Research Project Descriptions at Colorado State University and University of California, Berkeley

The 10-week summer program will be centered on engaging students in exciting and authentic research projects. Interns will be assigned specific research projects based on interest, level of prior preparation and challenge, and fit with faculty and graduate mentor research. The projects will allow interns to engage in advanced research that builds on concepts they may be familiar with, such as microscopes, interferometers, or Fourier Transformations, and will be designed to familiarize the interns with new concepts in optics, lasers, advanced light sources, and extreme ultraviolet (EUV technology). The projects reflect the varied and complementary expertise of the EUV ERC faculty and examples are listed below by core capabilities of partnering research institution. The REU intern's research activities will be aligned with the primary research thrusts of the Center.

Projects at Colorado State University

Generating the world's brightest laser light (CSU Prof. Jorge Rocca). Colorado State University has developed one of the most powerful lasers in the world: ALEPH (Advance Laser for Extreme PHotonics) [1](Fig. 1). This laser produces light pulses of very short duration, $3x10^{-14}$ seconds, with a peak power of 850 Terawatts, a power equivalent to 850 times the power produced by all power plants in the United States. When focused into a small spot its high intensity heats materials to extreme temperatures (many millions of degrees) and pressures similar to those found in the center of stars, producing flashes of ultrashort duration of x-ray and gamma rays for imaging. This powerful laser can also achieve nuclear fusion in a micro-scale. The project will consist in the development of laser amplifiers and optical systems that will make ALEPH even more powerful. Building these amplifiers will require both modeling and hardware, which will utilize concepts of electromagnetics, optics, and mechanical design.

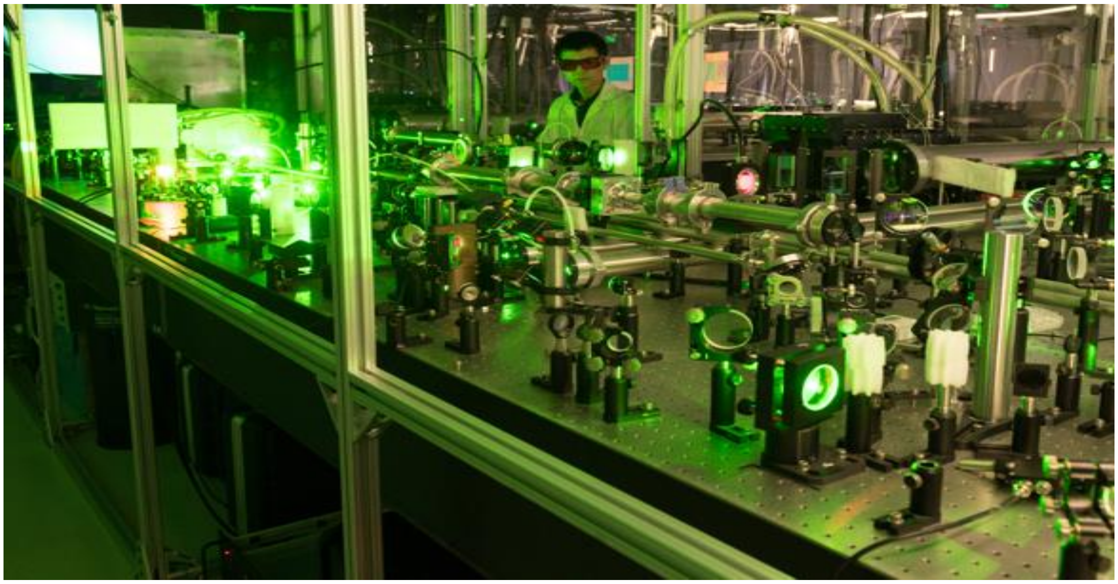

Figure 1. Ultrahigh power laser. The green laser beams energize Ti:Sapphire crystals that amplify light at 800 nm wavelength.

1. 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 400 nm second-harmonic beamline.* Optics Letters, **42**, 3828-3831, (2017)

Development of an Extreme Ultraviolet laser to study dynamics in magnetic materials (CSU Prof. Jorge Rocca & Prof. Mario Marconi, Prof. Kristin Buchanan). We will build a compact diode-pumped/solid state laser that will pump a EUV laser source (Fig. 2) to be dedicated to magnetic imaging. This laser will be based on EUV light generation in inverted atomic transitions in a laser-created plasma, a topic in which CSU is a world leader. Strategies to obtain wavelengths in the 20-30 nm spectral region from atomic transitions will be implemented to probe magnetic materials containing Co and Fe. This EUV laser will be used in holographic imaging described below to image magnetic materials in collaboration with Profs. K. Buchanan and M. Marconi. A spatial resolution of ~25 nm and picosecond temporal resolution are expected. The high energy per pulse of the CSU EUV laser source, orders of magnitude higher than what is available at a synchrotron, will enable single-shot dynamic imaging of magnetic processes. An REU student participating in this project will work on the design and implementation of the optical system necessary to create the plasmas in which the EUV light will be amplified. She/He will use programs such as Zemax ®, and subsequently will diagnose the laser-created plasmas learning how to use an EUV spectrometer and to analyze atomic spectra. In a follow-on project, a second REU will work to optimize these plasmas to obtain EUV laser action at different wavelengths of interest, using the same instrumentation and EUV photodiodes. The students will become familiar with EUV laser design and diagnostics.

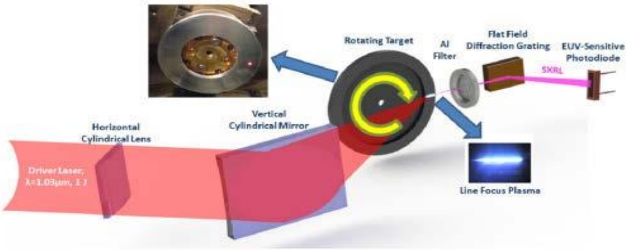

Figure 2: Schematic of table-top EUV laser. An optical laser beam is focused into a selected solid rotating target to generate a line focus plasma from which an EUV laser beam is generated.

Generation of intense ultrafast x-ray flashes from nanostructures irradiated with ultra-intense laser pulses (CSU Prof. Jorge Rocca). The interaction of femtosecond laser pulses of relativistic intensity with arrays of aligned nanostructures offers an opportunity to create extraordinarily bright, compact x-ray sources (Fig. 3). The REU student will have the opportunity to work growing arrays of nanowires and characterizing them by electron microscopy and will participate in conducting experiments in which these nanostructures are irradiated with one of the world's most powerful lasers. A recent experiment has shown converting a record ~ 20% of the laser energy into > 1 keV photons. Previously, the conversion efficiency of optical laser light into picosecond x-ray pulses was limited to less than 1%, owing to the rapid hydrodynamic expansion of the thin, hot plasmas created near the surface. The measured increase in x-ray yield is made possible by volumetrically heating arrays of vertically aligned gold nanowires with relativistic laser pulses (5×10^{19} W cm^{-2})**.** The laser energy is deposited deep into the nanowire array, where is practically totally absorbed to form a hot, near solid density plasma several microns in depth. This leads to a condition where the plasma energy is dissipated primarily by x-ray radiation greatly increasing the x-ray flux.

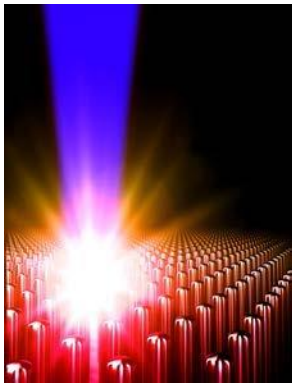

Figure 3. The interaction of femtosecond laser pulses of relativistic intensity with arrays of aligned nanostructures offers an opportunity to create extraordinarily bright, compact x-ray sources.

Active control of an ultra-high-power laser (CSU Prof. Jorge Rocca). Colorado State University has developed one of the most powerful lasers in the world: ALEPH (Advanced Laser for Extreme PHotonics). This laser produces pulses of very short duration, 30×10^{-15} seconds, with a peak power of 850 Terawatts, a power equivalent to 850 times the power produced by all power plants in the US. When focused into a small spot its high intensity heats materials to extreme temperatures and pressures similar to those found in the center of stars, producing flashes of ultrashort duration of x-ray and gamma rays for imaging. It also achieves nuclear fusion in a micro-scale (Fig. 4). When conducting experiments, the results of a single laser shot are analyzed, and the laser parameters are changed manually for the next shot. This process takes minutes, while on the other hand the laser is capable to fire up to several times per second. Therefore, the data acquisition rate is slowed more than two orders of magnitude. The project will consist of installing a suite of energy monitors, cameras, and other sensors to monitor the laser in combination with rapid plasma diagnostics. The data will be used to automatically make decisions to control devices within the laser to change its parameters as the experiment requires. REU students will have the opportunity to merge software with advanced hardware. This project is part of a collaboration with Lawrence Livermore National Laboratory in which artificial intelligence will be used to analyze experimental results in real time to make the decisions of the laser parameters for the next shot, closing the loop by automatically adjusting the laser parameters. This can approach can speed data acquisition by two orders of magnitude, potentially helping to transform high intensity laser science.

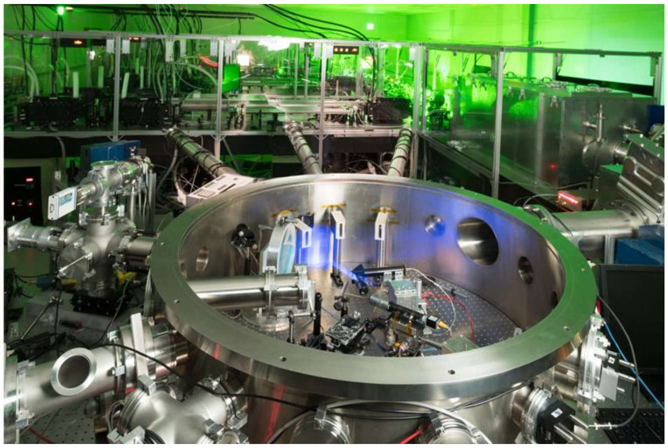

Figure 4. Target chamber for the interaction of ultrahigh intensity laser pulses with materials.

Development of a compact high average power ultrafast laser (CSU Prof. Jorge Rocca). A new generation of compact ultrafast high-power lasers promises to impact the printing of the next generation of integrated circuits by producing extreme ultraviolet light, generate x-ray beams for material science and medicine, and enable a new generation of particle accelerators. The CSU group is developing advanced high-power solid-state lasers using semiconductor laser diodes to provide the "pump" energy that excites the laser media, and cryogenic cooling to extract the heat (Fig. 5)[1]. The project will consist in finding solutions to heat dissipation and optical challenges to scale the concept of an existing laser amplifier prototype to higher pulse energy and average power. The REU student will be involved in aspects of the design, construction, and optimization of a thermally efficient high power laser amplifier.

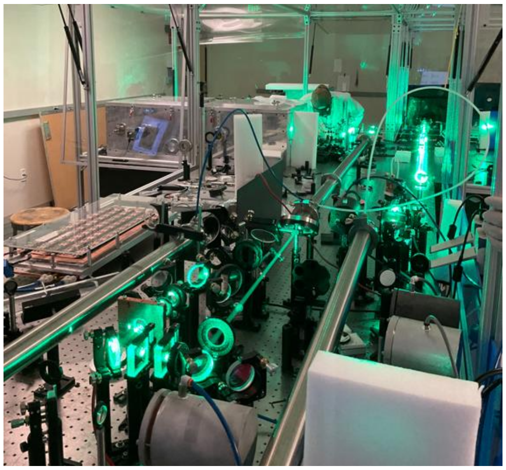

Figure 5. High average power infrared Yb:YAG laser efficiently frequency doubled to produce green pulses of 1 J energy at a record 1 kHz repetition rate (1 kW average power)

1. Y. Wang, H. Chi, C. Baumgarten, K. Dehne, A.R. Meadows, A. Davenport, G. Murray, B.A. Reagan, C.S. Menoni, and J.J. Rocca, *1.1 J Yb:YAG picosecond laser at 1 kHz repetition rate.* Optics Letters, **45**. 6615-6618 (2020).

Design, Fabrication and Diagnostics of interference coatings for high-intensity drivers (CSU Prof. Carmen Menoni). This project relates to 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 optical characterization to determine their absorption loss at near infrared wavelengths and for their stress. In particular, the REU student will be involved in the design and characterization of ultrabroad band coatings for ultrashort pulse lasers.

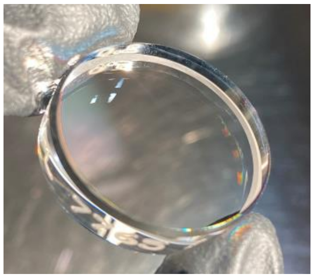

Figure 6. Multilayer mirror consisting of a stack of GeTiO and SiO2 layers, designed for high reflectivity at 1064 nm wavelength.

Amorphous oxides synthesis and characterization (CSU Prof. Carmen Menoni). 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 properties either by the synthesis method or by adding impurities. At CSU we have the capability to deposit metal oxide thin films by ion beam sputtering. We can deposit, binary, ternary and quaternary mixtures, as 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 to study how microstructure affects these properties Optimized thin film materials are used in the engineering of multilayer interference coatings for the ultrastable interferometer cavities of gravitational wave detectors. 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.

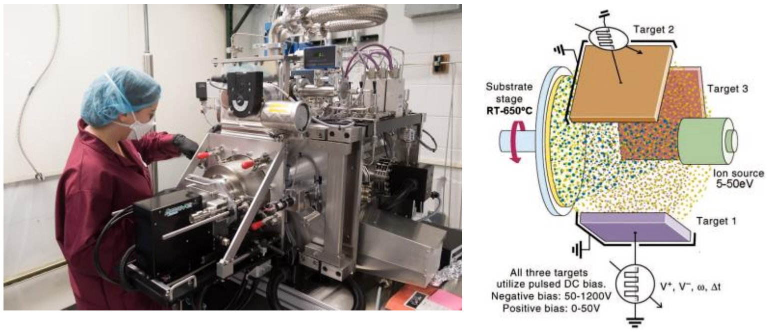

Figure 7. Bias target deposition system used to deposit mixtures of several oxides to create ternary and quaternary thin films. In this process, metal targets are biased to accelerate Ar ions into the target and sputter the target in a reactive oxygen atmosphere.

Super-resolution microscopy for defect identification and characterization (CSU Prof. Carmen Menoni). During the deposition of multilayer dielectric coatings, micron size particulate deposits on the growing thin films. When the coatings are illuminated by an intense laser beam, these impurities become point absorbers that can lead to thermos-mechanical instability causing catastrophic damage on the coating. In this project we are developing super-resolution imaging schemes that when implemented in a microscope 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.

Projects at University of California, Berkeley

Transient Absorption in Solids Utilizing High Harmonic EUV Light (UCB Prof. Stephen Leone). REU students will participate in transient absorption and transient reflectivity experiments utilizing high harmonic and attosecond EUV radiation. A project that is well suited to the summer REU program involves the measurement of dynamics in metal oxide materials or metal dichalcogenides to observe charge state dynamics. In MoTe2, for example, holes and electrons are observed after excitation across the band gap. In addition, coherent phonon motion is readily detected, and carrier cooling is measured. In Fe2O3 hematite, the initial photoexcitation with visible light results in the transfer of charge from an oxygen atom to an iron atom, changing the oxidation state of the iron from 3+ to 2+. This change is then accompanied by the formation of a polaron, where the vibrational motion of the lattice (phonons) adjusts to trap a charge on the iron atom. By probing these dynamics in materials that are tailored to alter the propensity for polaron formation, it is possible to characterize materials that have better or worse properties for charge separation (the formation of polarons reduces the possibility for charge separation.) New measurements are being initiated with four wave mixing of EUV light in solids. In these experiments, students will learn about charge carrier dynamics in materials that can provide for solar utilization and energy conversion from sunlight to electricity. In addition, students will learn modeling of EUV spectra to interpret their meaning, effects such as hot carrier relaxation and polaron formation, as well as deposition of energy into phonon modes. Concepts of electronic charge migration and recombination are also acquired.

Molecular Photophysics at the Carbon K Edge[5] (UCB Prof. Stephen Leone). The photochemistry of organic 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 ultraviolet pulses and 300 eV photons are used to probe the changes in orbital structure around carbon atoms in the molecule. An example is ring opening (Figure 5), in which is found that ring shaped molecules containing heteroatoms such as oxygen have dramatically different spectra at the carbon K edge when one atom of carbon becomes free from its initial bond to the heteroatom. The timescales for the dynamics are directly obtained in the ultrafast 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 provide important mathematical concepts for future careers.

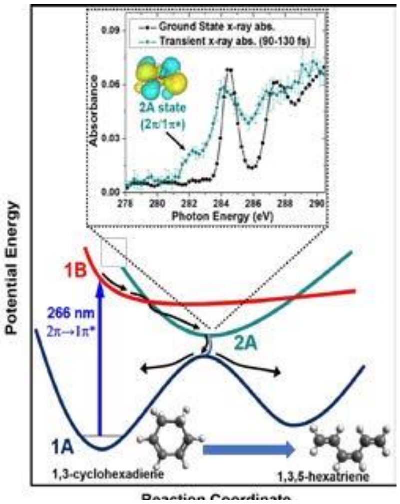

Figure 8. Direct fs identification of the transition state 2A, arrow, for cyclohexadiene ring opening.

Light matter interactions in solid-state high harmonic generation spectroscopy (UCB Michael Zuerch). Solid-state high harmonic generation (sHHG) is an emerging nonlinear spectroscopy technique driven by 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. The electron then oscillates in the conduction band under the driving field, resulting in harmonic emission from intraband currents, and then recombines resulting in an interband contribution to harmonic emission in the visible to NUV/VUV. The resulting harmonic spectrum imprints information of the electronic band structure and crystal symmetry of the material. An NSF REU student will participate in sHHG measurements of single-crystal transition metal oxides and chalcogenides with the goal of developing a better understanding of how properties of the driving field such as chirp 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. This will enable the NSF 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.

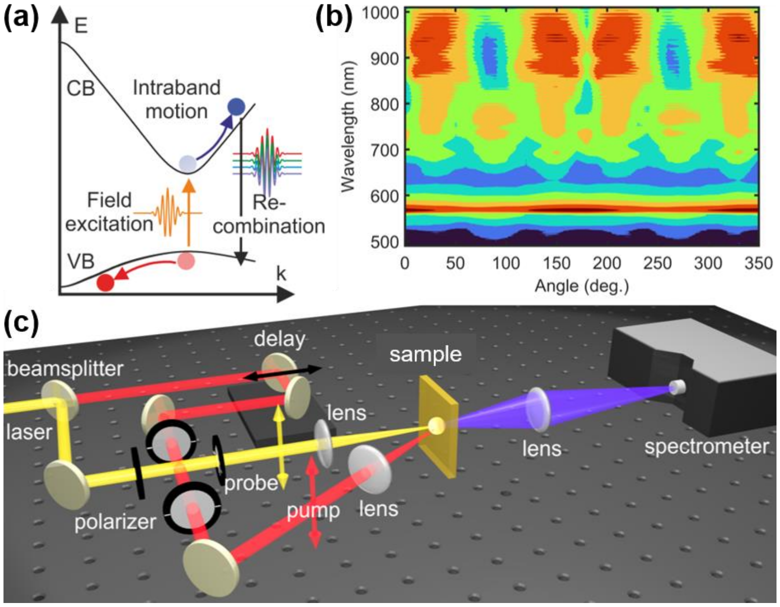

Figure 10. (a) Schematic mechanism of sHHG showing strong-field electron tunneling, intraband motion, and recombination resulting in emission of high harmonics. (b) Example sHHG anisotropy measurement of (110) oriented ZnTe. (c) Diagram showing the optical layout of the pump-probe sHHG spectrometer in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