Sample Research Project Descriptions

The 10-week summer program will be centered on engaging students in exciting research projects with lasers, optics, and laser/matter interaction. Interns will be assigned specific research projects based on their interest, level of prior preparation, and fit with the research of the faculty and graduate mentors. The projects will allow interns to engage in research that builds on concepts they may be familiar with to introduce new concepts in lasers and optical techniques and technology. The projects reflect the variety of topics.

<u>Research Projects at CSU</u>

Development of a High Power Laser for Fusion Energy Studies: towards the generation of practically unlimited energy

(CSU Professors Jorge Rocca, Brendan Reagan, and Reed Hollinger)

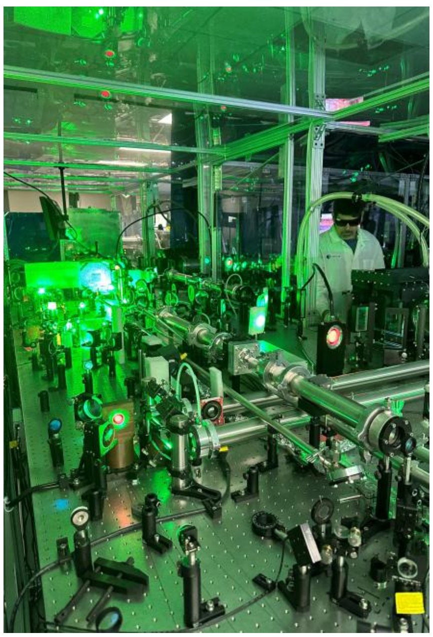

Fig. 1. The ALEPH laser Petawatt-class laser at CSU.

Y. Wang, S.J. Wang, A. Rockwood, B.M. Luther, R. Hollinger, A. Curtis, C. Calvi, C.S. Menoni, and J.J. Rocca, *0.85 PW laser operation at 3.3 Hz and high-contrast ultrahigh-intensity lambda=400 nm second-harmonic beamline,* Optics Letters, **42**: 3828-3831, (2017).

Fusion, the process by which two light atoms are fused into a heavier one releasing energy, is how the sun makes energy. The successful engineering of power plants based on nuclear fusion would create practically unlimited amounts of clean energy. Such an achievement would change human destiny. A laser experiment conducted in December 2022 at Lawrence Livermore National Laboratory has shown for the first time that energetic laser pulses can produce more energy than that of the laser pulse. Further engineering is expected to lead to energy gains of 10 to 100. A few stadium-size laser-driven fusion power plants could power the entire state of Colorado. This will require more powerful and efficient lasers.

CSU has developed one of world's most powerful lasers [1], ALEPH (Advanced Laser for Extreme Photonics), which is used for fusion studies by scientists from government labs, universities, and industry. CSU is working to further increase the power and efficiency of ALEPH. This project will focus on specific aspects of the development of this new laser. The students will learn laser physics and engineering, as well as computer-aided design and hands-on fabrication of components.

Generation of the fastest light: energetic few-cycle laser pulses for relativistic laser/matter interactions

(CSU Professor Jorge Rocca)

Ultra-intense, ultrashort laser pulses are the workhorse for creating and controlling matter under extreme conditions (ultra-high temperatures and pressures combined with extreme electromagnetic fields). Most experiments operate with ultrashort laser pulses for which the pulse duration of 30-50 fs, corresponds to tens of oscillations of the underlying electric field. However, further reducing the duration of these pulses to cover only a few oscillations of the electric field (few-cycle pulses), will enable research into an until-now unexplored regime of matter under extreme conditions. The generation of such extremely short pulses requires a very broad spectrum. CSU students and faculty are developing a few-cycle laser to spectrally broaden the pulses by interaction with helium gas in a hollow core fiber [2].

Over the course of this project, the student will participate in the generation and characterization of energetic few-cycle laser pulses [2]. Due to their ultrashort nature, specific optical setups are required to generate, propagate, and measure the properties of these pulses. The student will have the opportunity to design, build, and operate optical setups to address one or several of these important aspects, and learn about laser physics and engineering.

Fig. 2. Few-Cycle laser
A.R. Meadows, K. Yamamoto, I. Graumann, F. Szlafsztein, V. Chvykov, R. Hollinger, C. Aparajit, Z. Shpilman, O. Geiss, P. Abdolghader, B.E. Schmidt, and J.J. Rocca, *Fifteen millijoule, few-cycle pulse compression using a large-bore hollow fiber for relativistic laser–matter interactions*, Optics Letters, **50**:560628, (2025).

Interaction of ultra-intense femtosecond laser pulses with nanostructures: acceleration of particles to MeV energy and efficient generation of X-ray and Gamma ray radiation (CSU Professors Jorge Rocca and Reed Hollinger)

The interaction of ultrafast laser pulses of relativistic intensity with high aspect ratio nanostructures can efficiently heat matter to an ultra-high-energy-density regime encountered in the center of stars and within the core of fusion capsules compressed by the world's largest lasers. It also generates gigantic quasi-static electromagnetic fields that accelerate particles and efficiently generate intense flashes of x-rays [3]. The REU students will experiment with the interaction of ultra-intense, ultrafast laser pulses with arrays of aligned nanostructures, and optimize it for the generation of high energy photons to be able to acquire high resolution 3D images of dense objects. Nanowire arrays irradiated by laser pulses of ultra-high intensity can very efficiently absorb the laser light and convert it into intense picosecond flashes of high energy photons. CSU is fully equipped to conduct these experiments: it has one of the most powerful lasers in the world (ALEPH, 850 TW), has a facility to grow nanowire arrays, and all the equipment necessary to perform high resolution x-ray tomography. Students will learn about high power lasers, intense laser/matter interactions, and X-ray imaging.

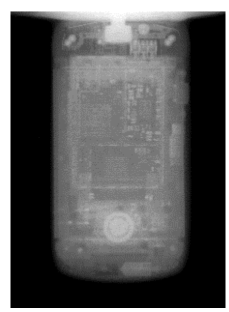

Fig. 3. X-ray radiograph of cell phone acquired with photons produced by CSU's ALEPH laser.

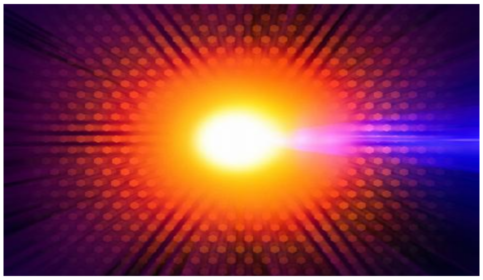

Fig. 4. J.J. Rocca, M.G. Capeluto, R.C. Hollinger, S. Wang, Y. Wang, G.R. Kumar, A.D. Lad, A. Pukhov, and V.N. Shylyaptsev, *Ultra-intense femtosecond laser interactions with aligned nanostructures*, OPTICA, **11**: 510542, (2024).

Growth and characterization of nanostructures for interaction with ultra-intense laser pulses (CSU Professors Reed Hollinger and Jorge Rocca)

Experiments conducted at CSU have shown that the irradiation of high aspect-ratio aligned nanowire arrays (see Fig. 5. j-m) with intense femtosecond laser pulses provides a unique combination of nearly complete optical absorption and drastically enhanced light penetration into near-solid density targets that allows to heat materials to extreme temperature and pressures. Using ALEPH (Advance Laser for Extreme Photonics), a Petawatt-class laser developed at CSU, we demonstrated that femtosecond laser pulses of relativistic intensity can volumetrically heat near-solid density plasmas to multi-keV temperatures, reaching pressures that are only surpassed in the laboratory in the central hot-spot of highly compressed thermonuclear fusion plasmas [5]. This project will consist of growing metallic and plastic nanowire arrays using different techniques. The student will learn how to grow nanostructure arrays following procedures such as the one illustrated in Fig.1, and to characterize them using a scanning electron microscope. The project will end by irradiating the fabricated nanostructure arrays with ultra-intense laser pulses. Students will learn nanofabrication techniques and the use of a scanning electron microscope to characterize them.

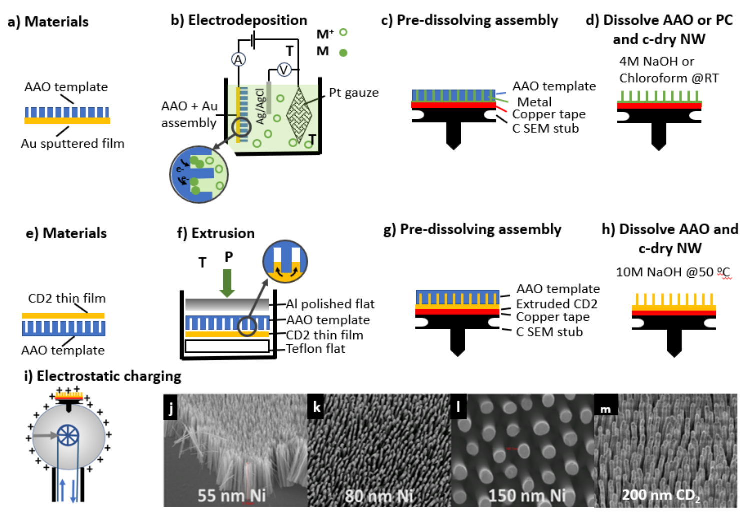

Fig. 5. Schematic of the fabrication process for metallic nanowires a-d) and polymer nanowires e-h). An AAO Au or PC sputtered templates are used an anode for the 3-electrode cell (b). After depositing at a constant voltage and temperature, the sample is mounted in a Carbon stub using a Cu tape (c). Templates are dissolved using NaOH or Chloroform for AAO or PC respectively (d). For polymer nanowires, AAO and a thin CD2 film are used (e), the CD2 film is extruded into the AAO pores (b) at constant temperature and pressure. Then the template and CD2 are placed on a Carbon stub (g) to be able to dissolve the AAO (h). A Van der Graaf is used to charge the wires

J.J. Rocca, M.G. Capeluto, R.C. Hollinger, S. Wang, Y. Wang, G.R. Kumar, A.D. Lad, A. Pukhov, and V.N. Shylyaptsev, Ultra-intense femtosecond laser interactions with aligned nanostructures, OPTICA, 11: 510542, (2024).

Design, Fabrication and Diagnostics of interference coatings for high intensity laser drivers (CSU Professor Carmen Menoni)

Fig. 6. Multilayer mirror consisting of a stack of GeTiO and SiO2 layers, designed for high reflectivity at 1064 nm wavelength.

In the most advanced high intensity lasers, multilayer dielectric coatings play a very important role in maximizing output power and continuous operation. In this project REU students will be involved in the growth and characterization of interference coatings for near infrared ultra-high intensity lasers that are used as drivers to generate intense beams of soft and hard x-rays. These advanced thin film structures consist of stacks of thin layers of transparent amorphous oxides that are deposited by ion beam sputtering. The REU student will participate in the design of these structures, in their synthesis, and in their optical characterization to determine their absorption loss at near infrared wavelengths and their stress. In particular, the REU student will be involved in the design and characterization of ultrabroad band coatings for ultrashort pulse lasers. The REU student will participate in experiments that will test the resistance of the coatings to laser damage.

Synthesis of amorphous oxides and their characterization (CSU Professor Carmen Menoni)

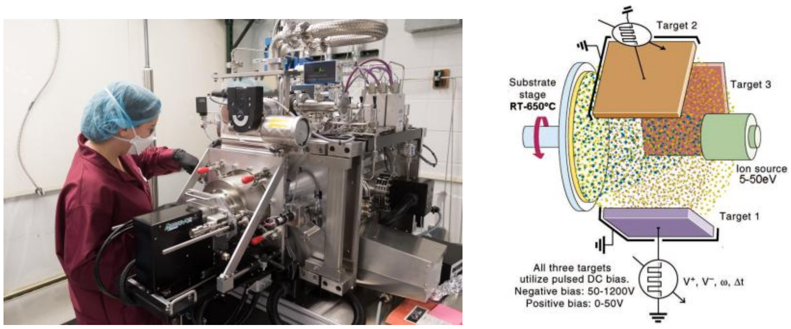

Fig. 7. Bias target deposition system used to deposit mixtures of several oxides to create ternary and quaternary thin films. In this process, metal targets are biased to accelerate Ar ions into the target and sputter the target in a reactive oxygen atmosphere.

Amorphous oxides are broadly used in many technologies. Thin layers of SiO2 are used as barriers in the most advanced semiconductor chips. In bulk form, SiO2 makes up the optical fibers in optical communication systems. With the addition of controlled impurities, SiO2 can be made into one of the strongest materials, which in combination with being transparent, is used for windows in every mobile phone. The key to functionality is in understanding how to control the materials structural and mechanical properties by adding impurities. At CSU we have the capability to deposit metal oxide thin films through ion beam sputtering. We can deposit binary, ternary, and quaternary mixtures, for example TiO2 doped GeO2 (TiGeO). We study the optical, structural, and mechanical properties of the thin films using a variety of techniques with the goal of studying how microstructure affects these properties. This project will offer the REU student opportunities to learn how to grow thin film metal oxides by sputtering. The REU student will learn how to characterize the materials by ellipsometry and spectrophotometry to analyze their optical properties. The REU student will be exposed to interferometry, spectroscopy methods, and x-ray diffraction to determine mechanical and structural properties of the thin films.

Super-resolution microscopy for the identification and characterization of defects in optics (CSU Professor Carmen Menoni)

During the deposition of multilayer dielectric coatings, particulates deposit on the growing thin films. When the coatings are illuminated by an intense laser beam, the particulates become point absorbers that can lead to thermos-mechanical instability causing catastrophic damage on the coating. In this project the REU student will be involved in developing super-resolution imaging schemes in a microscope that will allow us to identify the location of the point absorber in the stack and its characterization. The REU student working on this project will learn how to develop software using MATLAB ® to take images and analyze them to identify and categorize defects in coatings using intelligent algorithms, which will also enable the microscope to achieve a resolution beyond its diffraction limit.

Research Projects at UC Berkeley

Attosecond Molecular Photophysics by EUV Light Spectroscopy (UCB Professor Stephen Leone)

The photochemistry of complex molecules is a highly investigated field of study, in which processes such as ring opening, singlet-to-triplet transfer, and radical formation are ubiquitous. In this platform, small molecules are excited with a strong field at 800 nm wavelength or with ultraviolet pulses, and EUV attosecond pulses are used to probe the changes in orbital structure around carbon atoms in the molecule. An example is the Jahn-Teller distortion of methane cation (Fig. 8), in which it is found that upon abrupt ionization of methane a rapid geometry change occurs with concurrent coherent scissoring vibrational motion that is rapidly damped. The timescales for the dynamics are directly obtained in the few-femtosecond time domain. Students will learn about EUV spectroscopy, bond breaking, simulation of spectra, differential absorption, and molecular photophysics. Combining data analysis with simulation and global fitting provides important mathematical concepts for future careers.

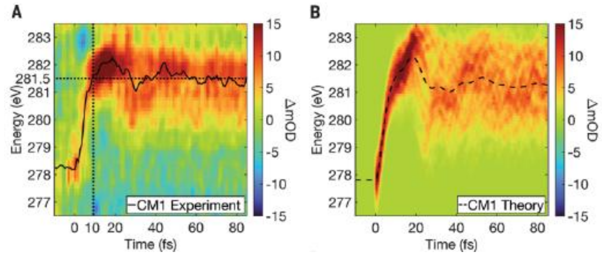

Fig. 8. (A) Experimental X-ray absorption signal from the C 1s orbital in methane cation to the vacant sigma CH bonding orbital, showing the rapid shift as the molecular geometry changes, and concurrent ringing of the scissoring vibrational mode. (B) Theoretical calculation of multiple trajectories of the same abrupt geometry change. CM indicates the first central moment of the spectral changes.

Attosecond Carrier Relaxation and Coherent Phonon Dynamics via X-Ray Spectroscopy (UCB Professor Stephen Leone)

REU students will participate in understanding atomic motion in solids, which is of interest for several areas of materials science, including photocatalysis and phase-change materials via x-ray spectroscopy. Following excitation by the broadband pump pulse, the Peierl's distortion in a solid (a periodic distortion of the lattice in a one-dimensional crystal) such as antimony (Sb) is lifted, allowing for the well-reported coherent phonon motion to take place. The temporal resolution of attosecond pulses allows this oscillation to be traced from the earliest timescales following excitation (Fig. 9), which offers the opportunity to understand how initial and thermalized distributions of carriers interact to influence the overall lattice motion. The clear oscillations in the transient absorption signal are related to both the excited carrier population and to the motion of the lattice, which can be separated with suitable mathematical decomposition. Students learn about solid state dynamics from electronic carrier interactions, lattice motions, lasers and attosecond pulse generation, as well as important mathematical analysis methods.

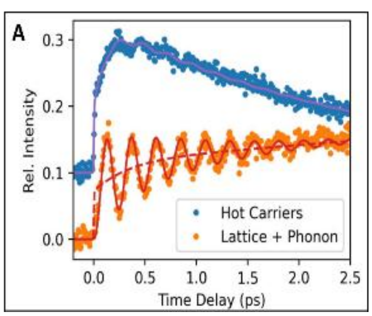

Fig. 9: Singular value decomposition of principal components of transient Sb signal. Blue curve corresponds to the signal attributed to carriers excited by the pump, with a decay related to the thermal relaxation and recombination of carriers. Orange curve describes the lattice temperature and position (phonon).

Light Matter Interactions in Solid-State High Harmonic Generation Spectroscopy (UCB Prof. Michael Zuerch)

Solid-state high harmonic generation (sHHG) is an emerging nonlinear spectroscopy technique based on strong-field interactions in a solid. In sHHG, an ultrafast pulsed driving field (typically mid-infrared, 3-4 μm wavelength) causes electron tunneling from the valence to conduction band in a semiconductor (Fig. 10). The electron then oscillates in the conduction band in concert with the driving field, resulting in harmonic emission within that band (called intraband); the electron can also recombine with the valence band hole resulting in an interband contribution to harmonic emission. The nonlinear outputs are in the visible to near ultraviolet. The resulting harmonic spectrum contains information on the electronic band structure and crystal symmetry of the material. An REU student will participate in sHHG measurements of single-crystal transition metal oxides and metal chalcogenides with the goal of developing a better understanding of how properties of the driving field, such as chirp (e.g. low frequency comes before high frequency in time), as well propagation through bulk materials affect the resulting harmonic spectrum. This project will enable accurate modeling of future sHHG measurements on bulk quantum materials for applications in energy conversion and quantum information. The project will enable the REU student to gain experience in applications of ultrafast lasers and the theory of strong-field light-matter interactions in solids while helping to develop a new and promising spectroscopy technique.

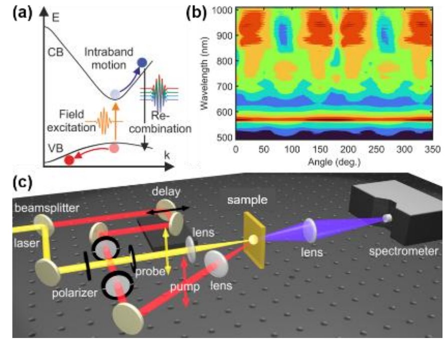

Fig. 10: (a) Schematic mechanism of sHHG showing strong-field electron tunneling, intraband motion, and recombination resulting in emission of high harmonics. (b) Example sHHG anisotropy measurement of (110) oriented ZnTe. (c) Optical layout of the pump-probe sHHG spectrometer.

<u>Second Summer Experience in Industry</u>

A unique aspect of this REU program is that students who complete one REU summer in CSU or UCB laboratories, still have two academic years before graduating with their undergraduate degree, and will be attending graduate school the year following graduation, will have the opportunity for a Second Summer Experience with an industrial partner.