 2024 will lead to the construction of a prototype, which will be used to improve our estimates of the experimental requirements. Scattering of the focused MTW-OPAL laser from residual gas will be measured by the prototype detector as a function of the chamber pressure. This study will characterize the performance of the detector's spatial and temporal isolation, and will inform the requirements on vacuum pressure to perform the SPPS experiment at NSF OPAL. We will use this capability to test detector improvements, such as implementation of beam dumps or isolation baffles to reduce background, that will inform the system requirements for the NSF OPAL experiment.

A critical developmental component of the preferred three-color design is second harmonic generation (SHG) of PW-intensity beams. We calculate an estimated conversion efficiency of 60% for SHG of an OPAL beam with wavelength of 850-1010 nm (full width at 10%). Due to the ultra-short pulse duration of 20 fs, the proposed OPAL beams would require extremely thin (350 µm) and large (85 cm x 85 cm) nonlinear crystals. One approach is to support the thin, large-aperture crystal using a thick substrate; however, the ultra-high intensity beam cannot be propagated through the substrate, as that would introduce dramatic self-modulation. We propose to demonstrate a novel 2ω conversion scheme, in which a thin KDP crystal and supporting substrate are separated by a high reflection (HR) coating. We consider two designs: either SHG occurs after the 1ω OPAL beam reflects from the HR coating, or SHG occurs on the first pass and the 2ω light is reflected. In either case, the 2ω pulse avoids significant self-modulation. In 2024, an adhesive that is tolerant to high intensity damage will be developed to attach the thin crystal to the substrate, and a fabrication method for the large aperture, ultra-thin nonlinear crystals will be developed, in collaboration with LLE's Optics Manufacturing group. During FY'25, the SHG technique will be tested at full intensity using the MTW-OPAL laser. This work will be led by Dr. Ildar Begishev (LLE). The results of this study will provide valuable data regarding the achievable quality of the 2ω-converted Alpha-1 beam, and will be used to make a final determination as to which design of the SPPS experiment will be pursued on NSF OPAL.

Concept of operations: The SPPS experiment on NSF OPAL will be designed to record the scattered photon signal ($N > 1000$) from single shots. This experiment will be performed in Experimental Area 1 and will make use of the Alpha-1 and Alpha-2 beams at full power. The Alpha-1 beam will be split using a mask and novel steering optic (with expected loss of ≤ 10% of power) and focused to intersect with the focused Alpha-2 beam at the specified angles. If 2ω conversion of the Alpha-1 beam is feasible, we will use this capability to perform the "three-color" experiment; otherwise, we will perform the "one-color" version. The experiments include no targets, no secondary sources, and generate no ionizing radiation hazard (high-energy electrons, ions, x-rays) in the experimental area.

The campaign will begin with shots of each beam at reduced power and controlled residual gas pressure to verify beam co-timing, co-pointing and detector alignment. We will then collect data using individual full-power beams, to verify background level and introduce additional mitigations, if necessary. We will proceed to three-beam shots, collecting data from tens to hundreds of shots to observe scattering signal and characterize shot-to-shot variations. These results will provide the first direct measurement of a nonlinear vacuum QED effect. We will then vary the relative beam power of individual beams, to assess the predicted dependence of scattering probability. Modifying beam polarization would also be valuable. In follow-on campaigns, we may modify the geometry of the interaction by adjusting the final focusing optic of the split Alpha-1 beam: the scattering angle alters the center-of-mass frequency of the photons to probe the predicted (ω^6) dependence of the scattering cross-section.

Primary Risks and Mitigations: The first risk is in frequency-doubling the Alpha-1 beam. This simplifies detection of the scattered signal by spectrally isolating it from the laser frequency; however, it is a technical risk that has not yet been demonstrated at full intensity. Dr. Ildar Begishev will demonstrate and characterize SHG of a compressed pulse using the MTW-OPAL laser. If 2ω conversion is impractical, the one-color scattering experiment will be pursued.

The second risk is in sufficiently co-timing and co-pointing the three beams. Our experimental scheme involves splitting beam Alpha-1 and co-focusing both halves to intersect the focused Alpha-2 beam. All three beams must be focused with high-power optics (we have assumed f/2) to produce near-diffraction-limited beam spots (on the order of 1-micron). Scattering will only occur when these beams overlap in space and time. The requirements for pointing and timing stability will be quantified in numerical studies during the summer of 2024. We will also assess the beam pointing stability in low-power experiments to statistically evaluate the distribution of the expected overlap results.

The third risk is in robustly measuring a signal of the order of 1000 photons. The use of the three-color design mitigates this risk by significantly reducing the background at the signal frequency. We are otherwise mitigating this risk by beginning detector research and development during 2024, and recruiting a graduate student to continue this work starting in fall of 2024. We will validate the detector and background suppression methods using the MTW-OPAL laser throughout the course of the project.

Prospects for Grant Support: The design project of the single-photon-counting detector, related background-suppression methods, and the experiments to measure scattered light of the MTW-OPAL laser from residual gas represent an opportunity to pursue outside grant support. This project will be led by a graduate student mentored by Dr. Hans Rinderknecht. The project to demonstrate frequency doubling of the MTW-OPAL beam post-compression, which will be led by Dr. Ildar Begishev, represents another opportunity for outside grant support.

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HFP/QED

Stimulated Photon-Photon Scattering

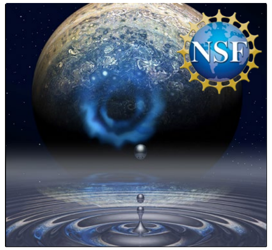
FSWG Lead/Co-PI: Antonino Di Piazza (U. Rochester)
Champion: Hans Rinderknecht (U. Rochester)

Graduate and Early Career PIs

Flagship Campaign →	Estimated timeline: FY24 ……………………… FY39	Science Capabilities			Laser Capabilities			Target Capabilities	Diagnostic Capabilities	
		Realistic beam simulations	Sensitivity & optimization	Residual gas scattering	Alpha-1 2ω conversion	Background mitigation	Cotiming / Copointing	Vacuum 1e-8 torr	Single-photon detector	Background mitigation
EUC1: Detector R&D H. Rinderknecht, TBD GS	FY24 – FY25	●	●						●	
EUC2: MTW-OPAL 2ω conversion I. Begishev, S.-W. Bakh	FY25 – FY26				●					
EUC3: Residual gas scattering study H. Rinderknecht, TBD GS	FY25 – FY27		●	●		●		●	●	●
Flagship: Stimulated Photon-Photon Scattering H. Rinderknecht (UR/LLE) + A. Di Piazza (UR)	FYnn_{FS} – FYmm_{FS}	●	●	●	●	●	●	●	●	●

First Day → Mature → Flagship

Community Leadership and Involvement


FSWG Logo

University of Rochester
UR LLE
Helmholtz
Helmholtz Institute Jena
University of Plymouth
LMU
Ludwig-Maximilians-Universität München

Laser Teams	Diagnostic Teams
Begishev (LLE)	Rinderknecht (LLE) Schreiber (LMU) Zepf (HI Jena)

Undergrad, Graduate and Early Career STEM Opportunities

pairs. This renders the precursor of avalanche-type (or selfsustained) QED cascades characterised by an exponential particle number growth. To achieve this, we propose to focus strongly two NSF OPAL Alpha-beams with the peak power in a (transparent for the laser) gas jet of heavy-atomic gas (e.g. Argon). The initial electrons will result from the ionization process. The study of outgoing photon radiation and electron spectral features will allow identifying the radiation-domination regime, whilst registering positrons will give strong evidence of a QED avalanche onset.

NSF OPAL Flagship Proposal Cover Page

Proposal Deadline: Monday, June 3, 2024

Title of Proposed Experiment: Testing strong-field QED with the avalanche precursor

Flagship Experiment Champion:
Name: Gianluca Gregori
Institution: Department of Physics, University of Oxford
Email: gianluca.gregori@physics.ox.ac.uk
Telephone: +44 (775) 626-4658

Flagship Experiment Team: add/delete rows, as appropriate

Name	Affiliation	Tentative Role	Email
S. S. Bulanov	LBNL, CA, USA	Theory	[redacted]
A. Di Piazza	LLE, University of Rochester, NY, USA	Theory	[redacted]
M. Grech	CNRS, LULI, École polytechnique, France	Simulations	[redacted]
L. Lancia	CNRS, LULI, École polytechnique, France	Experiment	[redacted]
S. Meuren	CNRS, LULI, École polytechnique, France	Experiment	[redacted]
A. Mironov	LULI, Sorbonne University, France	Theory	[redacted]
J. Palastro	LLE, University of Rochester, NY, USA	Theory	[redacted]
C. Riconda	LULI, Sorbonne University, France	Theory	[redacted]
H. G. Rinderknecht	LLE, University of Rochester, NY, USA	Experiment	[redacted]
P. Tzeferacos	LLE, University of Rochester, NY, USA	Simulations	[redacted]

Abstract: ~1,500 Character Limit (incl. spaces)

The NFS OPAL facility will deliver extreme optical fields that will allow probing, for the first time, a fundamentally new regime of the electromagnetic radiation interaction with matter when the dynamics of electrons is dominated by quantum radiation reaction and light can be transformed into high-brilliance gamma radiation and even electron-positron pairs. Electrons injected into the mutual focus of two multi-PW counterpropagating laser pulses can be repeatedly accelerated by the extreme electric field to GeV-scale energies at a sub-cycle time, with a rapidly increasing probability rate to emit high-energy photons causing strong recoil. With 3D PIC-QED simulations, we show that in two laser pulses with a total power >40 PW, the energy transferred to high-energy photons exceeds that of electrons by an order of magnitude. At increasing power, a fraction of photons can also create secondary electron-positron

NSF Opal: Testing strong-field QED with the avalanche precursor

A. Mironov,[1] S. S. Bulanov,[2] A. Di Piazza,[3] M. Grech,[4] L. Lancia,[4] S. Meuren,[4]
J. Palastro,[3] C. Riconda,[1] H. G. Rinderknecht,[3] P. Tzeferacos,[3] and G. Gregori[5]

[1]Laboratoire pour l'Utilisation des Lasers Intenses,
Sorbonne Université, CNRS, CEA, Ecole Polytechnique,
Institut Polytechnique de Paris, Paris, France
[2]Lawrence Berkeley National Laboratory, Berkeley, CA
[3]University of Rochester, Laboratory for Laser Energetics, Rochester, NY
[4]Laboratoire pour l'Utilisation des Lasers Intenses,
CNRS, Sorbonne Université, CEA, Ecole Polytechnique,
Institut Polytechnique de Paris, Palaiseau, France
[5]Department of Physics, University of Oxford, Oxford, UK

Scientific merit. The electromagnetic (EM) or QED cascade is probably one of the most fascinating phenomena of the strong-field QED. Naturally, such cascades can onset in extreme astrophysical environments near compact stars [1–3], and they can play an important role in the formation of the brightest gamma-flash events in the Universe [4]. A QED cascade is the process of electron, positron, or photon energy transformation during their interaction with a strong EM field into multiple secondary particles [5–7]. While this transformation can take different forms, depending on field configuration and origin, as well as the initial distribution of charged particles and photons, there are two basic types: the *shower* and the *avalanche* cascades. The former is characterized by the fact that the initial energy of charged particles (or photons) entering the strong field region is transformed into secondary particles. Thus, the total energy of all particles, initial and secondary, remains roughly constant during the interaction [8–10]. In the latter, charged particles are continuously re-accelerated (both initial and secondary ones) by the EM field [11, 12] (see Fig. 1). In this case, the total particle energy grows over time exponentially as it is drawn from the field. Both cascades operate in the so-called *radiation dominated regime* of interaction when the charged particle dynamics in strong EM fields is dominated by the radiation it emits. However, the avalanche-type cascading process has never been observed experimentally. Notably, the development of avalanches in polar caps of rotating neutron stars can potentially explain radio-pulsar emission [13].

In order to access the QED-plasma regime through avalanche-type cascades and probe the transition of the interaction from the particle dominated to radiation dominated, a facility capable of delivering at least two colliding laser pulses to the interaction point at extreme intensities is needed. Assuming focusing to a spot-size of order of a wavelength, the laser power should satisfy $P_{laser}[PW](\lambda_{laser}[\mu m])^{-1} \gg 10$ to achieve that, which brings the total facility laser power into 10s to 100s of the PW domain (see Fig. 1).

The onset of a QED avalanche in a strong field requires [15] (i) a field configuration that can accelerate electrons and positrons to relativistic energies *and* induce the key quantum processes for these particles (the nonlinear Compton emission and Breit-Wheeler pair

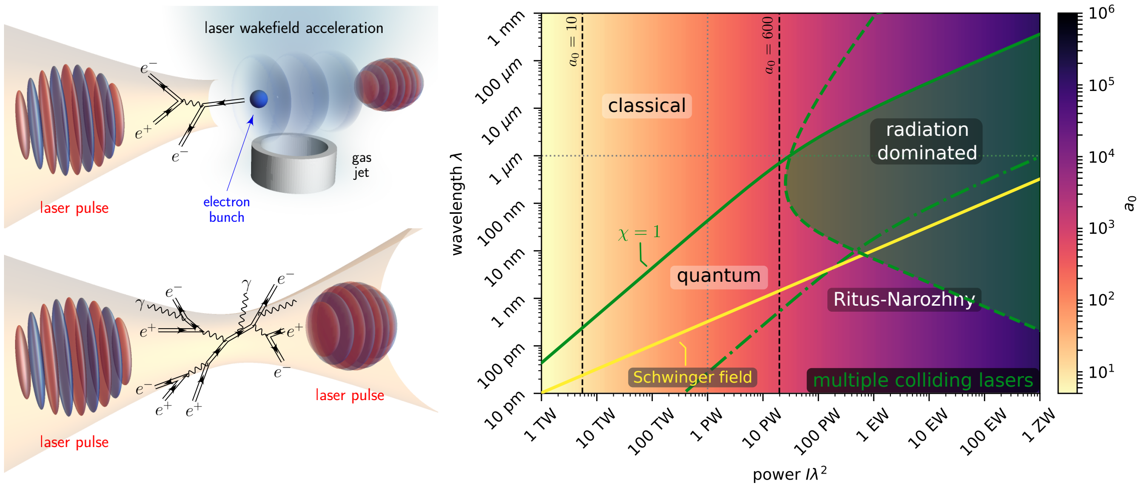


FIG. 1: Left: Principal experimental schemes aimed at the study of nonlinear QED: (upper panel) laser–electron-beam interactions (all optical setup). (lower panel) colliding laser pulses. Adapted from [6]; Right: The map of different regimes of laser-particle interactions depending on what laser power and wavelength is used in the case of colliding pulse configuration. The radiation dominated regime is reached around 30 PW and 1 μm. A 2 μm spot size is assumed. Adapted from [14].

production) at a sub-cycle scale; (ii) injection of seed particles into the high-field region. The former can be achieved in alternating *electric* fields. For laser fields, an avalanche can onset in magnetic nodes of a standing wave formed at the mutual focus of (at least) two synchronized counter-propagating laser pulses as shown in Fig. 1. In this case, the threshold total laser power is $P_{laser} \gtrsim 25$ PW for laser pulses focused to the diffraction limit ($f/1$) [16]. Among the existing suggestions for particle injection, one of the least technically stringent is ionization of a heavy-atomic number noble gas jet [17]. The inner atomic shells are ionized only by a strong field at the focal spot, hence the resulting electrons can serve as the cascade seed.

Description of the avalanche precursor experiment. The peak field strength is the key parameter for reaching the radiation dominated interaction regime and QED avalanches. Under the expected parameters at NSF OPAL, this can be achieved by combining two counter-propagating synchronized and mutually focused Alpha-beams with (i) maximum power ($P_0 = 25$ PW each beam), (ii) focused to the best possible degree (at least $f/2$, preferably stronger), (iii) with aligned polarization axes in order to form a standing electromagnetic wave. For these parameters, the maximum combined dimensionless peak field strength can be as high as $a_0 \approx 1100$ for the focusing $f/2$ (2.1 μm at FWHM) and $a_0 \approx 1500$ for $f/\sqrt{2}$ (1.48 μm). These values for a_0 are around the threshold for the avalanche onset [18, 19], ensuring that (at least) we can observe the *avalanche precursor* [9]. The avalanche precursor is defined as the regime where the efficient generation of high energy photons by electrons oscillating in the EM field of two counter-propagating laser pulses is powered by the continuous re-acceleration of these electrons, but the field strength is not high enough to facilitate copious production of electron-positron pairs from these photons. Lastly, we assume the laser pulse duration is 20 fs FWHM.

To initiate the process, we propose illuminating a gas jet of $_{18}$Ar of density 10^{19} cm^{-3}

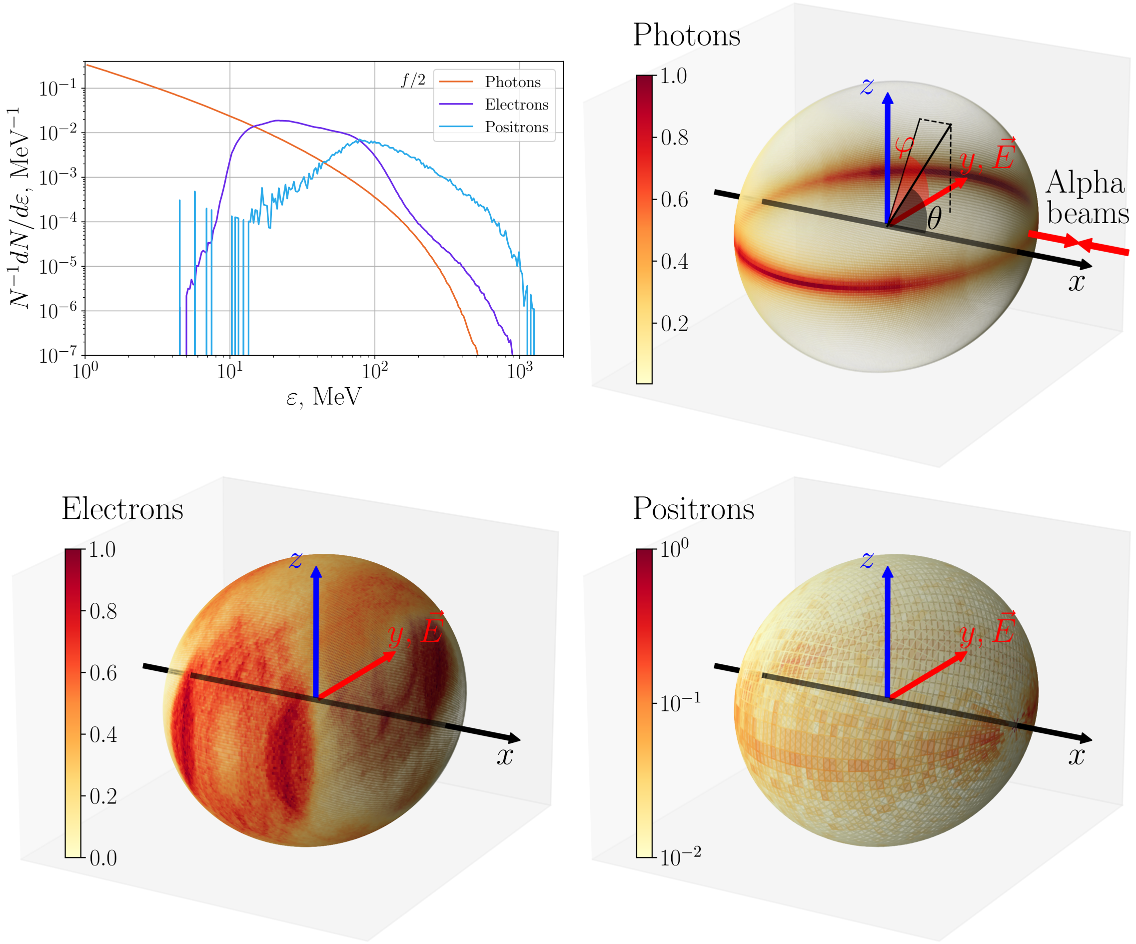


FIG. 2: Normalized particle spectra and angular distributions ($d^2N/\sin\theta d\theta d\varphi$, in a.u.) after the interaction. The polar angle θ is counted from the x-axis aligned with the laser propagation direction, φ is the azimuthal angle in the (y, z)-plane. The positron angular distribution is shown in the logarithmic scale. The parameters of each Alpha-beam are $P_0 = 25$ PW, $f/2$.

(see also Fig. 1), which is feasible with current technology. Argon will be fully ionized in the focal spot, and this will provide a large amount of seed electrons. At this density the ionized gas remains transparent to the laser, therefore not distorting the driving field. In addition, a gas jet is suitable for high-repetition shots.

We performed 3D Particle-In-Cell simulations of the described setup with the code SMILEI [20]. It allows for Maxwell-consistent modelling of the strongly focused laser pulse propagation and accurate treatment of the nonlinear quantum processes of photon emission by $e^{\pm}$, $e^{-}e^{+}$ pair creation, and multi-photon ionization.

The signatures of the radiation domination interaction regime and the onset of a cascade can be extracted from particle spectra. The energy spectra and directional distributions of high-energy photons (> 1 MeV) and $e^{\pm}$ after the interaction are shown in Fig. 2. Photons are predominantly emitted in the plane of the electric field polarization. While electrons are scattered much wider than high-energy photons, our simulations show that the produced positrons on average co-propagate with photons. This defines the optimal placement of the particle detectors.

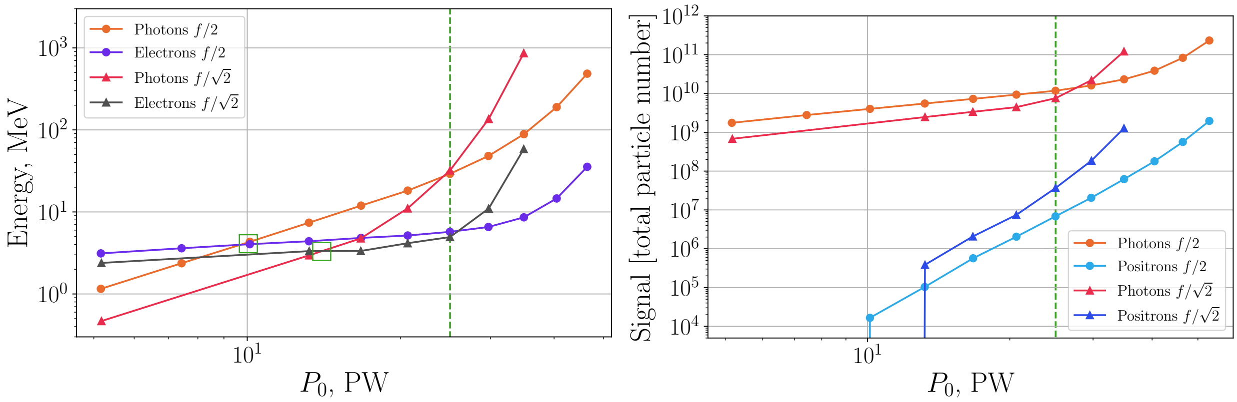


FIG. 3: Left: Average energy (per seed electron) of photons and electrons propagating in a narrow azimuthal angle opening $-0.1\pi < \varphi < 0.1\pi$ as a function of P_0 (the electric field is directed along $\varphi = 0$, see Fig. 2). The overlap between the lines corresponding to the photon and electron energy (shown by the squares) signifies the transition to the radiation domination regime. Right: Total number of photons and positrons in the interaction area as a function of the power P_0 of one Alpha-beam. The initial seed electron number corresponds to fully ionized Ar of density $n_0 = 10^{19}$ cm^{-3}. The vertical dashed line corresponds to $P_0 = 25$ PW.

Fig. 3 summarizes the predicted detected quantities as a function of the laser power. The measurement of the average energy per particle collected in the electric field polarization plane can signal the emergence of the quantum radiation domination regime. As shown in the left plot, when the laser power is increased, the average emitted photon energy exceeds the electron energy. Note that the overlap is well below the peak power of $P_0 = 25$ PW, meaning that the *deep* radiation domination regime is in fact accessible in the proposed experiments. At $P_0 \gtrsim 20$ PW, the energy transferred to photons exceeds that of electrons by an order of magnitude.

The exponential growth of the particle number and energy signifies the onset of an avalanche. For the $f/2$ focusing, the point $P_0 = 25$ PW is near the threshold of such dependence. The stronger focusing ($f/\sqrt{2}$) will allow observing the exponential increase of the signal with P_0 in the parameter range of NSF OPAL. This can be clearly seen for particles propagating in the electric field polarization plane, as the particles generated in the cascade are predominantly accelerated in this direction.

Finally, the ultimate signature of the avalanche onset would be the measurement of positrons. We believe that under given NSF OPAL parameters the positron number will be sufficiently large (see the right plot in Fig. 3) to be in principle measurable [21].

Flagship experimental team. The current team members and roles are:

- A. Mironov, M. Grech, P. Tzeferacos: Particle-in-cell and hydrodynamic simulations;
- A. Di Piazza, J. Palastro, S. Bulanov, A. Mironov: High-field and cascades theory;
- H. Rinderknecht, L. Lancia, S. Meuren, G. Gregori: Experimental implementation and planning.

This team includes established scientists able to provide resources for all phases of the proposed project: 1) established theoretical and computational expertise in support of the experimental conceptual design; 2) advanced laser-diagnostics experience demonstrated in a variety of facilities in the US and abroad. Moreover, the current team has all the required capabilities to perform prototyping and test experiments at ultra-high intensity laser facilities such as Zeus (University of Michigan), ELI (EU), Apollon (LULI, France), EPAC (RAL, UK) or the upgraded Vulcan laser at RAL (UK) - where some of the concepts discussed in the present proposal could be investigated (albeit only with a single beam configuration). The current team members are active and recognized leaders in high-intensity laser-plasma theory, computation and experiments. However, we also realize that in order to complete successfully the proposed tasks we will need to further expand the present team, particularly with a dedicated student(s), scientist(s) and/or postdoc(s) that can commit a significant fraction of their time on this project.

Path to CDR. At present, the size and composition of the team are sufficient to start the initial design phase for the proposed experiments. However, as we progress towards CDR several points need to be addressed. These are:

1. Realistic multi-scale simulations of the 25 PW beam interaction with the gas target. These should include the effect of prepulse, laser-plasma interaction processes, and would likely require a combination of radiation-hydrodynamics simulations and particle-in-cell (PIC) ones, or possibly some hybrid simulations. While the present team composition includes an expert in running radiation-hydrodynamic codes (FLASH), these effects have not yet been studied and they are on the critical path for the next few months.

2. The current PIC simulations need to be run in full 3D geometry to capture the exact beam orientation, pointing errors and overlap. We will also study whether exact counter-propagating beams are needed or having them cross at an angle <180° would still achieve all the scientific goals of this proposal. This can be important if a counter-propagating configuration is not immediately available at NSF Opal. The simulations will include calculations of the photon, electron and positron angularly-resolved energy spectrum, and they will inform on realistic signal intensities we expect to obtain in the proposed experiments.

3. We would also need to perform a full Monte Carlo simulation with FLUKA (or GEANT4) of the entire interaction chamber, including various diagnostics configurations. These FLUKA simulations will take the calculated particle and photon outputs from PIC simulations and estimate all possible sources of background, assessing the feasibility of the measurements - whether single or multiple shots will be needed for high confidence positive detection.

4. Finally, We need to develop all the required diagnostics for the experiment. While this task is expected to be common to other NSF OPAL proposals, there are specific requirements unique to the present one. In particular, we need to have both

electron/positron spectrometers as well as gamma-ray detectors working in the range 10–1000 MeV with about 1% energy resolution. The development of these detectors is not trivial, but it could be based on some preliminary designs already developed on other laser facilities [22].

We believe that the timeline for tasks 1 and 2 is one year. Once these are completed, we intend to write a white paper that describes the whole experimental proposal. This is important as it will allow us to receive further feedback from the international scientific community, and decide whether amendments are needed on the final CDR. Completion of items 3 and 4 will go in parallel with the design progress of the whole facility, and it is difficult to put exact timescales at this point. However, those tasks are essential for finalizing the CDR. Again, we expect to have another publication submitted to peer review when tasks 3 and 4 are finalized.

Path to flagship experiments. As discussed above, we would require additional students and, in particular, a dedicated postdoc (or a facility researcher) to work for a significant fraction of their time on this project. After CDR is completed, we expect this dedicated scientist to lead the day-to-day planning of all the experimental components and provide feedback to the theory/simulation group and the NSF OPAL facility to finalize the commissioning of all the required components for the experiment.

Moreover, preparatory experiments can be performed at current facilities either with only one high-intensity laser beam or with two (like at ELI NP) but below the threshold in Fig. 3. In the one-beam setups, we can explore the case of beam-solid interaction as a first step towards the avalanche precursor [23], such that the regenerating feature of the avalanche process is not present and the pair production is complicated by concurrent plasma screening effects [23]. In the two-beam setups, we can address important experimental issues like beams co-timing and overlap.

We are currently investigating various options on how to proceed, but an obvious path forward is for this team to submit proposals to NSF in the US, UKRI in the UK (and possibly ERC in the EU) to support all the preparatory work. In parallel, we also aim to submit dedicated proposals to various laser facilities (e.g., Zeus, ELI, Apollon and EPAC) to start developing the experimental programme and provide meaningful data against which our kinetic models can be tested and validated.

Conclusions. In summary, the proposed experiment will be able to access, for the first time, the strong-field QED regime at the boundary between the particle-dominated to radiation-dominated interaction – thus providing a platform to test and validate models for high-intensity QED. This is a truly unexplored regime that can also be found near compact stars featuring strong magnetic fields - and it is somehow likely that our current theoretical modelling will have to be refined once accurate data is obtained. We expect our work will increase public scientific literacy and public engagement with STEM - many of our team members have expertise in this. GG, for example, has led a Royal Society Summer of Science event to publicize laboratory astrophysics to the general public and high-school pupils. We envision that similar activities can be undertaken in the present activities and more catered towards the US audience.

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HFP/QED3

Testing strong-field QED with the avalanche precursor

FSWG Lead/Co-PI: A Di Piazza (U. Rochester)
Champion: G Gregori (U. Oxford)

Flagship Campaign

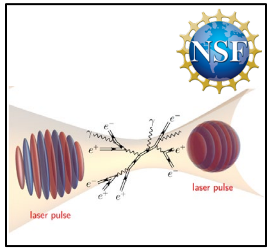
Approximate timeline: FY24 ……………………… FY39

Graduate and Early Career PIs

		Diagnostic Capabilities										Laser Capabilities		Target Capabilities					
		XRPHCs, X-ray streak	VISAR / SOP	Broadband reflectivity	SPC, XRS	e^-/e^+ spectrometer	Gamma flash	XAS, EXAFS, XANES, …	X-ray imaging	Betatron	Diffraction	UV/ns pulses	1ω Alpha	Planar Foils	EOS Packages	Structured Foils	Gas jet	f/2 focussing	f/1.4 focussing
EUC1 – Double pulse overlap Palastro (UR/LLE), Meuren (LULI)	**FYnn$_1$ – FYmm$_1$**	●							●			●	●	●			●		
EUC2 – Gamma FLASH Mironov (Sorbonne), Rinderknecht (UR/LLE)	**FYnn$_2$ – FYmm$_2$**					●	●		●			●	●	●			●	●	●
EUC3 – Pair Plasmas Mironov (Sorbonne), Lancia (LULI)	**FYnn$_3$ – FYmm$_3$**					●	●		●			●	●				●	●	●
Flagship: Avalanche Precursor A Di Piazza (UR/LLE)	**FYnn$_{FS}$ – FYmm$_{FS}$**	●				●	●		●			●	●	●			●	●	●

First Day → **Mature** → **Flagship**

Community Leadership and Involvement



FSWG Logo

Target Teams			Diagnostic Teams								
Team 1 (Inst.)	Team 2 (Inst.)	Team 3 (Inst.)	Team 1 (Inst.)	Team 2 (Inst.)	Team 3 (Inst.)	Team 4 (Inst.)	Team 5 (Inst.)	Team 6 (Inst.)	Team 7 (Inst.)	Team 8 (Inst.)	Team 9 (Inst.)

Undergrad, Graduate and Early Career STEM Opportunities

NSF OPAL Flagship Proposal Cover Page

Proposal Deadline: Friday, May 31, 2024

Title of Proposed Experiment: Ultrafast laboratory astrophysics and planetary physics

Flagship Experiment Champion: Danae Polsin
Institution: University of Rochester
Email: dpol@lle.rochester.edu
Telephone: +1 (585) 273-2631

Flagship Experiment Team:

Name	Affiliation	Tentative Role	Email
Eva Zurek	Univ. at Buffalo	Theory	[redacted]
Michael MacDonald	LLNL	Experiment	[redacted]
Heath LeFevre	U Michigan	Experiment	[redacted]
Hui Chen	LLNL	Experiment	[redacted]
Mianzhen Mo	Stanford	Experiment	[redacted]
Stefano Racioppi	Univ. at Buffalo	Theory	[redacted]
Ji Hoon Kim	Cornell	Experiment	[redacted]
G. W. Collins	LLE	Experiment	[redacted]
J. R. Rygg	LLE	Experiment	[redacted]
Arnold Schwemmlein	LLE	Experiment	[redacted]

Abstract: ~1,500 Character Limit (incl. spaces)

The Laboratory Astrophysics and Planetary Physics (LAPP) Flagship capability aims to examine materials under intense pressure, 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. To understand the origin, nature, and evolution of these planets and astrophysical objects, it is necessary to understand the properties and evolution of high energy density matter. The LAPP Community seeks to combine three cutting-edge capabilities offered by NSF OPAL: dynamic compression, impulsive heating, and ultrafast probing. We present three stages of experiments leading to the flagship experiment: (1) the NSF-OPAL Alpha short-pulse beams will be activated at 1ω and 2ω to create laser-produced relativistic pair plasmas in a new intensity regime; (2) dense plasma spectroscopy experiments will be performed where the NFS-OPAL Alpha beams will be used to isochorically heat shock- and ramp-compressed targets to explore a wide range of temperatures and densities using high-resolution x-ray emission and absorption spectroscopy; (3) the OMEGA EP long-pulse UV beams will be activated to ramp-compress planetary materials (ex. SiO_2, H_2O, Fe) to conditions inside the cores of planets. This staged approach will lead to the flagship capability to shock and ramp-compress these planetary materials to terapascal pressures and use the femtosecond PW beams to create ultrafast probes for time-resolved x-ray and electron diffraction, radiography/phase contrast imaging, and x-ray emission and absorption spectroscopy to identify structural and electronic phase transitions and unravel their nonequilibrium dynamics. These experiments will answer key questions spanning the existence of exotic low temperature quantum phases to the high-temperature plasma opacity of stellar components at HED conditions.

Introduction/Background – A new generation of experimental capabilities makes it possible for scientists to explore the extreme pressures and temperatures common to deep interior conditions of planets and stars throughout the universe. At such pressures, quantum mechanics can enter the macroscopic realm, producing a new frontier in physics. Early quantitative experiments approaching this regime are rich with discovery. Examples include unexplained chemistry in warm dense plasmas [1-3] , the insulator-to-metal transition for many materials that occurs at the onset of disorder [4-6], first-order plasma-phase transition in hydrogen[7, 8] , localization and pairing of electrons in ultra-dense matter [9-11] , ionization potential depression[12, 13], and general photon transport in hot dense matter that disagree significantly with state-of-the-art calculations [14, 15]. A next-generation, high-energy-density (HED) facility able to produce and probe these conditions can lay the foundation for understanding dense astrophysical plasmas, the recently discovered and yet to be discovered compact astrophysical objects throughout the universe, and the emergent scions evolving from these objects.

A variety of loading pathways will explore wide-ranging pressure-temperature conditions, including steady, decaying, and multi-shock loading. The Omega-EP multi-kJ, UV beamlines will generate well-defined pressure changes over a wide range of strain rates well beyond one Terapascal. Isochoric heating in combination with compression will greatly increase the range of accessible material conditions. The long-pulse UV beamlines will be capable of driving hydrodynamic instabilities deep into their nonlinear evolution. At these conditions, it will be possible to resolve the development of chemical reactions, phase changes, and produce ultrafast snapshots of highly turbulent media with unprecedented spatial and temporal resolution. With this unique and flexible combination of multi-kJ UV beamlines with state-of-the-art PW short pulse beams, many possible experimental use cases (EUCs) have been identified by the astrophysics and HED communities. Therefore, this proposal is for a “flagship capability” that showcases the possibilities for community-driven exploration of LAPP-relevant science and NSF OPAL as a user facility.

Table 1. The LAPP proposed experimental use cases (EUCs) and flagship.

Campaign	Laser Capabilities	Key Diagnostics
Pair Plasmas (short-pulse activation)	1ω + 2ω Alpha beams	e^-/e^+ Spectrometer, Gamma flash
Dense Plasmas	1ω + 2ω Alpha + UV beams	High-res x-ray spectrometer
Dynamic Compression (long pulse activation)	UV/ns pulses	VISAR/SOP
Ultrafast Phase Transition Kinetics	1ω/2ω Alpha + UV pulses	e^-/x-ray diffraction, XAS, x-ray imaging, VISAR, SOP

Scientific Proposal – The LAPP Community seeks to combine three cutting-edge capabilities offered by NSF OPAL: dynamic compression, impulsive heating, and ultrafast probing. The staged approach leading to the flagship experiment is shown in Table 1. The short pulse (1ω and 2ω) will be activated in dense plasma spectroscopy experiments with direct target interactions with multi-PW lasers for the first time at these intensities. The long pulse (30-ns UV long pulse beams) will be activated to ramp-compress planetary materials (ex. Hydrocarbons, SiO2, H2O, Fe) to conditions inside the cores of planets. This staged approach will lead to the flagship experiment to shock and ramp-compress these planetary materials to terapascal pressures and use the femtosecond PW beams to create ultrafast x-ray probes for time-resolved x-ray diffraction, radiography/phase contrast imaging, and x-ray emission and absorption spectroscopy to identify structural and electronic phase transitions and unravel their nonequilibrium dynamics.

The proposed LAPP target geometry was defined based on the community proposals and encompasses all the required configurations from those experiments. The UV-beam geometry is distinct from the current Omega-EP configuration. The UV beams now are arranged to allow for single-sided and colliding setups; this alone opens up an entire new set of experiments that are not currently possible on Omega-EP. Single-sided and opposing UV beam geometries maximize opportunities for dynamic compression, shock interactions, and advanced hydrodynamics. This allows for shock, multi-shock, and ramp compression of driven planar packages and shock tubes as well the generation of complex hydrodynamic flows with the colliding geometry (instabilities, jet, colliding/collisionless, and dynamos). The short pulse beams (Alpha-1 and Alpha-2) are also highly configurable and allow for simultaneous face-on and side-on probing and detection with optical, x-ray, and particle diagnostics. Experiments with multi-petawatt beams require the option to access UV-irradiated, as well as compressed, but unperturbed target surfaces. Critical to the LAPP community, we require frequency doubling of the alpha beams for improved coupling for impulsive heating experiments and we envision scaling experiments at both 1ω and 2ω.

I. LAPP target chamber geometry:

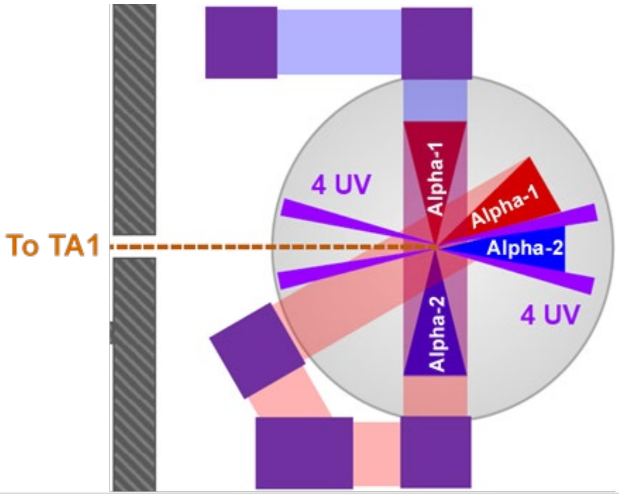


Figure 1. The LAPP proposed UV (purple) and Alpha beam (red/blue) geometry. The highly configurable geometry includes single-sided and colliding UV beam geometry and adjustable Alpha-1 and Alpha-2. There will be a line of sight to target area 1 (TA1).

II. Short-Pulse and Long-Pulse Activation:

The LAPP community proposes two EUCs for activation of the NSF-OPAL alpha beams as they are ramped to full specification. As we approach this new intensity frontier, these EUCs will provide different physics methodologies to provide insight into how these lasers are performing and will be very important to ensure we have confidence in the system performance.

The first experiment will use NSF-OPAL to create laser-produced relativistic pair plasmas in the laboratory using the NSF-OPAL short pulse beams[16, 17]. Unlike electrons and ions in conventional plasmas, the electrons and positrons in a pair plasma have equal masses, so many standard plasma approximations break down. Instabilities and shocks in pair plasmas have been theorized as key mechanisms in particle acceleration to extraordinarily high energies as well as magnetic field generation, amplification, and dissipation. The possibility to produce and study a relativistic pair plasma in the laboratory is compelling as it would enable a detailed understanding of the collective processes associated with these extreme astrophysical conditions and provide a new route to benchmark numerical and theoretical models. Making relativistic electron-positron (antimatter) plasmas in the laboratory has proved challenging. Key difficulties include producing pair plasmas with high enough number of particles and maintaining charge neutrality to study collective plasma processes given the short lifetime of positrons. As a result, no reliable experimental platforms are available yet that can simulate the relativistic pair plasma processes relevant to astrophysical conditions. In the last decade, however, it has become clear that multi-petawatt lasers can play a very important role in this endeavor.

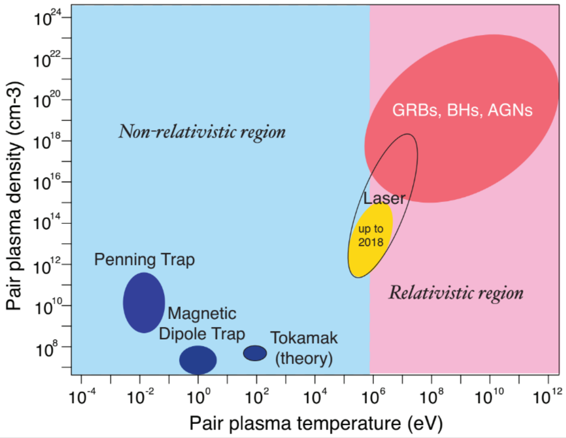


Figure 2. The densities and temperatures from laboratory antimatter (electron-positron) plasmas and some astrophysical objects. The temperature in the relativistic case refers to the bulk Lorentz factor of the plasma. The black ellipse represents potential pair parameters achievable with NSF-OPAL entering the relativistic regime relevant to gamma-ray bursts (GRBs), black-holes (BHs), and active galactic nuclei (AGN).

The production of laser-produced pair plasma experiments relevant to relativistic gamma-ray bursts (GRBs), black-holes (BHs), and active galactic nuclei (AGNs) (Fig. 2) are only possible at NSF-OPAL because of the current limitations associated with the pre-pulse on Omega-EP short pulse beams. The scaling of pair parameters with intensity and frequency (1ω vs 2ω) will be measured as NSF-OPAL is ramped to full specification. Theoretically, extremely high density (>10^{19} cm^{-3}) of relativistic pairs can be produced from ultra-high intensity (>10^{24} W/cm^2) lasers [18, 19]. Once realized, this would open up new parameter regimes for this relativistic laboratory astrophysics.

We propose to activate the Omega-EP UV kJ long pulse lasers in a series of dynamic compression experiments. As the Omega-EP beams are ramped to full specification, we will conduct shock, multi-shock and ramp compression experiments on planetary relevant equation-of-state (EOS) targets (ex. SiO2, H2O, Fe). We propose to upgrade the current Omega-EP beams to increase the maximum pulse length from 10 nanoseconds to 30 nanoseconds. This is critical for generating low-temperature ramp-compressed states where it is predicted that hydrogen-rich materials transition to exotic quantum phases[20]. The long pulse commissioning will also activate critical diagnostics such as x-ray pinhole cameras, x-ray streak cameras, velocity interferometer system for any reflector (VISAR), streaked optical pyrometry (SOP), and spectrally-resolved SOP. Using VISAR and SOP, EOS (pressure, density, sound speed) of ramp-compressed materials can be measured at pressures greater than one Terapascal and compared to first-principles density functional calculations that are used to model astrophysical objects.

Next, we propose a series of dense plasma spectroscopy experiments where extremely high-intensity short-pulse laser-solid interactions will create hot, high-density states relevant to the interiors of giant planets and stars and diagnosed with high-resolution x-ray spectroscopy. Understanding the ionization balance is critical to modeling the EOS, opacity and conductivity of dense plasmas. At high energy densities, phenomena such as ionization potential depression play an important role determining the properties of the plasma as materials undergo both temperature and pressure ionization[21]. Current experiments reveal that there are gaps in our understanding of HED opacity and atomic physics models in the dense plasma regime [13, 15].

This will be the first time the NSF-OPAL short pulse beams will interact with HED matter driven by the Omega-EP long pulse beams to measure the equation of state and radiation transport over a large range of temperature and pressure parameter space. The NFS-OPAL alpha beams will be used to isochorically heat buried layer targets to explore a wide range of temperatures at near solid density using high resolution x ray emission spectroscopy. Next, the UV beams will shock or ramp compress the buried layers to higher densities and at a later time, the alpha beam will isochorically heat the sample from the high-pressure state to study the delicate balance of temperature and pressure ionization. This is only possible with the proposed LAPP geometry where the alpha beam can directly interact with the buried layer on the non-UV irradiated surface. Lastly, the other alpha beam will be used to create an x ray source to perform absorption spectroscopy measurements while the other alpha and UV beams are used to create the high temperature, high-density plasmas. The ability to perform both emission and absorption x ray spectroscopy experiments enables measurements at a wide range of temperature and ionization states, where emission spectroscopy is appropriate for the highest temperatures when the buried layer is highly ionized and absorption spectroscopy is necessary to probe partially ionized states. These experiments would benefit from the development of high spectral resolution x-ray spectrometers to measure line shapes and line shifts at high densities, where experimental measurements have shown large discrepancies between experimental measurements and theory[22]. High-resolution measurements will require high throughput x-ray spectrometers to obtain sufficient signal to noise from the buried layer targets using curved crystal optics, such as spherical crystals [23] or advanced crystal geometries optimized for TIM-based diagnostics [24]. Additional key diagnostics will be activated: single-photon counter, survey x-ray spectrometer, BHx + Flexible XRS, TCS (High Energy), Electron/Positron Spectrometer, and Gamma Flash.

III. Flagship Capability: Ultrafast probing of HED matter

Over the past decade, tremendous advances in high-pressure x-ray diffraction (XRD) have revealed the structure and chemical identity of elements and compounds at extreme conditions is fundamentally altered. With the development of *in situ* XRD using lasers as the high-pressure drivers, measurements of the structure, strength, and melting of materials have been extended to 2TPa and thousands of Kelvin [25-27]. Advances in more traditional diamond anvil cell experiments, now reaching over 500 GPa, have enabled comparison of statically and dynamically determined sample responses [28]. Differences in the observed phases, phase transition boundaries, coexistence and onset of melting have emerged [29, 30]. These differences have been attributed to nonequilibrium kinetics, the nature of the shear-relieving mechanism i.e., material strength, temperature, and phase transition pathways. Understanding the nature and mechanism of phase transitions under shock and ramp compression will elucidate the origin of these differences.

Today there exists advanced x-ray sources such as LCLS, XFEL, SACLA, APS-DCS etc. combined with modest 10-100 Joule laser drivers for dynamic high-pressure studies and separately multi-KiloJoule to MegaJoule laser facilities with inferior diagnostic probes. Hundreds of publications reveal the cutting-edge nature of the potential integrated capability from mapping complex structures of solids and fluids, dynamic imaging of dislocations giving rise to real time mapping deformation and structural transformations, HED chemistry, temperature and thermal properties, transport and more at HED to atomic pressure to nuclear pressure regimes. The next step is to combine the multi-10's of KJ laser drivers with x-ray free electron laser capability at high repetition rate. This flagship will use NSF-OPAL to bridge where we are today to such a capability.

After commissioning of the short and long pulse OPAL beams, we propose to shock and ramp-compress these planetary materials to Terapascal pressures and use the femtosecond PW beams to create ultrafast probes for time-resolved electron and x-ray diffraction to identify structural and electronic phase transitions and potentially unravel their nonequilibrium dynamics. These probes are not limited to diffraction techniques but could be used for radiography/phase contrast imaging, and x-ray emission and absorption spectroscopy.

Because the electron bunches produced via laser wakefield acceleration (LWFA) are nearly synchronized to the laser source, they provide a mechanism for creating ~femtosecond, high Q electron bunches for the purpose of electron diffraction studies[31-33]. Electron diffraction can provide atomic scale resolution of the structure of materials under compression. These high energy multi-fs electron bunches will be used for imaging and diffraction, much like a transmission electron microscope (which typically operate at 100's of KeV), at NSF-OPALs multi-KJ laser facility. We propose exploiting laser wakefield generated electrons, and potentially Compton scattering produced coherent x-rays [34, 35], for these extreme materials science experiments. Understanding exactly how to use the NSF-OPAL beams to generate monoenergetic, small bandwidth, low divergence electrons and x rays is a flagship in its own right and optimizing these sources will be one of many discoveries that will be explored by the LAPP community. Depending on the target geometry, 1-100 MeV electrons with ΔE and divergence of better than about 0.1 % with ~1-10 pico-coulombs NSF-OPAL would bring about a new materials capability as today's energy spread and divergence ~10% is too large for these applications. At the higher electron energies, the detector distance will have to be on the order of meters away from the sample in order to resolve the scattering features and will influence the design of the target chamber.

Ultimately, with multi-pulse electron bunches this would enable fs imaging on sub-Angstrom resolution, ultra-high Q diffraction for complex structures and chemistry. We propose starting with the shock and multi-shock compression of hydrocarbons where they are expected to have diamond precipitation[36-38]. Understanding the timescales for the nucleation of diamond is currently not well understood and the role of other light elements in the hydrocarbons and their influence on the diamond growth are key questions that can be understood with NSF-OPAL. The results will have important implications for understanding the depth at which diamond precipitation occurs in the interiors of icy planets.

This experimental configuration is shown in Figure 3. The 4 UV beams will shock and ramp compress hydrocarbons to conditions where they are expected to have diamond precipitation. Because the electrons lose their phase relation compared to the incident beam as they penetrate deeper into the sample, we will only detect diffraction from the rear surface of the target and will time the electron bunch with the shock breakout. Therefore, femtosecond co-timing will be critical for this experiment. The diffracted electrons will be detected in a reflection geometry on an image plate detector. The time delay between the shock breakout and the electron bunch will be adjusted to determine the timescales over which diamond forms. Such a capability will transform the way today's HED measurements are performed.

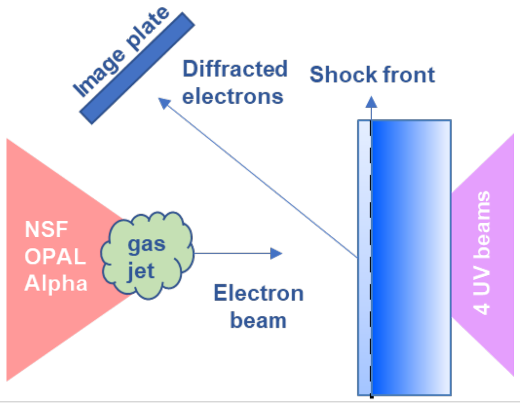
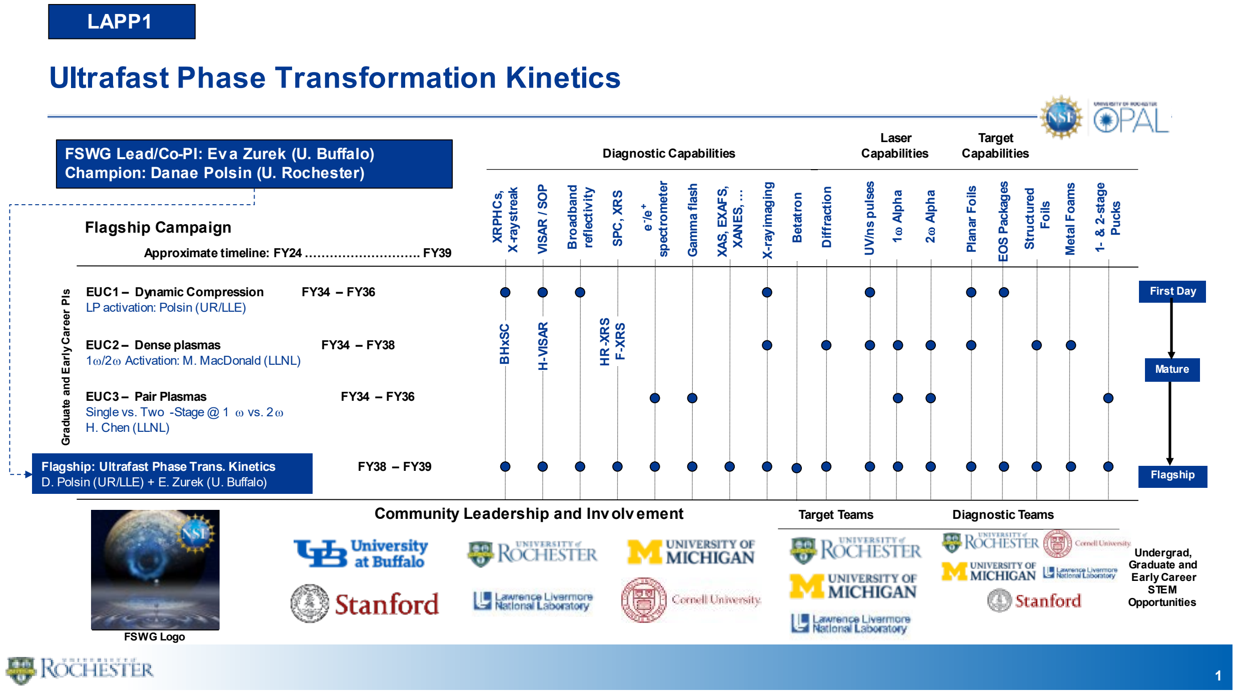


Figure 3. NSF-OPAL configuration for ultrafast electron diffraction studies. The NSF OPAL alpha beam will irradiate a gas jet to create a high-energy electron beam. These electrons will diffract from the rear surface of an EP-OPAL shock compressed sample and will be collected in a back-scattered geometry on an image plate.

Team and Resources – Please address assessment criteria 2 in this section. Include an NSF formatted biosketch for each team member.

In this path to CDR, the LAPP members have proposed or planned experiments at the NSF ZEUS laser facility to create x-pinches using the return current from high-intensity laser interactions with solids for high-resolution x-rage radiography measurements and experiments at Brookhaven National Laboratory for preliminary experiments on inverse Compton scattering. LAPP members are also participating in NSF center CMAP related experiments and projects to understand the properties of matter at atomic pressures. This flagship capability will engage a large scientific community: CMAP (~100 members, 77 early career), planetary science (>25,000 attendees at the 2023 American Geophysical Union conference), advanced plasma diagnostic community (370 participants at the 2022 high-temerature plasma diagnostics conference), hydrogen, theoretical physics and chemistry communities. **E.Z., S.R. (theory), D.P, H.L., M.M., J.K., G.C, R.R, A.S (ultrafast phase transformations experiments), M. M. (dense plasmas experiments), H. C. (pair plasmas experiments), D.P, H.L, M.M, J.K., G.C., R.R., A.S., M.M., H.C. (diagnostics and targets).**



LAPP1

Ultrafast Phase Transformation Kinetics

FSWG Lead/Co-PI: Eva Zurek (U. Buffalo)
Champion: Danae Polsin (U. Rochester)

Flagship Campaign
Approximate timeline: FY24 .... FY39

Graduate and Early Career PIs

		Diagnostic Capabilities										Laser Capabilities			Target Capabilities				
		XRPHCs, X-raystreak	VISAR / SOP	Broadband reflectivity	SPC, XRS	e^-/e^+ spectrometer	Gamma flash	XAS, EXAFS, XANES, ...	X-ray imaging	Betatron	Diffraction	UV/ns pulses	1ω Alpha	2ω Alpha	Planar Foils	EOS Packages	Structured Foils	Metal Foams	1- & 2-stage Pucks
EUC1 – Dynamic Compression LP activation: Polsin (UR/LLE)	FY34 – FY36	●	●	●					●			●			●	●			
		BHxSC	H-VISAR		HR-XRS F-XRS														
EUC2 – Dense plasmas 1ω/2ω Activation: M. MacDonald (LLNL)	FY34 – FY38								●		●	●	●	●	●		●	●	
EUC3 – Pair Plasmas Single vs. Two -Stage @ 1 ω vs. 2ω H. Chen (LLNL)	FY34 – FY36					●	●						●	●					●
Flagship: Ultrafast Phase Trans. Kinetics D. Polsin (UR/LLE) + E. Zurek (U. Buffalo)	FY38 – FY39	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

First Day → Mature → Flagship

FSWG Logo

Community Leadership and Involvement

Target Teams

Diagnostic Teams

Undergrad, Graduate and Early Career STEM Opportunities

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Appendix A7 – LDNP1

NSF OPAL Flagship Proposal Cover Page

Proposal Deadline: Friday, May 31, 2024

Title of Proposed Experiment:	Tritium-induced nucleosynthesis
Flagship Experiment Champion:	Ani Aprahamian
Institution:	University of Notre Dame
Email:	aapraham@nd.edu
Telephone:	+1 (574) 631-8120

Flagship Experiment Team:

Name	Affiliation	Email
B. Appelbe	Imperial College	[redacted]
A. Crilly	Imperial College	[redacted]
N. Dover	Imperial College	[redacted]
A. Schwemmlein	LLE	[redacted]
C. Forrest	LLE	[redacted]
S. Padalino	SUNY Geneseo	[redacted]
H. Schatz	MSU	[redacted]
C. Stoeckl	LLE	[redacted]
M. Wiescher	University of ND	[redacted]
M. Yuly	Houghton Unverisity	[redacted]

Relevant Research Areas of Interest

Studying reaction rates between light nuclei, particularly tritium reactions, with applications to ICF, fundamental nuclear structure theory of Li and Be isotopes, including stellar, big-bang, and heavy element nucleosynthesis in neutron star mergers.

Abstract: A controllable, high-yield triton beam is an invaluable tool for nuclear physics in studying the properties of light nuclei. One of the unresolved challenges in Nuclear Astrophysics is how nucleosynthesis proceeds beyond the A=5 and A=8 gaps for nucleosynthesis in core collapse supernovae, big bang nucleosynthesis, and even in neutron star mergers. The mass A=5 gap prohibits the production of substantial amounts of lithium and beryllium whereas the mass A=8 gap prohibits the production of heavier elements such as boron, carbon, and beyond. The answer lies in tritium reactions. Li reactions can perhaps explain why the ^{7}Li abundance is three times lower than predicted. The reactions of ^{7}Li(t,γ)^{10}Be and ^{7}Li(t,n)^{9}Be may hold the key. Tritium induced reactions may further explain the origin of neutrons and ^{12}C for nucleosynthesis to proceed beyond the lighter elements via the ^{9}Be(α,n)^{12}C reaction .

Di-neutron transfers onto ^{6}Li or ^{9}Be create neutron-rich nuclei that theorists only recently were able to model in ab-initio calculations. In addition, these reactions provide the opportunity to study di-neutron correlations during the transfer. Such light-ion reaction cross sections are also essential for nucleosynthesis models. A triton beam platform has been established on the OMEGA/OMEGA-EP facility that successfully measured neutrons produced by laser-accelerated tritons. Advances in activation detector development will make a series of lithium and beryllium reactions with tritium measurable to much higher precision with higher intensity beams. NSF-OPAL will be uniquely positioned to continue these measurements for two reasons. First, the high shot rate will significantly improve statistics, especially with activation detectors. Second, a dedicated tritium target chamber will eliminate the current requirement for joint shots using the OMEGA-EP laser to produce the triton beams in the OMEGA target chamber that includes tritium handling systems.

1. Introduction

Powerful short-pulse laser facilities provide a unique opportunity to study fundamental nuclear physics that is not accessible otherwise. Laser-ion acceleration mechanisms enable the generation of multi-MeV ion beams with miniaturized targets, which is especially attractive for the creation of radioactive triton beams. This technique can be adapted to nuclear science experimentation [Sch23], and has generated world-wide interest by the basic and applied nuclear science communities. New international laser projects such as LMJ and ELI, as well as existing laser facilities like NIF and OMEGA, have matured with the required capabilities to support nuclear science programs. However, the emphases at the ELI facility are the applications of energetic gamma-rays to induce nuclear reactions of interest. The powerful laser systems OMEGA and OMEGA-EP operating at the University of Rochester (UR), and ultimately NSF OPAL will play an important part in the development of a laser-accelerated triton beam platform with the goal of measuring cross sections of tritium-induced reactions at low energies. Very few measurements of these reactions have hitherto been made at any energy, even though tritium-induced reactions occur in all DT plasma thermonuclear fusion research, are critical for an understanding of both stellar and big-bang nucleosynthesis, and, as the lightest nucleus with two neutrons, can serve as a testbed for models of nuclear interactions and structure. For example, the neutron-rich nuclei involved in these reactions, e.g. ^{6}He, ^{8}Li and ^{11}Be, influence the r-process as “seed nuclei” [Ter01] and are also predicted to exhibit exotic structure [Qua18, Coc12, For05].

Light-ion reaction cross sections are essential inputs to nucleosynthesis models [Arc16, Cyb01]. Most of these cross sections have never been measured at the relevant thermonuclear temperatures required for stellar models, yet they are central to understanding the nuclear and the astrophysics components that explain what we observe in the universe. For this reason, in nucleosynthesis models the cross sections are usually extrapolated [Cas22] from higher energy cross section measurements using a constant S-factor fit, or by more sophisticated optical model or R-matrix parametrization fits. For tritium-induced reactions, however, even these higher-energy measurements often do not exist.

The reason that so few measurements, induced by tritium reactions, were possible is due to the technical challenges in creating triton beams at accelerators. Many have been discontinued due to problems with tritium contamination. Even during the heyday of the 1950s and 1960s there were few laboratories where this work could be performed. One of the last remaining examples from this period was the Los Alamos three-stage Van de Graaff Ion Beam Facility [Woo74] which ended tritium beam production in 1994, was deactivated in 1999 [USG15], and decommissioned, decontaminated, and demolished starting in 2005 [Loo05]. At the present time there are essentially no laboratories that generate intense tritium beams. To avoid radiological hazards, recent tritium-beam experiments have been forced to use very low intensity secondary beams produced via ^{9}Be(α, t) (10^6/s) [She99] at NSCL, in-flight heavy-ion fragmentation of ^{16}O (5×10^6) [Hit06] at NSCL, or very low current accelerated triton beams (10^8/s) using the AGOR cyclotron [Bra01]. There are plans for an accelerator-based triton beam at the Florida State University, but an appreciable beam current combined with acceptable levels of contamination has yet to be demonstrated. In addition, the accelerator limits the energies to 3-18 MeV, leaving out the interesting low-energy regime currently available with recent experiments on OMEGA-EP and that will be extended with the NSF-OPAL facility. [Wie24]

Several OMEGA EP campaigns have made steady improvements towards generating controllable tritium beams using laser-driven target-normal sheath acceleration (TNSA), and preliminary measurements of the ^{3}H(t,2n)α reaction. The proposed NSF OPAL platform aims to improve the measurement of total reaction cross sections of tritium-lithium and tritium-beryllium reactions by using a newly developed activation diagnostic in combination with a high shot rate to accumulate good statistics. The diagnostic consists of a lithium or beryllium target directly mounted on two scintillators (see figure 3 for details) that measure both the energy loss and total energy of decay betas produced in the reactions ^{7}Li(t, p)^{9}Li, ^{6}Li(t,p)^{8}Li, and ^{9}Be(t,p)^{11}Be. Based on the energy loss, background events can be eliminated efficiently (see below). Using deuterium as a non-radioactive surrogate, the diagnostic was already successfully tested on the MTW laser. OMEGA EP shot time has been awarded in FY25 to examine the relevant scaling laws and prepare tritium experiments. Steady improvements in target handling are expected to also improve the expected signal. These experiments will be an important milestone towards the NSF-OPAL flagship experimental series.

2. Tritium-beam capabilities on OMEGA/OMEGAEP

A number of experiments producing a TNSA triton beam have been conducted on the OMEGA-EP system [Sto19, Sch22]. The greatest challenge in these experiments is minimizing the acceleration of parasitic protons, which originate from thin contamination layers that are acquired on the target during even short ambient air exposures. Due to their high charge-to-mass ratio, protons accelerate fastest, thereby partially shielding the heavier ions from the electron sheath that accelerates all ions [Rot16]. Indeed, radiochemical analysis of the targets reveals that most of the tritium in the target remains unused (10^{16} available vs. 10^{13} accelerated tritons), and using targets with higher tritium content does not significantly improve the beam. Currently, individual targets are manufactured in close collaboration between LLE target fab and a commercial vendor for titanium coatings (Widetronix). Stainless steel substrates are titanium-coated and sealed in argon. At LLE, these targets are exclusively handled in helium, as opposed to dry nitrogen in the past. A recent experiment showed a reduction of protons from $\sim3\cdot10^{13}$ (shot 99206, Figure 1) to $\sim5\cdot10^{12}$ (shot 110218, Figure 1), with a triton yield of $\sim10^{13}$, which for the first time demonstrated a higher triton than proton yield. The lower proton yields also made more energy available to the tritons, whose spectrum moved noticeably towards higher energies (see Figure 1). These triton energies have never before been reached in accelerator experiments, so this platform has the potential to fill gaps in several datasets, most notably for reactions involving light nuclei like lithium and beryllium.

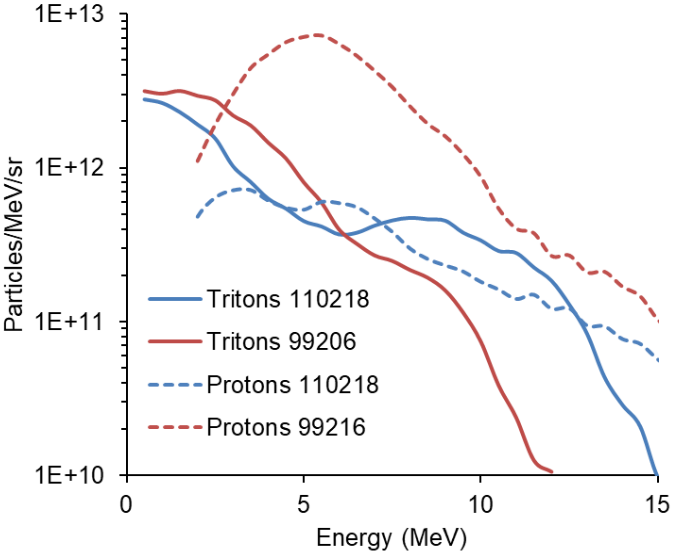

Figure 1:Tritium spectrum produced by targets with the "old" procedure (red) and the "new" procedure (blue).

However, nuclear reaction measurements using this beam and the existing neutron-time-of-flight (nTOF) detectors have been limited to reactions with high cross sections, most notably the deuterium-tritium reaction. The triton beam was directed onto a commercial deuterated polyethylene (CD) target, producing approximately 10^8 DT fusion neutrons (see Figure 2) [Sch22].

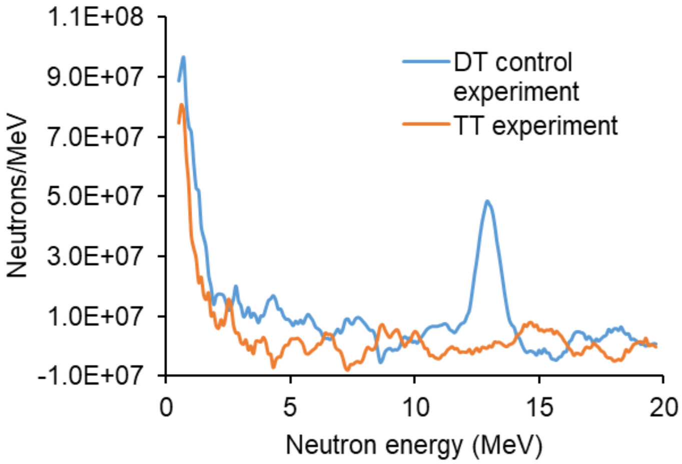

Figure 2: Neutron time of flight spectrum from the "8x4 nTOF" detector in energy space. While the TNSA triton beam generated a DT peak with a secondary deuterated target in the control experiment, no neutrons above the background were observed in the experiment with a secondary tritiated target.

A second experiment studied the triton-on-tritium (TT) reaction. Here, the deuterated physics target was replaced with a tritiated physics target. Figure 2 compares the resulting TT and DT data. The absence of neutrons above the background in the TT spectrum is consistent with the much lower TT reaction cross section, which has previously been reported up to about $E_t \approx 1$ MeV [Won65]. This finding suggests that the third excited state of ^{6}He, which is 2.3 MeV above the entrance channel, which was inaccessible in previous accelerator experiments, does not significantly contribute to the TT reaction via a resonance.

2.2 Neutron activation detector development

To measure cross sections for tritium-induced reactions other than DT, a new diagnostic was fielded and successfully tested on the MTW laser facility. This diagnostic assembly consists of a nuclear target and a Phoswich [Wil52] detector (see Figure 3).

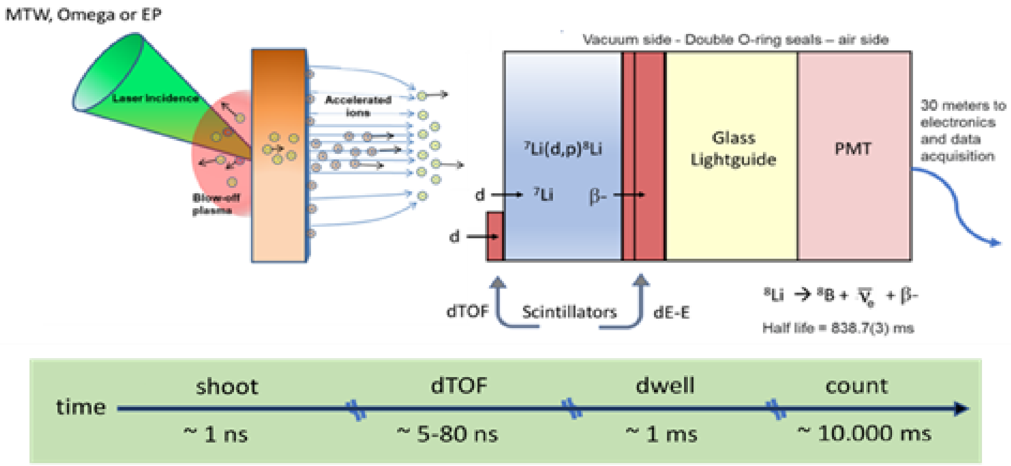

Figure 3: Schematic of the new activation detector. Deuterons (or tritons) react in the lithium target, producing beta-decaying isotopes. The beta-decay is analyzed to extract a total reaction cross section.

In the initial MTW test experiment, the nuclear target was a thin natural lithium film. Deuterons striking the nuclear target produced ^{8}Li via the ^{7}Li(d,p)^{8}Li reaction. The beta particles from the decay of ^{8}Li passed through the thin dE scintillator and stopped in the thick E scintillator of the phoswich detector, allowing background events to be separated from the decay betas by their energy loss. A ^{207}Bi source was used to identify the band of total energy and energy loss of similar betas in the detector (see red box in the top panels of figure 4). On the other hand, background events tend to have much lower energies and correspondingly lower energy losses (see black ellipse in the top panels of figure 4).

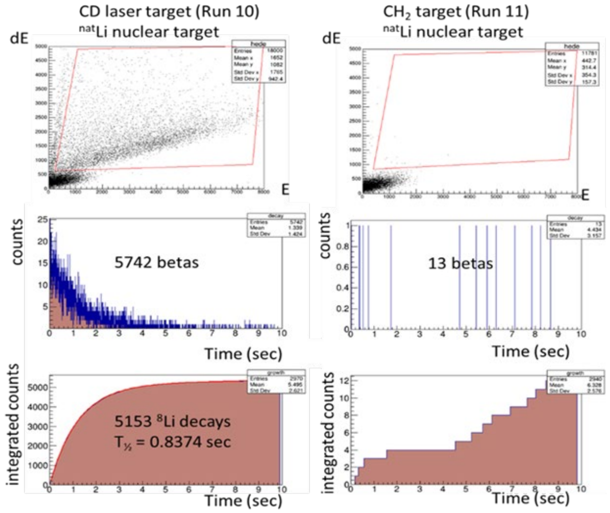

Figure 4: Results from the recent MTW laser campaign. Beta events (inside red box in dE-E histogram, top row) were selected and plotted as a function of time give a decay curve (second row). Fitting the integrated growth curve (third row) yielded the expected 8Li half-life and gave the number of 8Li nuclei. When a CH rather than CD target was used, no 8Li was produced.

The top panel of figure 4 shows that these background events are nearly identical between a shot using a CD target (producing a deuteron beam) and a shot using a CH target (producing a proton beam). Only 13 events occurred in the box qualifying for 8Li beta decays when using a proton beam, whereas approx. 5700 such events occurred when using a deuteron beam, indicating an excellent signal-to-noise ratio. The timing of these events was used to construct a decay diagram (center panels of figure 4). When using a deuteron beam, the decay followed the expected exponential shape, recovering the half-life of ^{8}Li. On the other hand, when using a proton beam, no recognizable decay was observed.

3. Proposed experiments on NSF-OPAL

Prior experiments have demonstrated that a tritium beam can be produced reliably on OMEGA/ OMEGA EP. Recently, improved targets produced more tritons than protons for the first time. In addition, the successful fielding of our new activation detector represented a milestone towards using this platform for the study of neutron-rich isotopes of lithium and beryllium produced in di-neutron transfer reactions. A similar experiment using deuterium as a surrogate has been scheduled on OMEGA-EP for FY25. After this test, these NSF-OPAL flagship experiments will be accessible:

1. ^{7}Li(t, p)^{9}Li
2. ^{6}Li(t, p)^{8}Li
3. ^{9}Be(t, p)^{11}Be

These reactions are of high interest for the early r-process and nuclear structure studies. Scaling the results from the MTW experiment to NSF-OPAL, assuming the triton spectrum shown in figure 1, gives a lower limit for the predicted yield of about 40,000 for a 2 μm thick lithium target, compared to the predicted yield of about 7000 for the MTW test experiment. The main advantage NSF-OPAL offers over OMEGA-EP is the high rep rate. Since laser-accelerated ion beams have a finite energy spread, the cross section has to be found through a deconvolution procedure. To reduce the uncertainties introduced by this procedure, many measurements with different beam energy distributions are necessary. The existing Thomson Parabola TPIE will be operated simultaneously with the phoswhich detector to obtain both beam spectrum and reaction products.

4. Path to NSF OPAL conceptual design

The proposed flagship experiments profit from the years of experience of our team with laser-accelerated triton beams. Our group will continue improving target designs and testing the activation detector simultaneously with Thompson Parabola Ion Energy (TPIE) on OMEGA-EP to validate and improve our estimates. Several operational PW laser facilities recently developed more advanced laser-ion acceleration techniques that should provide more efficient generation of ion-to-neutron production to achieve the goal of a controllable, mono-energetic ion beam around an MeV. Existing and proposed experiments are underway to test prescribed laser pulses and develop novel target designs.

a) Current experiments are ongoing at the OMEGA-EP Laser Facility to test alternative laser pre-pulse and main pulse configurations for target de-contamination and increase the ion acceleration yield.
b) Advanced laser-ion acceleration techniques are also be investigated and will be proposed for testing at the ZEUS PW Laser Facility.
c) Novel target ideas are being discussed General Atomics for upcoming campaigns that should allow for more ion acceleration yields including a mono-energetic spectrum.

Moving to NSF-OPAL high rep rate experiments introduces new challenges. First, the five-minute NSF-OPAL shot cycle requires the development and testing of a rotating target delivery system. Several conceptual ideas will be developed and tested on the ZEUS PW facility currently in operation.

5. Path to NSF OPAL flagship experiments

Early experiments on the newly NSF-OPAL facility will be used to perform the transfer knowledge gained from precursor experiments on existing PW facilities. In addition, several proof-of-principle experiments will be designed and executed to build experience with the new system.

a) Reproduce advanced laser-ion acceleration parameters achieved from what was learned with external experiments at current operating PW facilities.
b) This includes the feasibility of moving to tritiated targets will be examined, using data from the previous experiments to better estimate tritium contamination
c) The pilot NSF-OPAL experiments will use proton- or deuteron-doped foils as a surrogate.

After these milestones have been reached, our flagship experiments become feasible. Furthermore, the successful achievement of the milestones will attract the Nuclear Physics and Nuclear Astrophysics community.

6. Summary and Conclusion

In summary, a controllable, high-yield triton beam is an invaluable tool for the nuclear physics community in studying the properties of light nuclei. One of the unresolved challenges in Nuclear Astrophysics is how nucleosynthesis proceeds beyond the A=5 and A=8 gaps for nucleosynthesis in core collapse supernovae, big bang nucleosynthesis, and even in neutron star mergers. Advanced laser-ion acceleration techniques are maturing and will have the capability to reach the ion yields emitted from the conversion foil required for this flagship experiment.

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LDNP1

Tritium-induced nucleosynthesis

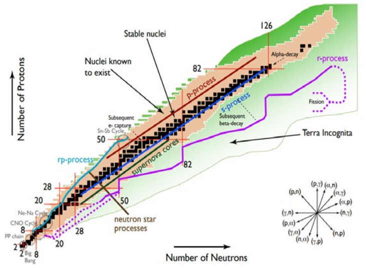
FSWG Lead/Co-PI: Ani Aprahamian (U. of Notre Dame)
Champion: Ani Aprahamian (U. of Notre Dame)

Flagship Campaign

Approximate timeline: FY24 ……………………… FY39

		Diagnostic Capabilities			Laser Capabilities	Target Capabilities		Target Chamber Capabilities
		Phoswich Detector	nTOF's	TPIE	1ω Alpha	Planar Foils	Cryogenic Planar Foils	Tritium Handling Capabilities
EUC1 – Ion Production Investigate proton- or deuteron-doped foils as a surrogate to optimize ion production. Ani Aprahamian (U. of Notre Dame)	FY27 – FY30		●	●	●	●		
EUC2 – Deuteron-Lithium and Beryllium Activation Perform proof-of-principle activation of $^{6(7)}$Li and ^{9}Be with deuterons to reproduce well known cross-sections. Ani Aprahamian (U. of Notre Dame)	FY30 – FY34	●	●	●	●	●		
Flagship: Tritium-induced nucleosynthesis Experiment with the activation of $^{6(7)}$Li and ^{9}Be with tritons in the 1 to 10-MeV energy range. A. Aprahamian (UND)	FY34 – FY35	●	●	●	●	●	●	●

First Day → Mature → Flagship



Community Leadership and Involvement

Target Teams	Diagnostic Teams
Arnold S. (UR) Tony R. (UR) Team 3 (Inst.)	Arnold S (UR) Chad F. (UR) Mark Y. (Houghton)

Neutron-Neutron Scattering with Two High Shot-Rate Neutral Beams (05/31/2024)

Flagship Experiment Champion: Chad J. Forrest
Institution: University of Rochester
Email: cforrest@lle.rochester.edu
Telephone: +1 (585) 275-8500

Flagship Experiment Team:

Name	Affiliation	Tentative Role	Email
Mark Paris	Los Alamos National Laboratory	Theory	[redacted]
Nicholas Dover	Imperial College London	Simulations	[redacted]
Aidan Crilly	Imperial College London	Theory	[redacted]
Brian Appelbe	Imperial College London	Theory	[redacted]
Stephen Padalino	SUNY Geneseo	Experimental	[redacted]
Mark Yuly	Houghton University	Experimental	[redacted]
Anthony Raymond	University of Rochester (LLE)	Simulations	[redacted]
Christian Stoeckl	University of Rochester (LLE)	Experimental	[redacted]
Arnold Schwemmlein	University of Rochester (LLE)	Experimental	[redacted]

Relevant Research Areas of Interest:

Advanced laser-ion acceleration mechanisms for the generation of beams of protons and deuterons using PW class laser facilities. Measurements of neutron-neutron elastic scattering is a direst test on charge symmetry and charge independence for strong interactions between elementary particles. Quantum chromodynamics (QCD) and an increased understanding in isospin symmetry attributed to interactions of quarks and gluons.

Abstract: The neutron-neutron scattering (a_{nn}) length is a direct check on charge symmetry and charge independence of the nuclear force. Presently, this quantity has only been inferred from indirect measurements from breakup reactions with neutral and charged particles on deuterons; no direct measurement of this quantity has been observed. Knowledge of neutron-neutron scattering length would be of considerable value for nuclear and particle physics community. A proposed experimental platform is under development at the University of Rochester Laboratory for Laser Energetics (LLE) that will utilize neutrons generated from advanced ion acceleration processes to impose neutron-neutron scattering interactions. The proposed laser facility (NSF-OPAL) is positioned to fulfill these measurements for two specific reasons; 1) the twin 25 PW beams are essential to generate the high luminosity due to the large number of neutrons emitted in a very short pulse and small dimensions in the interaction region to induce and measure the scattering length from neutron-neutron elastic scattering and 2) the high shot rate, short duration of pulse eliminates many sources of background that plagued previous attempts, and is a requirement to generate statistical significance for a direct measurement of this elastic cross section.

I. INTRODUCTION

The properties of symmetry have always been significant topic of interest when studying nuclear forces. The discovery of the neutron in 1932, a neutral non-ionizing particle with its mass nearly equal to that of the proton, inspired Heisenberg to propose the existence of a new intrinsic quantum number, isospin, which reflects the symmetry between protons and neutrons. [Hei32] Early studies, for example, of binding energies for hydrogen and helium isotopes, neutron-proton and proton-proton scattering, suggested that the nuclear neutron-neutron (n-n), n-p and p-p forces in the same state are equally strong, once corrected for electromagnetic interaction effects. [Bre36] This separate feature of nuclear interactions is called charge independence (CI). [Maj33] Consequently, the equality of n-n and p-p nuclear forces, called charge symmetry (CS), was then conjectured in 1935. [Fee35] However, the Coulomb interaction between protons breaking the proton-neutron symmetry, is considered a source of isospin-symmetry violation. Following the development of the Standard Model in the 1960s and 1970s, specifically of quantum chromodynamics (QCD), the approximate isospin symmetry is now attributed to interactions of quarks and gluons. Massive quarks are confined within nucleons (and mesons); they give rise to their internal structure and their strong interactions. Because of this quark confinement, nucleon-nucleon scattering remains important as one of only a few methods to access strong interactions by experimental observation.

Differences observed between the neutron-neutron and proton-proton scattering length would be a direct measure of charge symmetry breaking (CSB). Presently, the inferred neutron-neutron scattering length is obtained from indirect measurements in deuteron breakup reactions ^{2}H(n,nn)p and ^{2}H(π-,γn)n and disagree in both the magnitude and the sign of the difference between proton-proton (a_{pp}) and neutron-neutron (a_{nn}) scattering lengths. [Mac96]

One approach to study this problem is a direct evaluation of a_{nn} and a_{pp} scattering lengths. A number of experiments have reported on p-p and p-n interactions where two-body nucleon-nucleon forces (2NF) are used to sufficiently describe the results. In addition, validity of the charge-symmetry principle which consists of p-p and n-n forces in a singlet state, has not been fully resolved. This principle suggests that the a_{pp} scattering length should be smaller than the a_{nn} scattering length. However, current measurements reported in the literature infer a much larger a_{pp} scattering length, instead.

Earlier attempts to make a direct measurement of the a_{nn} scattering length have been attempted over the past four decades. One such attempt, using two fission-fusion devices to produce simultaneous neutron beams, was proposed to measure the elastically scattered neutrons. [Gla86] However, most other approaches considered Maxwellian thermal neutron gases in which the neutrons collide in an interaction chamber. [Fur02] A significant drawback from the latter of these two attempts was the densities of the steady-state thermal neutron targets were extremely small which resulted in a challenging background environment to separate out the neutron-neutron scattering signal. To this end, this proposed flagship experiment proposed here will finally address this still fundamentally unresolved scientific question. The following discussion outlines the specific novelties of the proposed experiment relative to earlier attempts.

II. EXPERIMENTAL PROCEEDURE

Powerful laser facilities provide a unique opportunity to study fundamental nuclear physics that is not accessible otherwise. In particular, laser-ion acceleration mechanisms enable the generation of multi-MeV ion beams with miniaturized targets, which is especially attractive for the creation of high luminosity, ultra-short pulsed fast neutron beams. This technique is sufficiently well developed to be adapted to nuclear science experimentation, and has generated world-wide interest in the basic and applied nuclear science communities. This mechanism is based on the earlier principles of the laser-induced acceleration process known as target-normal sheath acceleration (TNSA) in which enormous Coulomb fields ($\sim$GVm^{-1}) are produced on the back side of a primary “converter” foil during irradiation by a high-energy, short-pulse laser beam. Relativistic electrons generated in the laser–target interaction region escape the target, leaving ions behind and consequently generating a large sheath field E_z at the back side of the target. Ions on the rear surface are subsequently accelerated to high energies (~MeV) toward a secondary physics target in which they can induce nuclear reactions. This technique of laser-based neutron sources is well established and is also an interesting alternative to conventional neutron sources like reactors and spallation sources for many applications in science and engineering.

More recently, advanced acceleration laser generation mechanisms have been developed at currently available PW-class laser facilities, generating beams of protons [Zie24] and deuterons [Rot13] with maximum energies in excess of 100 MeV, and provide control of the generated energy spectrum. These advanced schemes typically involve very thin targets (~100 nm) combined with ultra-high laser intensities exceeding 10^{21} W/cm^2, utilizing the enormous radiation pressure of the laser to generate extreme localized space charge fields (> 10 TV/m). It is expected that utilizing higher laser intensities will also result in improved conversion efficiency from laser to ion energy. Therefore, NSF-OPAL will be well placed to exploit and extend these advanced schemes to generate high fluxes of energetic particles to drive nuclear reactions for collimated neutron generation. The general concept of the flagship experiment shown in Figure 1 uses two neutral beams at included angle of 40 to 60-degrees.

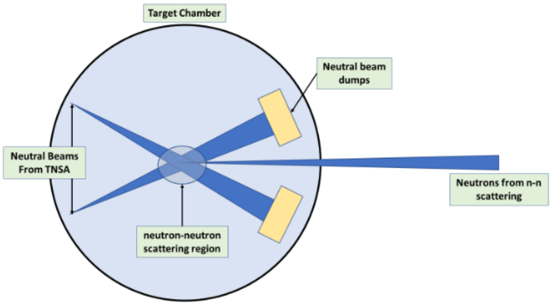


Figure 1: Schematic of two neutral beams from ion-acceleration with beam dumps to limit unwanted reactions from the target chamber walls. The neutron-neutron scattering events from the interaction region would be projected through a highly-collimated line-of-sight outside of the target chamber and experimental bay for measurements with neutron time-of-flight spectrometer.

Neutrons from the laser-ion acceleration process will intersect in a small interaction volume just beyond the conversion foils on the order of a few cm. The un-collided neutrons will be terminated with beam dumps from hydrocarbons to mitigate secondary reactions from the target chamber wall that could introduce an unwanted background in the spectrometers. The neutrons from the scattering events leaving the interaction volume will require a highly-collimated line-of-sight several meters from the target chamber and void of residual background signals.

Numerical simulations and experimental data in the literature [Dav10] have demonstrated that sufficient neutron flux can be generated from high-intensity laser-target accelerations interactions. As an example, the acceleration of energetic deuterons by high-intensity ultrashort laser systems approaching can result in 40 MeV deuterons focused on a lithium-fluoride target yields the reactions 7Li(d,n)9Be* and 7Li(d,2α)n in a sharply forward-focused kinematic beam of neutrons. Using these previous experiments, an estimate of the neutron-neutron scattering can be evaluated. Therefore, an estimate of the neutron-neutron yield can be calculated from the following expression,

$$Y_{nn} = \frac{\sigma_{nn} {Y_n}^2 l_p}{A_b v_n t_i},$$

where, Y_N is the total number of neutrons emitted from the foil, $l_p$is the width of the neutron pulse in cm, A_b is the area of the neutron beam in the interaction region, v_n is the velocity of the neutrons, t_i is the interaction time of the neutrons, and σ_{nn} is the neutron-neutron cross section given by,

$$\sigma_{nn} = \frac{4\pi a_{nn}^2}{\left(1 - \frac{1}{2} aRk^2\right)^2 + a^2k^2},$$

where, a_{nn} is the neutron-neutron scattering length, R is the effective range and k is the relative energy. For example, if two neutron beams from 0.1 MeV to 15 MeV each with a yield of 1x10^{14} emitted in a head-on geometry, and an area in the interaction region of 6x10^{-3} cm^2 with a neutron pulse of 1-mm, the estimated number of neutron-neutron scattering events is shown to be heavily dependent on the incident neutron energy as illustrated in Figure 2.

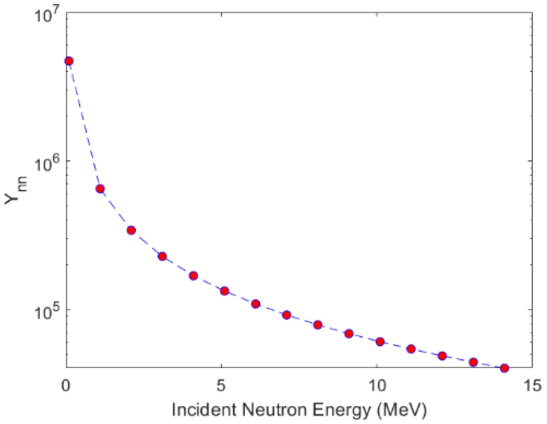


Figure 2: The expected neutron-neutron yield from two incident cones is highly dependent on the energy of the emitted neutrons from the laser-ion acceleration mechanism.

A primary takeaway from this example is to focus on designing this flagship experiment with incident neutrons at lower incident energy where the cross-section is significantly higher in the ~1 MeV region. In addition, the proposed configuration of the neutron-neutron scattering flagship experimental should focus on the neutron beams to overlap as small of an angle as achievable where the elastic scattering will take place at low center-of-mass energies while the detection of the n-n scattering events takes place at high laboratory energies. Therefore, the detected neutrons outrace the background neutrons produced near the scattering region. For this reason, the proposed experimental setup is being directed with the two neutron beams being emitted at an angle of ~30-degrees to induce the neutron-neutron scattering in a lower center-of-mass collision to promote more S-wave scattering which will help simplify extraction of the a_{nn} value.

Currently, no deterministic transport code exists currently to fully model neutron-neutron scattering experiments. A simulation to investigate beams with different neutron emission angles is essential to optimize signal-to-noise from the surrounding environment and the positioning of the time-of-flight spectrometers to measure the scattered neutrons from the interaction region. To calculate neutron-neutron scattering recent evaluations show that the neutron-proton and neutron-neutron scattering lengths as a function of energy are similar.

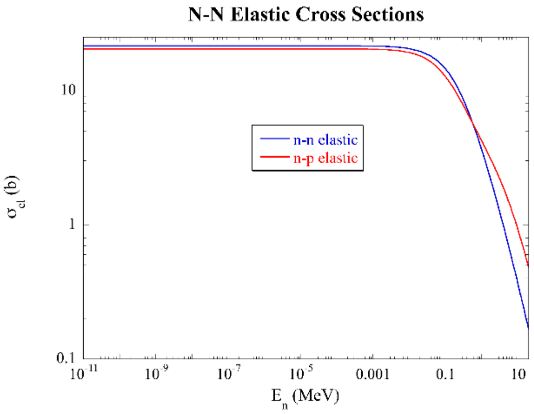


Figure 3: Elastic scattering cross-sections for n-p and n-n evaluated by Mark Paris at LANL. The calculations follow the drop-off in neutron-neutron scattering with increasing neutron energy.

To get a general idea of the expected signal, a model in a transport code uses a 1-mm spherical region of protons with a density of $1x10^{-8}/cm^3$ used to simplify the interaction volume approximately 5-cm from the neutron emission region on the backside of the conversion foil from the laser-ion acceleration process. Preliminary calculation used up to $1x10^{11}$ neutrons at 2 MeV in a near forward cone to overlap to spherical region of protons and produced $5x10^2$ neutron-neutron elastic scattering events. The setup for this calculation, as shown in Figure 4, scales to ~$5x10^5$ if the neutron emission history was set to $1x10^{14}$ which, however, would take many weeks to run with the current CPU's available for this calculation. It is important to note that this basic simulation matches the first principles calculation given above. At a shot rate of once every 5-mins, with up to 200 shots a day, and measuring $5x10^2$ events at ~10 meters using neutron time-of-flight spectroscopy from the interaction region an estimated $1x10^5$ neutron-neutron distribution can be recorded per day.

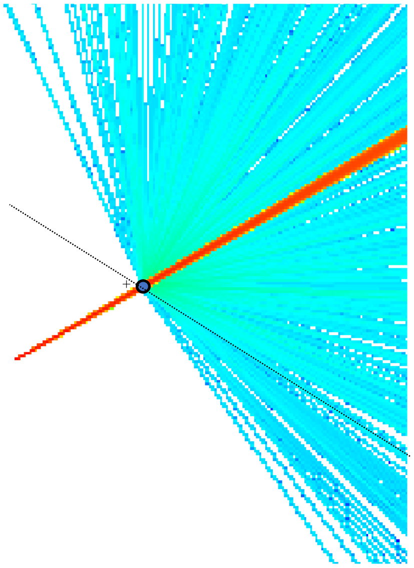


Figure 4: Calculation of neutron-proton scattering using MCNP. In this example, one beam of the 1e11 neutron (red) emitted in forward cone is incident on a sphere (black circle) of 1e14 protons. For this simulation, it was calculated that ~5e2 neutrons (green-blue) scattered from the proton sphere. The dashed line is just a reference for the second neutron beam (black) which is not used in this simulation.

III. ADVANCEMENT OF EXPERIMENTAL REQUIREMENTS

Success of this flagship experiment will require further investigation and the development of two distinct requirements before the proposed NSF-OPAL facility will be operational. An outline of these requirements is discussed below:

Optimization of the Neutron Beam

Several operational PW laser facilities recently developed more advanced laser-ion acceleration techniques that should provide more efficient generation of ion-to-neutron production to achieve the goal for a neutron flux of $1\text{x}10^{14}$ of mono-energetic neutrons around a MeV, using the ^{2}H(^{2}H,n)^{3}He reaction, to be emitted in a near-zero forward cone. This is required to keep the density of neutrons high when they interact in the overlap region. Existing and proposed experiments are underway to test prescribed laser pulses and develop novel target designs.

a) Current experiments are ongoing at the OMEGA-EP Laser Facility to test alternative laser pre-pulse and main pulse configurations for target de-contamination and increase the ion acceleration yield.
b) Advanced laser-ion acceleration techniques are also be investigated and will be proposed for testing at the ZEUS PW Laser Facility.
c) Novel target ideas are being discussed General Atomics for upcoming campaigns that should allow for more ion acceleration yields required to meet the $1\text{x}10^{14}$ neutron/pulse requirement.

Highly-Collimated Neutron Time-of-Flight Spectroscopy

One of the most challenging aspects of this flagship experiment will be dedicating a clear, ultimately evacuated, and highly-collimated line-of-sight to measure only the neutrons that scattered in the interaction volume near target chamber center. Fortunately, over the past several decades, a significant amount of work has been dedicated to the development of nuclear diagnostics required to measure implosion metrics on the

OMEGA Laser Facility from inertial confinement fusion (ICF) experiments. Many of the diagnostics required significant modeling and testing to make detailed measurements in a high-yield environment. The knowledge from the development of these diagnostics will be leveraged for this flagship experiment.

a) Once conceptual designs of the proposed laser facility are available, simulations of the target chamber and surrounding shielding will be modeled in a transport code. There simulations will be critical in designing a highly-collimated, evacuate, clear line-of-sight on the order of 10-meters from the interaction volume to clearly separate out the neutron-neutron scattering events from the surrounding room environment.
b) Present neutron time-of-flight diagnostic are operational in high electromagnetic pulses (emp) environments and have been shown to remain intact following high-intensity laser shots. However, development will need to be performed at existing PW facilities to investigate the reliability of these neutron spectrometers in a high-shot rate environment and maintain data recording.

IV. PATH TO FLAGSHIP EXPERIMENTS

Early experiments on the newly NSF-OPAL facility will be used to perform the transfer knowledge gained from precursor experiments on existing PW facilities. In addition, several proof-of-principle experiments will be designed and executed to build experience with the new system.

a) Reproduce advanced laser-ion acceleration parameters achieved from what was learned with external experiments at current operating PW facilities.
b) Investigate the neutron-proton cross-section by using a neutron beam incident on a micro-balloon filled with hydrogen on the ZEUS laser facility as a first proof-of-principle experiment.
c) Explore different angular positions of neutron emission angles to optimize scattering and minimize unwanted background signals.

V. SUMMARY AND CONCLUSIONS

In summary, we discuss the feasibility to measure the neutron-neutron scattering length using the proposed laser facility (NSF-OPAL) which is positioned to be adapted to fundamental nuclear science experiments and has generated world-wide interest in the basic and applied nuclear science communities. Advanced laser-ion acceleration techniques are maturing and will have the capability to reach the neutron yields emitted from the conversion foil required for this flagship experiment where the charge-symmetry principle, which consists of p-p and n-n forces in a singlet state, has not been fully resolved.

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LDNP2

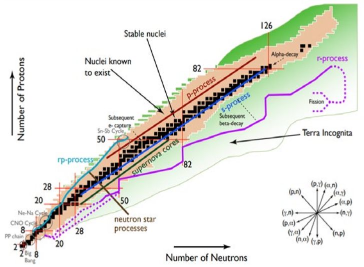
Neutron-Neutron Elastic Scattering

FSWG Lead/Co-PI: Ani Aprahamian (U. of Notre Dame)
Champion: Chad Forrest (U. Rochester)

Flagship Campaign

Approximate timeline: FY24 ………………………. FY39

		Diagnostic Capabilities		Laser Capabilities		Target Capabilities		
		nTOF's	TPIE	1ω Alpha	2ω Alpha	Planar Foils	Cryogenic Planar Foils	
EUC1 – Neutron Production Reproduce laser-ion acceleration to generate neutron yields achieved with external experiments at current operating PW facilities. C. Forrest (UR/LLE)	FY27 – FY30	●	●	●		●		First Day
EUC2 – Neutron-Proton Elastic Scattering Investigate the neutron-proton cross-section by using a neutron beam incident on a micro-balloon filled with hydrogen as a first proof-of-principle experiment. C. Forrest (UR/LLE)	FY30 – FY34	●	●	●		●		Mature
Flagship: Neutron-Neutron Elastic Scattering Perform neutron-neutron elastic scattering experiments by using two neutron beams incident on each other at predetermined angles. C. Forrest (UR/LLE) + A. Aprahamian (UND)	FY34 – FY35	●	●	●	●	●	●	Flagship



Community Leadership and Involvement

UR LLE
University of Rochester
University of Notre Dame
Imperial College London
Los Alamos National Laboratory

Target Teams	Diagnostic Teams
Arnold S. (UR)	Arnold S (UR)
Tony R. (UR)	Chad F. (UR)
Team 3 (Inst.)	Mark Y. (Houghton)

University of Rochester

Appendix B – NSF OPAL Flagship Experiment PRP Assessment Criteria

1. **Scientific Merit** – Does the proposal state a clear and compelling scientific question or hypothesis that the proposed flagship experiment will address?
    a. Does the proposal show how the results of the proposed work might impact the direction, progress, and thinking in its scientific field of research and possibly others?
    b. Does the proposal indicate the likelihood of achieving valuable results (high, medium, low) and why?
    c. Does the proposed work address the goals of NSF mission "to promote the progress of science; to advance the national health, prosperity, and welfare; and to secure the national defense?"
    d. Does NSF OPAL offer unique capabilities for the proposed research? How does the proposed work compare with other efforts in its field, both in terms of scientific and/or technical merit and originality? Where else might this research be completed?

2. **Flagship Experiment (FSE) team** – Does the proposal identify an appropriate champion and associated team to develop a conceptual design for the FSE that can be translated into conceptual designs for capabilities in the NSF OPAL facility?
    a. Does the team include committed and competent resources for all phases, including:
        1) theoretical and computational work to support experimental conceptual design;
        2) diagnostic and target conceptual design efforts; and
        3) any needed prototyping or preparatory experiments at existing facilities?
    b. Does the goal of the FSE and its team reflect the interests of a broad scientific community? How many researchers are active in the field domestically and internationally? Alternately, does the scientific field represent a growth opportunity for NSF OPAL?
    c. Does the FSE team include established or potential future leaders in the field?
    d. Are proposed plans for recruiting any additional scientific and/or technical personnel (new senior staff, students and postdocs) reasonable, justified, and appropriate? Does the proposal address the education of a diverse group of future researchers and other broader impacts per the NSF mission, such as: inclusion, STEM education/workforce development, partnerships; public engagement, national security, societal well-being, and economic competitiveness?

3. **Path to Conceptual Design Review (CDR)** – Does the proposal include a credible and comprehensive plan for 'doing the experiment on paper' before CDR?
    a. Does the plan clearly describe the current technology state and the technical gaps that must be addressed for diagnostics, targets, and any other capabilities needed? Does it identify the primary risks and appropriate mitigations for each?
    b. Does the proposal outline an experimental concept of operations needed to realize the FSE?
        i. Identification of system variables that will need to be changed during campaigns?
        ii. Number of shots needed for meaningful statistical analysis?
        iii. Would tuning of secondary sources be required?
        iv. Any other potential campaign variables?

    c. Does the proposal include timelines with milestones on the path to CDR, such as:
        1) completing experiment on paper to define requirements for the laser (energy, wavelength, pulse length, polarization, etc.), experimental geometries, targets, and diagnostics along with expected experimental results (type of signals, strength, bandwidths, etc.); and
        2) any other important milestones, necessary calculations or simulations?

4. **Path to Flagship**– Does the proposal include a credible plan that will lead to performing the flagship experiment on NSF OPAL if/when it is constructed?
    a. Does the proposal narrative describe a reasonable path for developing proposed NSF OPAL capabilities and/or exercising them at existing facilities to develop the needed NSF OPAL FSE platform?
    b. In addition to the proposal narrative, use the attached PowerPoint slide [NSF OPAL flagship experiment Phil-agram (draft1).pptx] to summarize the staged approach to realize the flagship. It provides a template and draft LAPP1 example based on the project response to the NSF site visit panel report. Does the "Phil-agram" show a credible path to flagship?
    c. What are the prospects for research and/or development grants (preparatory experiments, diagnostics, targets, and/or computational time) from NSF or other sponsors that could inform the RI-1 design project and/or a future construction project?

5. **Overall Summary** – In a few words, how does the PRP reviewer characterize the overall FSE proposal?

Sample PRP Scoring Sheet: Four scoring categories (scientific merit/impact, FSE team, Path to CDR, and Path to FSE) were scored 1-N, where N represented the top score and set the weighting among the categories.

Flagship ID	Flagship Title	Scientific Merit/Impact	FSE Team	Path to CDR	Path to FSE	Reviewer	Reviewer Ordinal	
	Proposal Reviewer	(1-5)	(1-5)	(1-3)	(1-3)	Subtotals	Ranking	COMMENTS
							(1-N where N is # of proposals reviewed)	
PAALS1	TeV-class Electron Acceleration							
	-- Name --					0		
PAALS2	HED Ion Acceleration							
	-- Name --					0		
HFP/QED1	Fully Non-perturbative Regime of Strong-field QED							
	-- Name --					0		
HFP/QED2	Stimulated photon-photon scattering							
	-- Name --					0		
HFP/QED3	QED cascade precursor							
	-- Name --					0		
LAPP1	Ultrafast Phase Transformation Kinetics							
	-- Name --					0		
LDNP1	Tritium-Induced Nucleosynthesis							
	-- Name --					0		
LDNP2	Neutron-Neutron Scattering							
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