NSF ERC for EUV Science and Technology

news from the EUV ERC

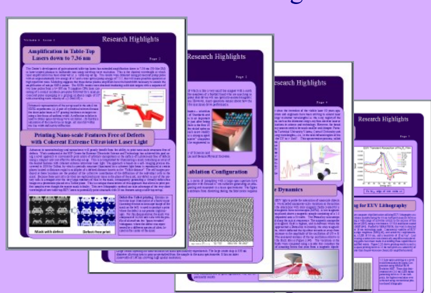
Volume 4 Issue 1 April, 2012

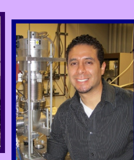
Special Edition - Focus on Research -

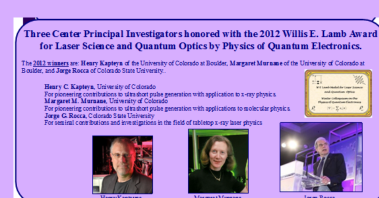
This edition of the EUV ERC Newsletter provides an extended focus on Center research. With the publication of the annual report to the NSF, we have selected topics from that report that demonstrate recent advances and accomplishments. In some cases, the results of this work have not yet been published. Members of the IAB receive advanced access to materials of this nature. Browse the research summaries and contact the Center if you would like to learn more. We have also included in this newsletter a list of publications released since the last newsletter distributed to you in 2011.

Other Features: For those of you attending CLEO 2012, we have provided a detailed list of all presentations that will be delivered by Center researchers. This edition of the newsletter also contains a list of awards and honors given to Center Principal Investigators, postdocs and graduate students. Finally, you will find an overview of this year's IAB meeting held in February. This year's meeting was highly successful thanks to the active participation of IAB members.

Inside This Issue

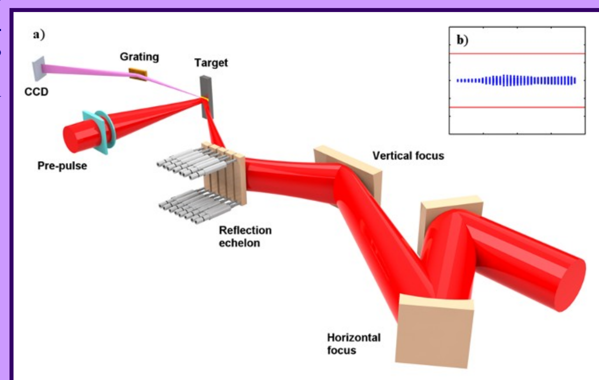


Amplification in Table-Top Lasers down to 7.36 nm

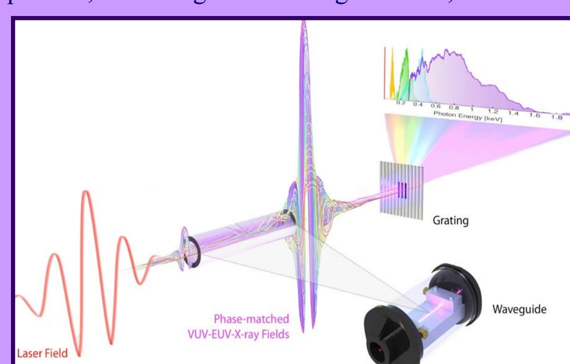
The Center's development of gain-saturated table-top lasers has extended amplification down to 7.36 nm (Ni-like SM) in laser-created plasmas in lanthanide ions using traveling wave excitation. This is the shortest wavelength at which laser amplification has been observed in a table-top set up. The results were obtained using picosecond pump pulse with an unprecedentedly low energy of 4 J and a total optical pump energy of 7.5 J, that will make possible operation at high repetition rates. Modeling suggests that these dense plasma amplifiers have the bandwidth necessary to sustain the amplification of sub-ps SXRL pulses. The SXRL results were obtained irradiating solid slab targets with a sequence of two laser pulses from a λ= 800 nm Ti:sapphire CPA laser consisting of a normal incidence pre-pulse followed by a main picosecond pulse impinging at a grazing incidence angle of 35º with a traveling wave velocity of ~(1.04±0.03) c as published in Phys. Rev. Lett., **84** 4834 (2000).



Schematic representation of the set up used in the sub-9 nm SXRL experiments. (a) A pair of cylindrical mirrors focuses the short pulse beam at 35º grazing incidence on target creating a line-focus of uniform width. A reflection echelon is used to obtain quasi-traveling wave excitation. (b) Raytrace simulation of the line-focus on target. All rays fall within the line width defined by diffraction.

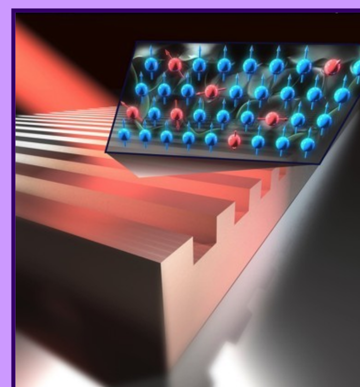
Bright Kiloelectronvolt X-Ray Supercontinuum from Tabletop Femtosecond Lasers

Ever since the invention of the visible laser 50 years ago, scientists and engineers have been striving to extend laser technology to shorter wavelengths i.e. the *x-ray* region of the spectrum. This quest has led to the construction of very large-scale facilities, such as the kilometer-long x-ray free-electron laser at Stanford, to reach the keV photon energy region that enables many applications in science and technology. However, for broad applications in science, medicine and industry, laser-like (i.e. coherent) x-ray sources need to be much smaller and cheaper. Fortunately, research at the NSF EUV ERC in Boulder in collaboration with the Technical University Vienna, Cornell University and the University of Salamanca has shown that by using ultrafast lasers with *long* wavelengths—i.e., in the mid-infrared region of the spectrum—bright x-ray radiation can be emitted at photon energies from the UV to > 1keV. This upconversion process, called high harmonic generation, traditionally combines up to ~100 near-infrared laser photons (0.8 µm wavelength), to generate bright, coherent, extreme ultraviolet beams at photon energies around 100 eV. The team found that by guiding a mid-infrared (4 µm) femtosecond laser in a high pressure gas, up to 5000 laser photons can be efficiently combined together, creating an x-ray supercontinuum that spans the entire electromagnetic spectrum from the ultraviolet to > 1.6 keV. This work essentially realizes a laser-like, coherent, tabletop, version of the Roentgen x-ray tube in the soft x-ray region. Moreover, the generated x-ray bursts are short enough (2.5 attoseconds or < 10^{-17} seconds) to capture all motion relevant to our natural world, even at the level of electrons. This work will soon be published in *Science*.



Spin-Sensitive Probes of Magnetic Dynamics

Strong magnets exist only because all the spins in a magnet, each of which is like a very small bar magnet with a north and south pole, are lined up to point in the same direction, much like members of a football band who are marching in unison. Many technology experts believe that next-generation computer disk drives will use optically-assisted magnetic recording to store more data, more efficiently, and with faster access. However, many questions remain about how the delivery of optical energy to the magnetic system can be optimized for maximum drive performance.

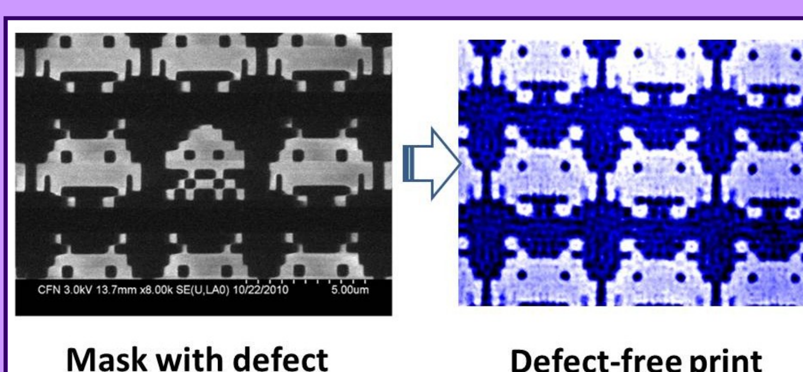


Using the world's fastest light source – bursts of laser-like X-ray beams -- scientists at the University of Colorado Boulder and the National Institute of Standards and Technology could see that the different microscopic bar magnets in an important magnetic alloy of iron and nickel (permalloy) behave differently just after being exposed to laser light (in the first few quadrillionths of a second which is the first 10 femtoseconds). The iron spins reacted slightly faster to light than the nickel spins as shown in the figure, suggesting that the iron spins "see" light much more readily than the nickel spins. Until now, it was assumed that all the spins in a strong magnet behaved in the same way. This finding could lead to faster and "smarter" computers because it suggests that the magnetic alloys in hard drives could be engineered to enhance the delivery of the optical energy to the spin system.

The results appeared in the Proceedings of the National Academy of Sciences and were featured in news articles by Physics Today and by the American and German Physical Societies.

Printing Nano-scale Features Free of Defects with Coherent Extreme Ultraviolet Laser Light

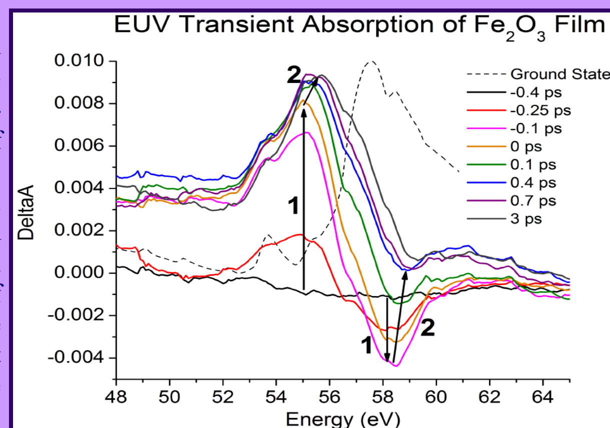
Advances in nanotechnology and nanoscience will greatly benefit from the ability to print nano-scale structures free of defects. Work conducted at the NSF Center for Extreme Ultraviolet Science and Technology has achieved this goal using a novel approach to conveniently print arrays of arbitrary nanopatterns in the surface of a photoresist free of defects using a compact and cost effective table-top set-up. This is accomplished by illuminating a mask containing an array of the desired features with coherent extreme ultraviolet laser light. The approach is based on a self- imaging process discovered in 1836 by Talbot, by which a periodic structure illuminated by a coherent light beam is reproduced at certain planes located at distances equal to multiples of a defined distance known as the "Talbot distance". The self images produced at these locations are the product of the collective contribution of the diffraction of the individual cells in the mask. Because these unit cells (or tiles) are replicated many times in the plane of the mask, any defect in any of the unitary cells is averaged over the very large numbers of tiles in the mask, consequently generating a virtually defect-free image on a photoresist placed on a Talbot plane. This is a unique characteristic of this approach that allows to print perfect samples even though the master mask is faulty. This new lithographic method can take advantage of the very short wavelength of new table-top EUV lasers to potentially print structures with 10 nm features using a table-top set-up.



Defect-free Talbot printing. Extreme ultraviolet laser illumination of a faulty mask (scanning electron microscope image of the mask on the left) is used to produce a print where the defect is not present (right image). For this demonstration the mask was composed of 10,000 unit cells with the profile of aliens from the "space invaders" videogame, where the defect was represented by a different species of alien, located in the center of the mask.

EUV Transient Absorption in the Solid-state Domain

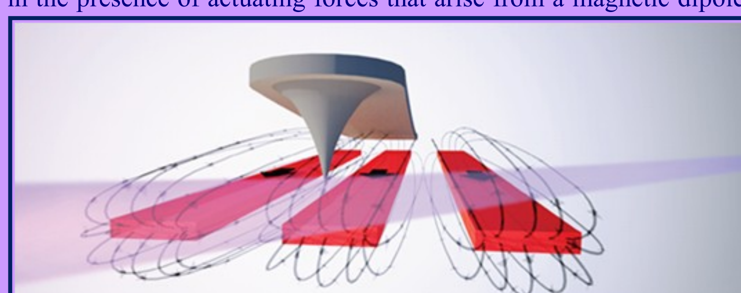
In the past year, we have expanded EUV transient absorption to the solid-state domain allowing for the probing of core level transitions in iron containing thin films in the non-perturbative regime. Currently, the $M_{2,3}$ absorption edges of iron, iron oxide, and cobalt oxide have been observed at ~54, 56, 62 eV, respectively, in static spectra. Iron oxide has been photoexcited at 400 nm to yield a time-dependent excited state spectrum showing a featuring arising 3 eV lower than the ground state metal edge followed by a 0.5 eV blue shift of the feature on the femtosecond timescale as seen in the figure on the right. Future work will focus on CdSe quantum dot semiconductors charge transfer dynamics, which will be probed through the selenium 3d $M_{4/5}$ shell transitions at 55 eV as well as the cadmium $N_{2/3}$ 4p levels at 64 eV.



Fe $M_{2,3}$ edge of iron oxide at

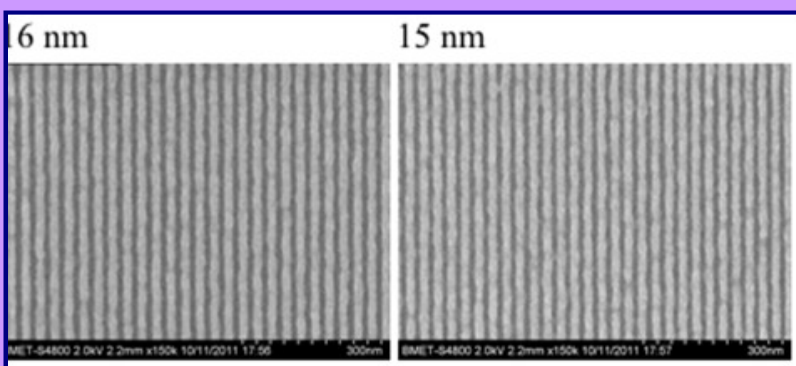
Proving Nano-scale Dynamics

The immunity of photon beams to electric and magnetic fields allows EUV light to probe the interaction of nanoscale objects in the presence of external fields. In a proof-of-principle experiment we recorded nanometer-scale variations in the motion of a standard cobalt-alloy coated magnetic nanoprobe tip induced by the interaction with stray magnetic fields created by a magnetic sample in a fashion that resembles the operation of standard magnetic force microscopes (MFM). A low magnetic moment MFM tip oscillating at a resonant frequency of 65.6 KHz was placed above a magnetic sample consisting of a 1:1 array of 2 µm wide strips patterned on a 40 nm thick Permalloy film deposited onto a Si wafer. The Permalloy microstrips exhibit strong uniaxial shape anisotropy and hence remain magnetized along the axis at remanence. The magnetic nanoprobe tip was positioned close to the end of the microstrips where the stray magnetic field is highest, and in-between where the stray field is nearly zero. As the resonating magnetic nanoprobe tip approached a Permalloy microstrip, the stray magnetic fields exerted a magnetic force with a gradient of the order of 10^{-2} N/m, which deflected the tip either towards or away from the sample surface depending on the sign of the magnetization. An increase in the amplitude of the oscillation of (30 ± 3) nm with respect to the natural oscillation amplitude was measured. The measured extrema of the tip oscillation relative to the magnetic surface determined from the images are represented by the black dots in Figure 3.34b. The variations in the oscillation amplitude due to the interaction with the stray magnetic fields were computed using a model that considers the magnetic tip to be a perturbed harmonic oscillator in the presence of actuating forces that arise from a magnetic dipole-dipole interaction. The non-uniform stray force fields effectively change the restoring force in the oscillating magnetic tip through a term that is proportional to the magnetic force gradient. As a consequence, when driving the tip at a fixed frequency, the amplitude and phase of the tip oscillation are modified. The computed loci of the tip during a full period oscillation are in good agreement with the experimental results



Nanometer Patterning for EUV Lithography

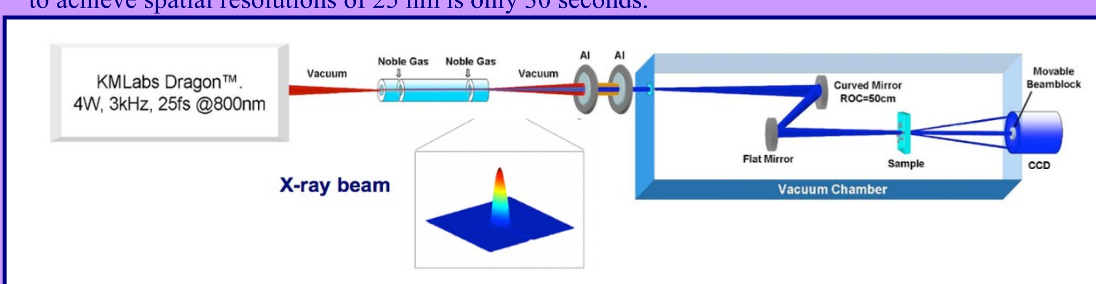
In support of the semiconductor industry's pursuit of future computer chip fabrication utilizing EUV lithography at a wavelength of 13.5 nm, which is expected to enter high volume manufacturing for 22 nm half-pitch memory devices as early as 2013, our NSF EUV Center has been pursuing a wide range of activities critical to the success of this international program. EUV pattern exposure (print) studies at LBNL using a two-bounce, 0.3 NA multilayer-coated aspheric system known as the Microfield Exposure Tool (MET)[48]. Funded by SEMATECH, this work is directed at EUV resist development to meet the challenges of the 16 nm technology node. Commercial viability of EUV requires resist to simultaneously achieve resolution, line-edge roughness (LER)[46], and sensitivity requirements. For example, 16 nm devices require a resolution of 8 nm, a LER of 0.9 nm, and a sensitivity of 10 mJ/cm^2. Last year we reported on breaking the 18-nm resolution barrier using a rather slow non-chemically amplifies resist developed by a start-up company called Inpria. This year, strong gains have been made in extending these capabilities to much faster and more commercially viable chemically amplified resists. Figure 2.26 shows printing results in such a material provided by JSR Corporation, demonstrating line-space printing down to 15 nm half-pitch at a sensitivity of approximately 30 mJ/cm^2 which is more the two times faster than the previous non-chemically amplified material.

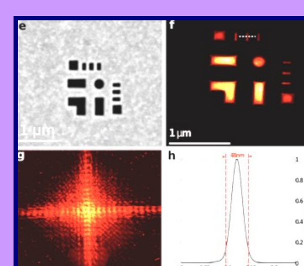


1:1 Line-space printing in a novel resist formulation by Inpria Corporation using SEMATECH Berkeley MET. These data demonstrate low (2.0 nm) LER dense patterning down to 15 nm half-pitch, the highest resolution ever achieved using conventional photon-based lithography

Coherent Diffractive Microscope using Compact HHG Sources

In work published in Physical Review Letters, PNAS, Optics Letters and Nature, the EUV ERC implemented a coherent diffractive microscope using compact HHG sources for the first time. News articles on this work also appeared in Nature and Nature Photonics. Rapid progress was made over a period of 4 years, increasing the achievable spatial resolution from an initial 200 nm, to 100 nm, to 50 nm and now 22 nm. The spatial resolution we have now demonstrated, at < 22 nm using 13 nm wavelength HHG illumination is the highest ever achieved using any table-top light-based microscope. Most importantly, the image acquisition time to achieve spatial resolutions of 25 nm is only 30 seconds.





Set-up for lensless imaging using HHG. A fully coherent EUV beam oversamples an object that is surrounded by a region that contains no diffracting objects. The diffraction pattern, minus the straight through x-ray beam, can be processed to retrieve the image of the object. (Left) Coherent diffractive imaging at 13 nm, with a spatial resolution of ≈ 22 nm . (e) SEM image of sample. (f) retrieved image. (g) diffraction pattern. (h) lineout.

If you have further interest in any of these topics, please contact Robert.Bower@colostate.edu

Publications H2, 2011-Q1, 2012

C. La-O-Vorakiat, E. Turgut, C. A. Teale, H. C. Kapteyn, M. M. Murnane, S. Mathias, M. Aeschlimann, C. M. Schneider, J. M. Shaw, H. Nembach, T. J. Silva, "Ultrafast Demagnetization Measurements using Extreme Ultraviolet Light: Comparison of Electronic and Magnetic Contributions", Physical Review X **2**, 011005 (2012). *See also associated Physics Viewpoint Highlight "Spin Sensitive Optics" by Jean -Yves Bigot in Physics* ***5****, 11 (2012)*

X. Zhou, P. Ranitovic, C. Hogle, J. H. D. Eland, H.C. Kapteyn and M.M. Murnane, "Probing and Controlling non-Born-Oppenheimer Dynamics in Highly Excited Molecular Ions", Nature Physics, 232, doi:10.1038/NPHYS2211 (2012)

R. M. Lock, S. Ramakrishna, X. Zhou, H. C. Kapteyn, M. M. Murnane, and T. Seideman, "Extracting continuum electron dynamics from high harmonic emission from molecules," Physical Review Letters, **108**, 133901 (2012)

L. Urbanski, M.C. Marconi, L.M. Meng, M. Berrill, O. Guilbaud,A. Klisnick, and J.J. Rocca, "Spectral linewidth of a Ne-like AR capillary discharge soft-x-ray laser and its dependence on amplification beyond gain saturation", Physical Review A, **85**, 033837, (2012)

H. Bravo , B.T. Szapiro , P.W. Wachulak, M.C. Marconi, W. Chao , E.H. Anderson, D.T. Attwood, C.S. Menoni, J.J. Rocca, " Demonstration of nanomachining with focuses extreme ultraviolet laser beams", IEEE Journal of Selected Topics in Quantum Electronics, **18**, 443, (2012)

F. Brizuela, I. Howlett, S. Carbajo, A. Sakdinawat, Y. Liu, D. Attwood, M. Marconi, M. Marconi, J.J. Rocca, C.S. Menoni, " Imaging at the nanoscales with practical EUV laser based full field microscopes", IEEE Journal of Selected Topics in Quantum Electronics, **18**, 434, (2012)

D. Alessi, Y. Wang, D. Martz, B. Luther, L.Yin, D.H. Martz, M.R. Woolston, Y. Liu, M. Berrill, and J.J. Rocca, "Efficient excitation of gain-saturated sub-9 nm wavelength table-top soft X-ray lasers and lasing down to 7.36 nm", Physical Review X , **1**, 021023 (2011)

L. Urbanski, M.C. Marconi, A. Isoyan, A. Stein, C.S. Menoni, J.J. Rocca, "Analysis of a scheme for de-magnified Talbot lithography", Journal of Vacuum Science and Technology B, **29**, 06F504 (2011)

D. Nardi, M. Travagliati, M. E. Siemens, Q. Li, M.M. Murnane, H. C. Kapteyn, G. Ferrini, F. Parmigiani, and F. Banfi, "Probing Thermomechanics at the Nanoscale: Impulsively Excited Pseudosurface Acoustic Waves in Hypersonic Phononic Crystals", Nano Letters **11**, 4126 (2011)

X. M. Tong, P. Ranitovic, C. W. Hogle, M. M. Murnane, H. C. Kapteyn, and N. Toshima, **"**Theory and experiment on laser-enabled inner-valence Auger decay of rare-gas atoms", Physical Review A, 84(1), 013405. (2011)

H. C. Kapteyn and M. M. Murnane,"Imaging in the Ultrafast Lane", Photonics Spectra, May (2011)

X. Zhang, E. Schneider, G. Taft, H. Kaptyen, M. Murnane, S. Backus, "Multi-microjoule, MHz repetition rate Ti:Sapphire ultrafast regenerative amplifier system", Optics Express, **20**, 7015-7021 (2012)

S. Mathias, C. La-O-Vorakiat, P. Grychtol, P. Granitzka, E. Turgut, J. M. Shaw, R. Adam, H. T. Nembach, M. E. Siemens, S. Eich, C. M. Schneider, T. J. Silva, M. Aeschlimann, M. M. Murnane, H. Kapteyn "Probing the timescale of the exchange interaction in a ferromagnetic alloy", PNAS, doi:10.1073/pnas.1201371109 (2012)

B. Doughty, L. H. Haber, C. Hackett, and S. R. Leone, "Photoelectron angular distributions from autoionizing $4s^1 4p^6 6p^1$ states in atomic krypton probed with femtosecond time resolution," J. Chem. Phys. **134**, 094307 (2011)

O. Bünermann, O. Kornilov, S. R. Leone, D. M. Neumark, and O. Gessner, "Femtosecond extreme ultraviolet ion imaging of ultrafast dynamics in electronically excited helium nanodroplets," IEEE J. Sel. Top. Quantum Electron, **18**, 308 (2012)

M. J. Abel, D. M. Neumark, S. R. Leone, and T. Pfeifer, "Classical and quantum control of electrons using the carrier-envelope phase of strong laser fields," Laser Photonics Rev. **5**, 352 (2011)

If you have further interest in any of these topics, please contact Robert.Bower@colostate.edu

Publications H2, 2011-Q1, 2012

L. H. Haber, B. Doughty, and S. R. Leone, "Energy-dependent photoelectron angular distributions of two-color two-photon above threshold ionization of atomic helium," Phys. Rev. A **84**, 013416 (2011)

C. J. Koh, C. L. Liu, C. Harmon, D. Strasser, A. Golan, O. Kostko, S. D. Chambreau, G. L. Vaghjiani, and S. R. Leone, "Soft ionization of thermally evaporated hypergolic ionic liquid aerosols," J. Phys. Chem. A **115**, 4630 (2011)

O. Kornilov, O. Bünermann, D. J. Haxton, S. R. Leone, D. M. Neumark, and O. Gessner, "Femtosecond photoelectron imaging of transient electronic states and Rydberg atom emission from electronically excited He droplets," J. Phys. Chem. A **115**, 7891 (2011)

T. G. Habteyes, S. Dhuey, D. Cabrini, P. J. Schuck, and S. R. Leone, "Theta-shaped plasmonic nanostructures: bringing ′dark′ multipole Plasmon resonances into action via conductive coupling," Nano Lett. **11**, 1819 (2011)

A. A. Cordones, T. J. Bixby, and S. R. Leone, "Direct measurement of off-state trapping rate fluctuations in single quantum dot fluorescence," Nano Lett. **11**, 3366 (2011)

B. Doughty, L. H. Haber, and S. R. Leone, "Pump-probe photoelectron-velocity-map imaging of autoionizing singly excited $4s^1 4p^6 np^1$ (n=7,8) and doubly excited $4s^1 4p^6 5s^1 6p^1$ resonance in atomic krypton," Phys. Rev. A **84**, 043433 (2011)

J. Stiegler, Y. Abate, A. Cvitkovic, Y. E. Romanyuk, A. Huber, S. R. Leone, and R. Hillenbrand, "Nanoscale infrared absorption spectroscopy of single sub-10 nm particles enabled by scattering-type near-field microscopy," ACS Nano. **5**, 6494 (2011)

[T. J. Bixby, A. A. Cordones, and S. R. Leone, "CdSe/ZnS quantum dot intermittency in N,N'-diphenyl-N,N'-bis(3-methylphenyl)-(1,1'-biphenyl)-4,4'-diamine (TPD)," Chem. Phys. Lett. **521**, 7 (2011)

A. J. Trevitt, S. Soorkia, J. D. Savee, T. S. Selby, D. L. Osborn, C. A. Taatjes, and S. R. Leone, "Branching fractions of the CN + C_3H_6 reaction using synchrotron photoionization mass spectrometry: evidence for the 3-cyanopropene product," J. Phys. Chem. A **115**, 13467 (2011)

F. Goulay, S. Soorkia, G. Meloni, D. L. Osborn, C. A. Taatjes, and S. R. Leone, "Detection of pentatetraene by reaction of the ethynyl radical (C_2H) with allene (CH_2=C=CH_2) at room temperature," Phys. Chem. Chem. Phys. **13**, 20820 (2011)

F. Goulay, A. J. Trevitt, J. D. Savee, J. Bouwman, D. L. Osborn, C. A. Taatjes, K. R. Wilson, and S. R. Leone, "Production detection of the CH radical reaction with acetaldehyde," J. Phys. Chem. A, doi:10.1021/jp2113126 (2012)

S. Soorkia, C-L. Liu, J. D. Savee, S. J. Farrell, S. R. Leone, and K. R. Wilson, "Airfoil sampling of a pulsed Laval beam with tunable vacuum ultraviolet synchrotron ionization quadrupole mass spectrometry: application to low-temperature kinetics and product detection," Rev. Sci. Instrum. **82**, 124102 (2011)

A. Golan, K. B. Bravaya, R. Kudirka, O. Kostko, S. R. Leone, A. I. Krylov, and M. Ahmed, "Ionization of dimethyluracil dimers leads to facile proton transfer in the absence of hydrogen bonds," Nature Chem., **4**, 323, doi:10.1038/nchem.1298 (2012)

S. D. Chambreau, J. A. Boatz, G. L. Vaghjiani, C. Koh, O. Kostko, A. Golan, and S. R. Leone, "Thermal decomposition mechanism of 1-ethyl-3-methylimidazolium bromide ionic liquid," J. Phys. Chem. A, doi:10.1021/jp209389d (2011)

J. Bouwman, F. Goulay, S. R. Leone, and K. R. Wilson, "Bimolecular rate constant and product branching ratio measurements for the reaction of C_2H with ethane and propene at 79 K," J. Phys. Chem., doi:10.1021/jp30105b (2012)

M. D. Seaberg; D.E. Adams; E.L. Townsend; D.A. Raymondson; W.F. Schlotter; Y.W. Liu; C.S. Menoni; L. Rong; C.C. Chen; J.W. Miao; H.C. Kapteyn; M.M. Murnane, "Ultrahigh 22 nm resolution coherent diffractive imaging using a desktop 13 nm high harmonic source," Optics Express, **19** 22470-22479, (2011)

Volume 4 Issue 1

Industrial Advisory Board Meeting February 16, 2012 San Jose, California

Members of the Center's Industrial Advisory Board joined Center Principal Investigators and staff for a meeting held at the end of the SPIE Advanced Lithography conference in San Jose, California. PIs Margaret Murnane, Patrick Naulleau and Jorge Rocca provided updates on Center research. The Industrial Liaison Officer, Bob Bower, provided attendees with an overview of industry program activities. Much of the latter part of the meeting focused on sustainability planning that will insure the Center is able to continue and grow ERC programs of benefit to industry.

This year's meeting provided a kick-off of the SWOT process completed recently with the report delivered to the Center. The Center's Executive Committed is sincerely grateful for the IAB's input to this process.

This year's meeting included presentations from the Center's Deputy Director, Margaret Murnane, University of Colorado, Boulder, Patrick Naulleau, Director, CXRO at Berkeley, and the Center Director, Jorge Rocca, Colorado State University.

Research Updates

Progress in the Development of High Harmonic Lasers and Applications
Margaret Murnane

Progress in the Development of EUV Lasers and Applications
Jorge Rocca

Progress in EUV Metrology Systems and Applications
Patrick Naulleau

Copies of these presentations are available for download at:
https://www.engr.colostate.edu/euverc/cfolder/cfiles/2012RetreatPresentations.zip

The Industrial Advisory Board now has a Vice Chairman to assist the Chairman in activities such as the annual SWOT Analysis, communications among the IAB members and the planning and execution of IAB business. Kent Carey of Agilent Technologies joins our Chairman, Bruno La Fountaine of Cymer. Please join us in welcoming Kent and expressing our appreciation to both Bruno and Kent for their work in support of the Center and the IAB.

Bruno La Fontaine
IAB Chairman

Kent Carey
IAB Vice Chairman

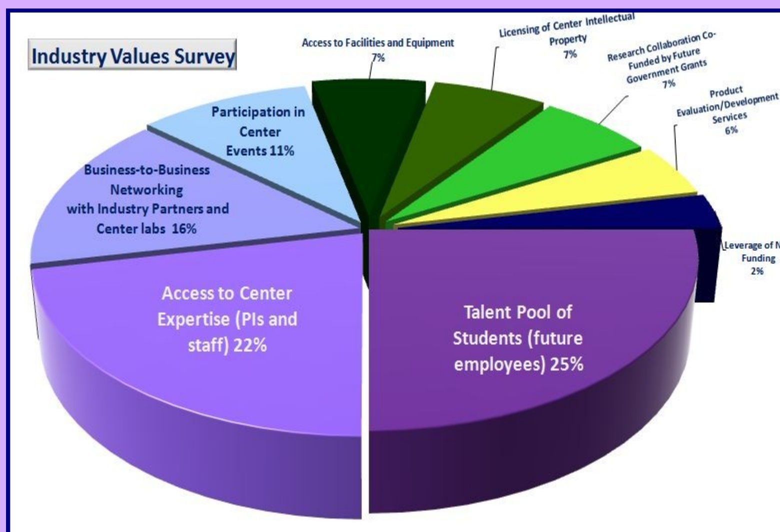
Industrial Advisory Board Meeting February 16, 2012 San Jose, California

Values Survey

Over a period of several weeks and culminating with the IAB meeting in February, 2012, the Center conducted an Industry Values Survey representing the areas of membership benefits in which industry members placed the highest value. The survey included:

- Access to Center expertise in lasers, advanced optical coatings, EUV sources and applications
- Access to facilities and equipment
- Research collaborations
- Joint proposals to gain federal funding
- Talented pool of students (prospective future hires)
- Leverage of NSF funding
- Licensing of Center IP

The results of this survey were presented for the first time at the IAB meeting in the form of the pie chart found in the figure to the right.



Integrative Graduate Education and Research Traineeship Program—IGERT

During the IAB meeting, we discussed the Center's plan to pursue an NSF IGERT grant. This NSF program has been developed to meet the challenges of educating U.S. Ph.D. engineers and scientists with interdisciplinary backgrounds, deep knowledge in chosen disciplines, and technical, professional, and personal skills. The program is intended to establish new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries The program will secure long-term support to continue training students in EUV Science and Technology. Graduates from this program enter industry with a broad range of interdisciplinary skills and experiences. In awarding an IGERT grant, the NSF is looking for a creative program that supports innovation to learn through hands-on experience and provides graduates with a view of how their own research may contribute to industry.

Industry's Role

Strong industry support for this program will have significant influence on an NSF decision to award an IGERT grant to the Center. With IAB endorsement, the Center proposes to dedicate net industry membership fees (after the Center's Industry Program expenses are met) to student fellowships in support of the IGERT program. At current levels, net industry fees would cover 2+ fellowships per year that, when added to the IGERT funding, would allow the Center to fund approximately 11 graduate fellowships per year. The Center's proposal envisions a program focused on an enhanced industry experience for our students. IAB member companies will have the opportunity to support that vision in a variety of ways within the following features:

- There should be an industry representative on each student's committee (2-3 year commitment)
- Industry representatives help teach an Industrial Entrepreneurship Seminar series providing insights into experiences in industry challenges, culture and operations.
- Each student has at least one industry-related project that
    - Enhances understanding of potentials for products and applications
    - Stimulates exploration of possible startup opportunities

As the Center works on and submits its proposal to the NSF, there will be requests for IAB members to write letters of support for the proposed program. We will continue to discuss this initiative in future IAB meetings and communications.

Awards and Honors

Dr. Margaret Murnane
Named the Winner of the 2011 RDS *Irish Times* Boyle Medal for Scientific Excellence.

An international team of judges conducted interviews with five finalists to select the winner of the 2011 medal. Dr. Murnane is only the second woman to be awarded the Boyle Medal since its inaugural year, 1899. The judges praised her work, saying that her super-fast laser systems represented outstanding research that would have a major impact on research activity in other disciplines.

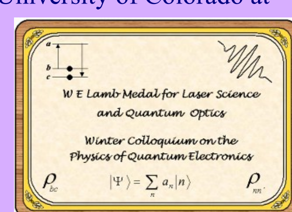
Dr. Murnane is originally from Co Limerick and attended University College Cork, completing a bachelor's and a master's degree in science before getting her PhD at the University of California, Berkeley, in 1989. She has won awards and fellowships throughout her career and was selected as a member of the US National Academy of Sciences in 2004. She was named a fellow of the American Academy of Arts and Sciences in 2006, before joining the President's Committee for the US National Medal of Science in 2010. She has also received distinctions from her University College Cork. Currently a member of the Department of Physics and Electrical and Computer Engineering at the University of Colorado in Boulder, Dr. Murnane is a Fellow at the Joint Institute of Laboratory Astrophysics and, since 2004, has been the Deputy Director of the National Science Foundation Engineering Research Center for Extreme Ultraviolet Science and Technology.

Professor Murnane's distinguished work has focused on the development of lasers which can operate at the fundamental limits of speed and stability. She designed the first laser able to pulse in the low trillionths of a second range (10 femtoseconds) which allows time almost to be halted to capture a freeze-frame view of the world. She has also developed a tabletop x-ray laser using very short laser pulses to generate coherent beams of x-rays. The output x-ray beam has all the directed properties of a laser - rather than the incoherent, light bulb-like, properties of the x-ray tubes used in science, medicine and security

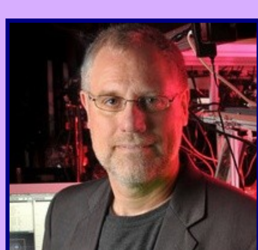
Dr. Murnane received her medal and delivered a public lecture at the Royal Dublin Society (RDS) on November 9, 2011. A broadcast of the lecture is available on the RDS website. See http://www.rds.ie/boylemedal for details.

Three Center Principal Investigators honored with the 2012 Willis E. Lamb Award for Laser Science and Quantum Optics by Physics of Quantum Electronics.

The 2012 winners are: **Henry Kapteyn** of the University of Colorado at Boulder, **Margaret Murnane** of the University of Colorado at Boulder, and **Jorge Rocca** of Colorado State University.



Henry C. Kapteyn, University of Colorado
For pioneering contributions to ultrashort pulse generation with application to x-ray physics.
Margaret M. Murnane, University of Colorado
For pioneering contributions to ultrashort pulse generation with applications to molecular physics.
Jorge G. Rocca, Colorado State University
For seminal contributions and investigations in the field of tabletop x-ray laser physics

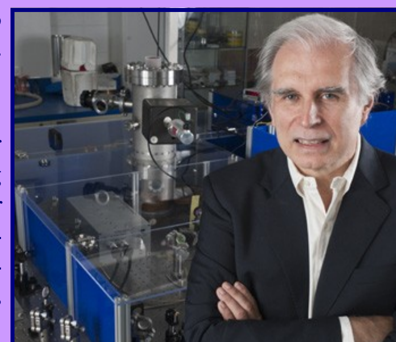

Henry Kapteyne


Margaret Murnane


Jorge Rocca

Awards and Honors

Arthur L. Schawlow prize Awarded to Dr. Jorge Rocca



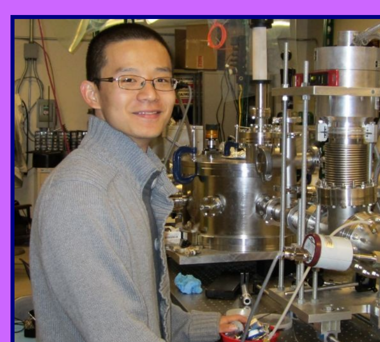
The Arthur L. Schawlow prize recognizes outstanding contributions to basic research which uses lasers to advance our knowledge of the fundamental physical properties of materials and their interaction with light.

Dr. Jorge Rocca, the Director of the EUV ERC, received the 2011 Arthur L. Schawlow Prize from the American Physical Society for his pioneering work in the development of compact "tabletop" soft X-ray lasers and their applications in areas such as nanoscale imaging, plasma and materials diagnostics, interferometry and photochemistry. Dr. Rocca accepted the prestigious award and gave a plenary address during the Frontiers in Optics (FIO) meeting 16 - 20 Oct. 2011, in San Jose, Calif.

EUV ERC Students win CPIA Annual Meeting Poster Competition

The Colorado Photonics Industry Association's 14th Annual Focus on University Research featured a student poster competition in which several dozen graduate students from research universities across Colorado explained their work to meeting attendees. The meeting was held at the University Memorial Center at the University of Colorado, Boulder, on October 25th. The judging team, made up of CPIA industry members, made their award selections based on communications skills as well as demonstrated knowledge of the research. Three prizes were awarded including two to EUV ERC students, one from the University of Colorado, Boulder, and one from Colorado State University.

Kathy Hoogeboom-Pot is working on her Ph.D. with advisors, Margaret Murnane and Henry Kapteyn at the University of Colorado, Boulder. Her winning poster is titled, "Surface Acoustic Wave Metrology using EUV Light".



Wei Li is a Masters candidate at Colorado State University. His advisor is Dr. Mario Marconi. Wei Li won this award for his poster titled, "Photolithography Process Using Extreme Ultraviolet Laser".

CLEO 2012
May 6 - 11
San Jose Convention Center

Monday, May 7
Ultrafast Mid-IR 8:00 AM - 10:00 AM; A2

8:00 – 8:15 CM1B.1. Ultrafast Optical Parametric Oscillator Pumped by an All Normal Dispersion (ANDi) Yb:Fiber Oscillator *Matthew Kirchner; Andrew Niedringhaus; Charles G. Durfee; Frank W. Wise; Daisy Raymondson; Lora Nugent-Glandorf; Henry C. Kapteyn; Margaret M. Murnane; Sterling Backus*

Ultrafast Sources 10:30 AM - 12:30 PM; C1 & C2

11:30 AM – 11:45 AM CM2J.2. Direct Diode Pumped Kerr Lens Modelocked Ti:Sapphire Laser Oscillator *Charles G. Durfee; Tristan Storz; Jonathan Garlick; Steven Hill; Jeff A. Squier; Matthew Kirchner; Greg Taft; Kevin Shea; Henry C. Kapteyn; Margaret M. Murnane; Sterling Backus*

Dynamics of Laser-Matter Interactions; 1:30 PM - 3:30 PM; San Jose Salon 1/2

2:15 PM – 2:30 PM CM3L.3. Nanoscale 3D composition imaging by soft x-ray laser ablation mass spectrometry *Ilya Kuznetsov; Jorge Filevich; Feng Dong; Weilun Chao; Erik Anderson; Elliot Bernstein; Dean Crick; Jorge Rocca; Carmen Menoni*

Tuesday, May 8
Molecular Attosecond Dynamics; 11:00 AM - 1:00 PM; A3

12:15 PM – 12:30 PM QTu1C.3. Ultrafast Dynamics of Ozone Exposed to Ionizing Radiation *Predrag Ranitovic; Craig W. Hogle; Leigh S. Martin; William Peters; Austin P. Spencer; Xiao Min Tong; David Jonas; Margaret M. Murnane; Henry C. Kapteyn*

Nonlinear Plasmonics and Nanophotonics, 11:00 AM - 1:00 PM; A6

12:45 PM – 1:00 PM QTu1F.8. Plasmon-assisted Photoemission from Gold Nanopillars in Few-cycle Laser Fields *Joseph S. Robinson; Phillip M. Nagel; Bruce D. Harteneck; Mark J. Abel; James S. Prell; Daniel M. Neumark; Thomas Pfeifer; Stephen R. Leone; Robert A. Kaindl*

XUV and X-Ray Attosecond Sources and Applications; 4:30 PM - 6:30 PM; A8

5:15 PM – 5:30 PM: QTu3H.4. Role of Self-focusing in Bright Coherent X-Ray Generation by Mid-Infrared Driving Lasers *Bonggu Shim; Samuel E. Schrauth; Tenio Popmintchev; Ming-Chang Chen; Dimitar Popmintchev; Skirmantas Ališauskas; Audrius Pugzlys ; Andrius Baltuška; Margaret M. Murnane; Henry C. Kapteyn; Alexander Gaeta*

5:30 PM – 5:45 PM QTu3H.5. Temporal structure of ultra high-order harmonic generation in the keV regime driven by mid-infrared lasers *Carlos Hernandez-Garcia; Tenio Popmintchev; Margaret M. Murnane; Henry C. Kapteyn; Agnieszka Jaron-Becker; Andreas Becker; Luis Plaja*

5:45 PM – 6:00 PM QTu3H.6. Demonstration of an 8.85 nm Gain-Saturated Table-Top Soft X-Ray Laser and Lasing down to 7.4 nm *Yong Wang; David Alessi; Brad Luther; Liang Yin; Dale Martz; Mark Berrill; Jorge Rocca*

Ultra-intense Laser Technology for Next-Generation Sources; 4:30 PM - 6:30 PM; A3

5:30 PM – 5:45 PM CTu3C.2. Table-top Short Pulse Driver for sub-10 nm soft X-ray lasers *Brad Luther; David Alessi; Yong Wang; Liang Yin; Dale Martz; Mark Woolston; Jorge Rocca*

CLEO 2012
May 6 - 11
San Jose Convention Center

Wednesday, May 9
Advanced Fabrication & Characterization Technologies; 10:30 AM - 12:30 PM; A8

11:45 AM – 12:00 PM AW1H.5. Defect Tolerant Extreme Ultraviolet Lithography
Lukasz Urbanski; Artak Isoyan; Aaron Stein; Jorge Rocca; Carmen Menoni; Mario Marconi

Thursday, May 10
Symposium on Advances in High-Power Lasers and their Applications II: Scientific Applications; 2:00 PM - 4:00 PM; B2/B3

2:00 PM – 2:15 PM JTh3I.1. Fully Spatially Coherent High Harmonic Beams in the keV Region of the Spectrum *Ming-Chang Chen; Tenio Popmintchev; Dimitar Popmintchev; Paul Arpin; Susannah Brown; Margaret Murnane; Henry C. Kapteyn; Skirmantas Alisauskas; Giedrius Andriukaitis; Tadas Balciunas; Audrius Pugzlys ; Andrius Baltuska*

Friday, May 11
High Harmonic and Diffractive Imaging; 8:00 AM - 10:00 AM; San Jose Salon 1/2

8:15 – 8:30 CF1L.2. Unified Microscopic-Macroscopic Picture of High Harmonic Generation from the VUV to the keV X-ray Region *Tenio Popmintchev; Dimitar Popmintchev; Ming-Chang Chen; Jonathas P. Siqueira; Carlos Hernandez-Garcia; Jose A. Perez-Hernandez; Luis Plaja; Andreas Becker; Agnieszka Jaron-Becker; Skirmantas Alisauskas; Giedrius Andriukaitis; Audrius Pugzlys ; Andrius Baltuska ; Margaret M. Murnane; Henry C. Kapteyn*

8:45 – 9:00 CF1L.4. Coherent Diffraction Imaging with an Apertured Illumination Support
Bosheng Zhang; Dennis Gardner; Leigh S. Martin; Matthew E. Seaberg; Daniel E. Adams; Margaret M. Murnane; Henry C. Kapteyn

9:30 – 9:45 CF1L.7. Fresnel-regime coherent diffractive imaging with with a 13 nm high harmonic source
Richard L. Sandberg; Dennis Gardner; Matthew E. Seaberg; Daniel E. Adams; Henry C. Kapteyn; Margaret M. Murnane; John L. Barber

9:45 – 10:00 CF1L.8. Tabletop Reflection Mode Coherent Diffractive Imaging of Periodic Nano-Structures with 100 nm Resolution *Matthew D. Seaberg; Daniel E. Adams; Bosheng Zhang; Margaret M. Murnane; Henry C. Kapteyn*

EUV Metrology; 8:00 AM - 10:00 AM; A3

8:30 AM – 8:45 AM CF1C.3. Thin film characterization using third harmonic generation microscopy*Cristina Rodriguez; Reed Weber; Duy Nguyen; Luke A. Emmert; Dinesh Patel; Carmen Menoni; Wolfgang Rudolph*

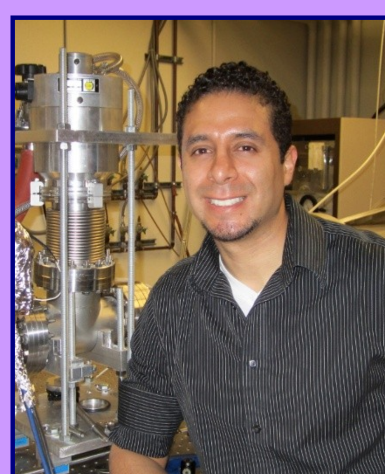
8:45 AM – 9:00 AM CF1C.4. Table-top Time-resolved Extreme Ultraviolet Nano-holography Scheme *Erik B. Malm; Christopher G. Brown; Przemyslaw W. Wachulak; Jorge Rocca; Carmen Menoni; Mario Marconi*

EUV ERC Students

Several Center graduate students will complete their degree work this year.

Lukasz Urbanski has been pursuing his doctorate degree at Colorado State University since 2008 and expects to graduate in the Fall of 2012. His research has focused on applications of compact EUV light sources to lithography. Concurrently, he is a guest researcher at the Center for Functional Nanomaterials at Brookhaven National Laboratory, where he is fabricating dedicated optics serving for EUV lithography experiments. His has expertise in nanofabrication using such techniques as: electron beam lithography, CAIBE (Chemically Assisted Ion Beam Etching), RIE (Reactive Ion Etching), plasma processing, thermal evaporation, electroplating. He is experienced in in surface characterization techniques such as: SPM (Scanning Probe Microscopy) and SEM (Scanning Electron Microscopy).

Erik Hosler has worked in EUV spectroscopy during his time at the EUV ERC. Erik is interested in a career in industry in the areas of research or development. During his graduate work at UC Berkeley, he has independently designed, and constructed a complex EUV transient absorption instrument, which included a high power femtosecond laser, a 10^{-9} torr vacuum apparatus, and EUV optical detection scheme. The instrument was employed in novel studies of molecular halide strong-field dynamics, including wavepacket formation and ionization-dissociation mechanisms. He has also led several scientific teams in experiments at the Advanced Light Source at Lawrence Berkeley National Lab, and collaborated with a large team of 26 scientists in a landmark experiment at the Linac Coherent Light Source at the SLAC National Accelerator Lab.



Herman Bravo expects to finish his M.S. in Mechanical Engineering later this year. His thesis is entitled, "Nanometer scale ablation and patterning with EUV light". His thesis work at the Center labs at Colorado State University has pushed the boundaries of nano fabrication by the employment of nanoscale ablation of 200 nm wide craters on thin film. The results were published in *Applied Physics*. His work in spectroscopy involved focusing light onto samples of chromium and then guiding that plasma to a spectrometer enabling the characterization of the chromium. This work would apply to materials contamination analysis in industry. He has extensive experience in systems design and integration and has supplemented this work with design of components and trouble shooting of operational systems. This work was supported by his skills in Mastercam, SolidWorks and CNC machining. Herman is very enthusiastic about a career in industry especially a position that would involve problem solving, creativity and interaction with both internal and external customers.

The Extreme Ultraviolet (EUV) Engineering Research Center is one of 15 centers established in the United States through the National Science Foundation and supplemented by industry funding. Colorado State University (CSU) is the host institution with partner sites at the University of Colorado (CU), UC Berkeley and Lawrence Berkeley National Laboratory. The Center research mission is the development of compact coherent EUV sources and EUV-engineered systems that provide solutions to challenging scientific and industrial problems, including the development of new tools for nanotechnology and nanoscience. The Center has an important educational mission providing a unique environment for the training of students, young engineers and scientists. An Industry Advisory Board (IAB) with members, ranging from large- to small- capitalized companies, spanning instrumentation, semiconductor, lasers and optics, nanotechnology and the biological and chemical sciences actively participate in early access to technologies, joint research projects, directed research projects and the hiring of the some of the best students in the world in these areas.

Industry Members

Industry Affiliates

Work supported by the National Science Foundation Cooperative Agreement No. EEC-0310717 and Matching Funds from Participating Institutions.