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 build 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 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

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 $\times 10^{-15}$ seconds, with a peak power of 850 Terawatts, a power equivalent to 850 times the power produced by all power plants in the United States. 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. 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 several 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 consists in installing a suite of energy monitors, cameras, and other sensors to monitor the laser. 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 in real time the results of an experiment to make the decisions of what should be 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.

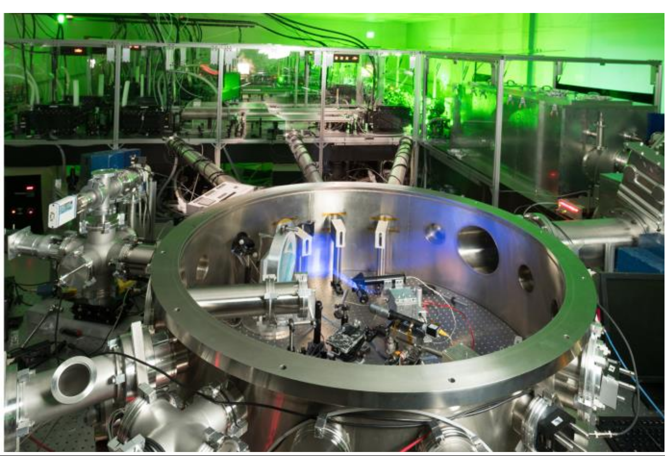

Fig. 1. Target chamber for the interaction of ultrahigh intensity laser pulses with materials.

Fig.2. High average power infrared Yb:YAG laser which output is efficiently frequency doubled to produce green pulses of 1 J energy at a record 1 kHz repetition rate (1 kW average power)

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. 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.

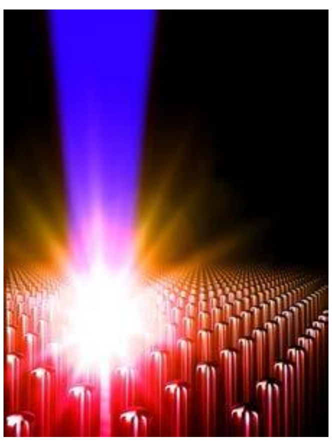

Figure 5. The interaction of femtosecond laser pulses of relativistic intensity with arrays of aligned nanostructures offers an opportunity to create extraordinarily bright, compact x-ray sources.

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. The REU student will have the opportunity to work growing arrays of nanowires and characterizing them by electron microscopy. The REU student will participate in experiment 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 > 1keV 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 micron in depth. This leads to a condition where the plasma energy is dissipated primarily by x-ray radiation greatly increasing the x-ray flux.

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.

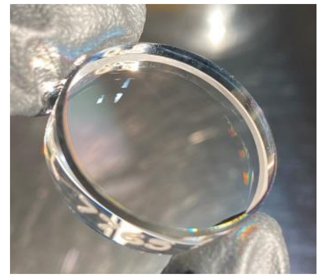

Figure 4. Multilayer mirror consisting of a stack of GeTiO and SiO2 layers, designed for high reflectivity at 1064 nm wavelength.

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.

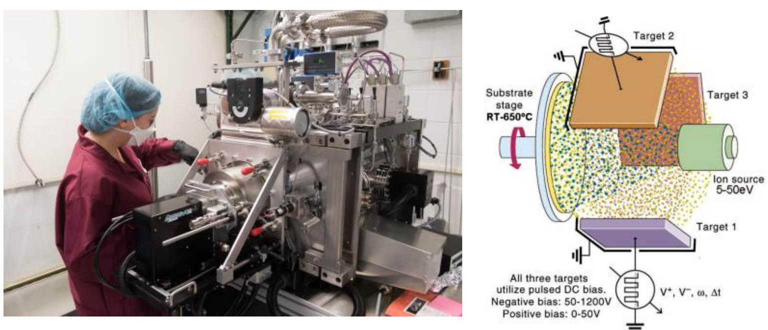

Figure 3. Bias target deposition system used to deposit mixtures of several oxides to create ternary and quaternary thin films. In this process, metal targets are biased to accelerate Ar ions into the target and sputter the target in a reactive oxygen atmosphere.

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.

<ins>Molecular Photophysics at the Carbon K Edge[5]</ins> (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.

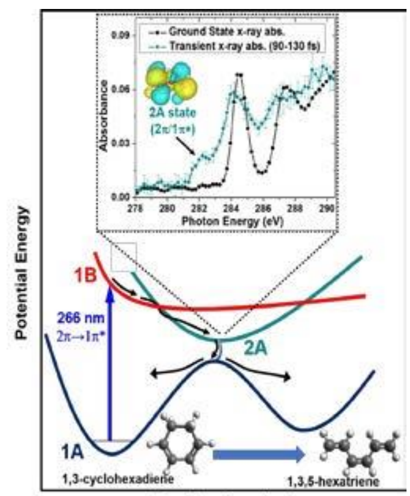

Figure 6: Direct fs identification of the transition state 2A, arrow, for cyclohexadiene ring opening.

<ins>Ultrafast x-ray dynamics in quantum materials</ins> (UCB Michael Zuerch). Quantum materials often host exotic, emergent properties as a result of strong correlations between electrons, for which superconductivity, magnetism, and Mott insulators provide some representative examples. Given the complex couplings between multiple degrees of freedom, so-called strongly-correlated materials often exist in a complicated phase space with multiple competing ground states. Ultrashort light pulses are the perfect tool to both probe the nature of emergent phenomena and control its properties on the natural spatiotemporal scales of charge, spin, and lattice motion. In the Zuerch lab, we use pump-probe methods to study quantum materials, with a particular interest towards mesoscale ordering phenomena and phase transitions. We are currently building a state-of-the-art beamline to perform attosecond time-resolved x-ray absorption spectroscopy and resonant x-ray diffraction in a single measurement to probe materials on ultrafast timescales with nanoscale resolution and element specificity (Fig. 6). With carrier envelope phase (CEP)-stabilized pump pulses, full intensity, and polarization control, the ultrafast dynamics that ensue following a sub-cycle optical perturbation can be followed with great detail. In the

summer of 2021, we will be performing experiments on multiferroic materials that exhibit coupled ferroelectric and ferromagnetic ordering and looking towards upgrading our beamline towards higher photon energies, generating circularly polarized x-rays to study chiral systems, and implementing a THz light source to excite low-energy excitations. An NSF REU student will assist in these endeavors, learning about quantum materials, ultrafast dynamics, and x-ray attoscience in the process.

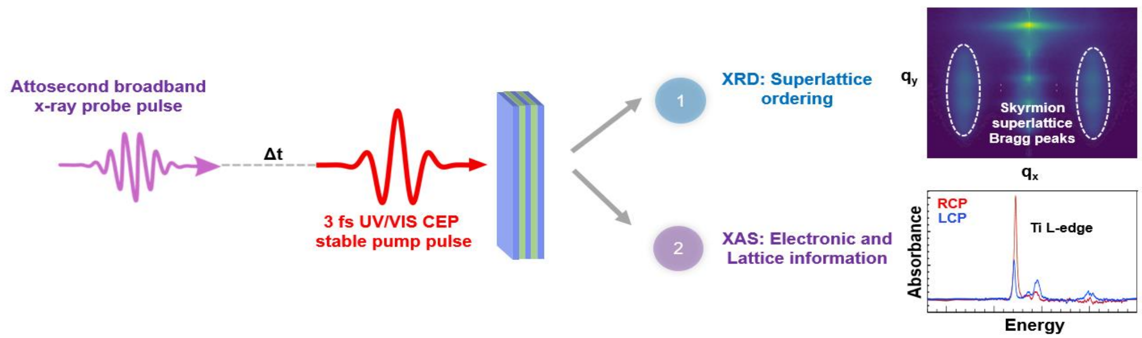

Fig 7. A few-fs UV/VIS CEP-stable pump pulse followed by an attosecond, broadband x-ray probe pulse after a variable time delay is incident on heterostructure with superlattice ordering. The diffracted beam (1) is scattered onto a camera, where the resulting Bragg peaks provide information about the superlattice periodicity. The transmitted beam (2) is simultaneously captured, yielding transient absorption spectra that report on electronic and lattice dynamics. Static diffraction and absorption spectra from ref. [S. Das et al, Nature **568**, 368 (2019)].