COLORADO HIGHER EDUCATION COMPETITIVE RESEARCH AUTHORITY

University of Colorado:Colorado State University:University of Northern Colorado:Colorado Schools of Mines:State of Colorado

March 1, 2024

Honorable Members of the House and Senate Education Committees
Colorado State Capitol
200 East Colfax Avenue
Denver, CO 80203

Re: Annual Report of the Colorado Higher Education Competitive Research Authority (CHECRA)

Dear Representatives and Senators:

Colorado Revised Statutes §23-19.7-103(3) requires the Colorado Higher Education Competitive Research Authority (CHECRA), housed at the Colorado Department of Higher Education, to report annually to the Education Committees of the Colorado House of Representatives and Senate on research projects funded by CHECRA in the previous calendar year. This letter reports on activities and projects funded in the calendar year 2023. This includes multi-year projects that received continued funding in 2023, and new initiatives funded for the first time in 2023.

CHECRA was created to provide a source of matching funds for National Science Foundation (NSF), U.S. Department of Energy, and other competitive federal grants that require or benefit from a state match. CHECRA funding has helped to bring significant research dollars to Colorado. Funding is used both to support multi-year research initiatives, including Engineering Research Centers and Science and Technology Centers, and to purchase large, expensive research instruments housed by one institution but used by faculty and staff from multiple colleges and universities.

CHECRA spent just over $2 million in 2023 to support eight multi-year research grants that collectively have brought many millions to the state. Following is a list of the multi-year research grants that received CHECRA funding in 2023:

University of Colorado

- In 2016, with CU Boulder as the lead awardee, the NSF awarded a $24 million, 5-year grant for the Science and Technology Center on Real-Time Functional Imaging (STROBE). STROBE brings together universities, national laboratories, industry, and international partners to create a powerful new set of real-time imaging modalities. STROBE was renewed after the initial 5-year period, and CHECRA pledged $400,000 per year for another five years; 2023 was the fourth year of funding for this project.

- The NSF Quantum Leap Challenge Institute, led by the University of Colorado Boulder, includes extensive collaborations with leaders from other academic institutions in the US and Europe, NIST, National Laboratories, and industry to make broad, fundamental advances in quantum science and engineering. The aim is to demonstrate and leverage quantum advantages in state-of-the-art quantum sensing across the field. The Institute is designed for core integration of research with education and workforce development. CHECRA has pledged $400,000 annually for five years; 2023 was the fourth year of funding.

- The NSF-funded Center for Integration of Modern Optoelectronics Materials on Demand STC, funded by the National Science Foundation, will develop new classes of optoelectronic materials, devices, and systems. These devices underpin the modern information technology era, and society is increasingly reliant on them for efficient lighting, information display, and optical data transmission. CHECRA made the third of five payments in 2023.

Colorado State University (CSU) and University of Colorado

- The NSF-funded ASPIRE ERC is a collaborative venture between the University of Colorado and Colorado State University (and other universities). The mission of ASPIRE is to improve the health and quality of life for everyone by catalyzing sustainable and equitable electrification across the transportation industries, using a holistic approach to eliminate range and charging as barriers to electric vehicle use. CHECRA made the 3rd of five payments of $325,000 to CU and 2nd of five payments of $75,000 to CSU in 2023.

Colorado State University

- The CSU ROOTS project funded by the Department of Energy Advanced Research Projects Agency – Energy (ARPA-E) is exploring the commercial use of soil sampling technologies and technologies in farm-scale soil carbon and greenhouse gas quantification. CHECRA has committed to providing $133,000 over three years and made the second payment in 2023.

- CSU's Optimizing Electric and Water Grid Coordination under Technical, Operational, and Environmental Considerations project under the DoE National Alliance for Water Innovation (NAWI) is examining strategies to manage and coordinate water system operations and the electric grid such that water treatment processes can be compatible with electrification efforts. CHECRA made the first payment of two payments of $29,612.

Colorado School of Mines

- CHECRA supported two NAWI projects at the School of Mines. The first focused on process controls for water treatment systems and the second on decontaminating water supplies. CHECRA provided the 2nd of three payments on each for a total of $95,420.

Appendices to this report include detailed information on each of the projects listed above. In addition to the millions of dollars in federal funding coming into the institutions and the state—and the impressive scientific results achieved under the projects—the research centers funded by CHECRA positively impact Colorado. These benefits include support for graduate and undergraduate students, outreach to K-12 students and teachers, and economic development benefits from spin-off technologies and companies.

Following are some highlights of these benefits to Colorado:

- CHECRA support to Colorado State University has created positive impacts that extend far beyond CSU's campus. These impacts span from increasing the understanding of – and contributing to the mitigation of – environmental and public health challenges associated with transportation in Colorado (via the APSIRE project, led by Dr. Jason Quinn); to enabling alternative water treatment technologies that are compatible with renewable energy sources that will help provide Colorado and beyond with the capacity to address constraints of water resource constraints (via the DOE NAWI project, led by Dr. Steve Conrad); and to contributing to - and catalyzing innovation in - the evaluation of root system traits for drought adaptation both at CSU and with private and public sector breeding programs, helping to support dryland agriculture both in Colorado and beyond (via the ARPA-E ROOTS project, led by Dr. John McKay). The support from CHECRA has enabled CSU research to address environmental challenges across water, agriculture, and transportation that are directly germane to Colorado and Coloradans.

- CHECRA supports impactful programs such as the NSF Quantum Leap Challenge Institute, which focuses on training the next generation of the quantum workforce and introducing underserved populations to opportunities in quantum science and engineering. Another significant initiative is the NSF Engineering Research Center for Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE), which is dedicated to eliminating range and charging as barriers to vehicle electrification. In addition to these, CHECRA funds outreach activities in K-12 schools. For instance, the Science and Technology Center on Real-Time Functional Imaging (STROBE) at CU Boulder collaborates with CU Science Discovery and teachers in the Four Corners region to develop engaging activities for middle school students.

During calendar year 2023, the Authority received a single distribution of Limited Gaming Funds of $2.1 million. Interest earnings on the Authority's funds totaled $28,046 in 2023. Expenses totaled $2,058,032.

Thank you for your support of this ongoing research. We welcome any questions.

Sincerely,

Dr. Angie Paccione

Dr. Angie Paccione
Executive Director, Colorado Department of Higher Education, and Chair, CHECRA

Cc: Dr. Walter Copan, Vice President for Research and Technology, Colorado School of Mines
Dr. Jeri-Ann Lyons, Associate Vice President for Research, University of Northern Colorado
Dr. Cassandra Moseley, Vice President for Research, Colorado State University
Dr. Massimo Ruzzene, Vice Chancellor for Research, University of Colorado Boulder
Dr. Tricia Johnson, Deputy Executive Director, Colorado Department of Higher Education, and Secretary, CHECRA

CHECRA Appendices:

Colorado School of Mines

Appendix A: Department of Energy National Alliance for Water Innovation (DOE-NAWI)

Title: Porous Polymer Networks and Membranes for PFAS and Selenium Removal from Water
Project Number: NAWI Task 6.10
Mines PI: Christopher Bellona, PhD; Collaboration between Colorado School of Mines, University of California-Berkeley (Jeffrey Long is Project PI) and Electric Power Research Institute (EPRI)
Period of Performance: 2/22 – 12/24
Mines Funding From NAWI: $455,901
Total CHECRA Funding: $90,952

Summary:

The presence of emerging contaminants in water resources poses a significant challenge for water and wastewater utilities in the United States. Per- and polyfluorinated alkyl substances (PFASs) has received significant recent press given their recalcitrance, toxicity and ubiquity in environmental matrices and blood. Both PFAS and selenium are difficult to remove from water, making treatment costly and labor intensive. This collaborative research project aims to utilize a novel material developed by Berkeley for adsorptive and membrane treatment of PFASs and selenium (**Figure 1** below). In particular, this material has the potential to transform PFAS and selenium treatment as it has very high adsorptive capacity and is relatively cheap to produce (compared to commonly used adsorbents). CHECRA funds are being used in this project to support staffing of this project (e.g., students) related to assessment of this media in real-world treatment applications. The Mines' research group has significant experience in PFAS and selenium removal and is providing treatment expertise to optimize the novel adsorbent material towards real-world application. The ultimate goal is to increase treatment longevity and reduce treatment costs before impending regulations force utilities to treat for these substances.

Project Objectives:

We intend to address the following scientific questions as they relate to improving pipe parity metrics:

1. *Water treatment performance*: Can new PFAS and selenium separation approaches with unprecedently high selectivities, uptake kinetic rates, capacities, and regenerabilities be developed using PPNs? Can favorable fluorous-fluorous interactions and anion-exchange be utilized in adsorbents to obtain high PFAS selectivity? Similarly, can appended aminopolyol and aminothiol binding groups enable selective selenium removal?
2. *Cost*: Guided by adsorption and TEA results, can the separation performance improvements offered by PPNs offset their predicted material costs, compared to other leading technologies? Can the selective capture of PFAS and selenium from wastewater and simultaneous desalination be achieved in one step by PPN-embedded electrodialysis membranes, significantly reducing capital and operational costs?
3. *Sustainability, and human health and environmental externalities*: Can significantly higher PFAS and selenium removal capacities be obtained by PPNs compared to leading technologies, reducing spent waste volumes in single-use applications? What regeneration conditions would allow PPN reuse as well as PFAS and selenium desorption into concentrated, low-volume waste?
4. *Compatibility, and process adaptability*: Can PPN performances be maintained when tested with actual industrial wastewater samples, and when tested in column and electrodialysis prototypes that reflect industrial operations? What factors (e.g., binding group variations) and conditions (e.g., competing ions) affect PPN performance?

Outcomes of Project over Past Year:

1. NAWI has brought significant opportunities to collaborate with researchers engaged in different types of research (e.g., fundamental versus applied). This is particularly true for this project as it brings together chemists developing new materials (Berkeley) and water treatment engineers developing solutions for PFAS contamination (Mines).
2. Mines has completed testing of adsorbent materials (PPNs) developed by Berkely. PFAS uptake by PPNs was shown to be hundreds of times better than commercially available sorbents such as activated carbon and ion-exchange resin. Further testing was conducted to evaluate the effectiveness of developed adsorbents for treating various contaminated water resources.
3. Mines and Berkeley are developing manuscripts for publication based on this research, and and are exploring potential for securing intellectual property related to the findings of the project.
4. This project is currently supporting two PhD student at Mines (Bahareh Tajdini; Seyed Khademi)

Figures and Graphics:

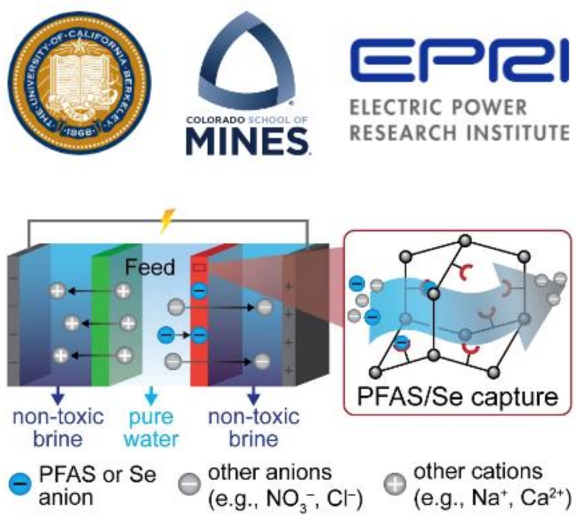


Figure 1. Overview of project including collaborators

Appendix B: Department of Energy National Alliance for Water Innovation (DOE-NAWI)

Title: Advanced Process Controls – Autonomous Control and Optimization
Project Number: NAWI Task 5.8
Mines PI: Tzahi Cath, PhD; Collaboration between Colorado School of Mines, Baylor University, and Oak Ridge National Lab (Kris Villez is Project PI).
Period of Performance: 3/22 – 12/24
Reporting period: CY 2023
Mines Funding From NAWI: $811,235
Total CHECRA Funding: $162,247

Summary:

Operations in water and wastewater treatment facilities are highly focused on continuously meeting the facility's performance standards regardless of disturbances caused by (a) variability in water source,

demand, and quality and (b) degradation of critical components, such as process equipment and sensors. So far, the need for reliability has been addressed through redundancy (volumes, equipment), thus leading to inefficient use of resources. Today, generic models rooted in machine learning, and adaptive control strategies offer a novel promise: the same reliability at unit- and plant-wide scale without redundancy, while spending minimal energy and resources. To evaluate this promise, in this project we develop and test broadly applicable control methods for adaptive optimization. The unique challenge is to design a single control framework that is applicable across a variety of water treatment systems, thus making efficient, low-cost operation available in rural, urban, coastal, and inland settings.

A demonstration-scale system at Mines is the core of the project; we are using a unique mobile lab that demonstrates direct potable reuse (DPR) of reclaimed water – a system that was design and constructed in CO with generous funds from the Colorado Water Conservation Board (CWCB), Colorado Springs Utilities, and the National Science Foundation. The core system is comprised of seven processes, including ozonation, biologically active carbon filtration (BAC), coagulation, ultrafiltration (UF), adsorption (GAC, ion exchange (IX), and Fluorosorb® (FS)), ultraviolet irradiation with advanced oxidation (UV-AOP), and chlorination. Influent into the DPR systems (reclaimed water from municipal wastewater treatment facilities) can have highly variable quality due to daily and seasonal quality changes of the original source water, water use patterns during the day, and plant operating conditions, to list a few. And with the need to continuously produce very high-quality water, a DPR system must adjust rapidly to changing conditions, while individual unit processes in the train have lower rate constants and slow process adaptation.

Project Objectives:

Adaptive plant-wide optimal control requires adoption of state-of-the-art methods for statistical process control, modelling, and machine learning. We selected methods based on successes in other industrial sectors and will solve the three most important challenges standing in the way:

1. Water quality sensors are prone to sensor faults. While short-lived faults, like outliers, can be addressed with state-of-the-art signal extraction tools, incipient and systematic faults, like drift and calibration errors, have resisted a highly automated approach.
2. While setpoint optimization, setpoint control, and disturbance rejection are feasible for simple process units with commercial hardware and software, there is no generally applicable control framework that allows optimization of complex processes or whole plants, thus preventing adoption in practice.
3. Treatment plants vary in their design, configuration, and operation. Indeed, a typical plant is customized to account for local and regional context (water demand, water source, legal requirements) and undergoes changes regularly (downtime, equipment degradation). This variety in design, status, and operation leads to customized control solutions for individual plants, which are expensive to maintain and often unaffordable for smaller plants.

We aim to develop and test technology and economic methods to address these challenges in coordination with multiple industrial partners, currently including Colorado Springs Utilities, Aurora Water, South Platte Renew (Englewood/Littleton), Hach, Toray Membranes, Trojan, Aqua Aerobic Systems, inCtrl Solutions Inc., IntelliFlux Controls Inc., and Rockwell Automation. Most importantly, they provide advice, equipment, and in-kind contributions:

1. Colorado Springs Utilities, Aurora Water, South Platte Renew: Access to data of the upstream plant, maintenance of a direct potable reuse (DPR) system, and water, power, and cellular services for the DPR tariler.

2. Hach: Donated water quality sensors valued at $160,000 (!)
3. Toray: New ultrafiltration membrane
4. Trojan: New ultraviolet reactors
5. IntelliFlux Controls Inc.: Access to software and industrial insights
6. Rockwell Automation: Provision of control hardware for testing with industrial equipment

Together, these contributions will ensure that the developed tools solve meaningful challenges and stand a chance to be broadly adopted in full-scale operations. Furthermore, our methods is being tested on at least three full-scale plant managed by Colorado Springs Utilities (past, 2021-2022), Aurora Water (past, 2022-2023), and Littleton/Englewood South Platte Renew (current, 2003-2024). The interest in the project is exceeding all expectations, with invitation to test it next at Metro Water Recovery (Denver) and showcase the trailer in Silicon Valley (CA).

Outcomes of Project over Past Year:

1. So far the trailer has produced more than 2,000,000 gallons of drinkable water from reclaimed water.
2. The DPR mobile lab was operational in Aurora Water (Sand Creek WWTP) from June 2022 to August 2023 (14 months) and at South Platte Renew (August 2023 to date).
3. The demonstration in Aurora brough more companies to invest in our research, including recent generous donations of $160,000 from Hach (water sensors), membranes from Toray (>$5000), and ultraviolet reactors from Trojan (>$15,000).
4. The research also attracted two more large scale funding from EPA ($800,000 to Mines and a larger sum to CU Boulder), and another recent successful proposal to NAWI in collaboration with Stanford University (~$1.5M, of which $500K are cash cost share from the California Department of Water Resources).
5. The project won a prestigious award: 2022 WateReuse Awards for Excellence in Outreach
6. We have installed a new reverse osmosis (RO) system in the trailer, thereby enabling us to compare different DPR approaches, with and without RO.

Media resources:

- With new regulations, wastewater gains momentum as a defense against drought
- Direct Potable Reuse (DPR) podcast
- Recycling Water: Direct Potable Reuse Explained
- Mines' DPR mobile lab
- Mines' DPR mobile lab at Colorado Springs Utilities
- PureWater Colorado Mobile Demonstration Project
- First day of potable water production
- Inside our new DPR mobile lab

Figures and Graphics:

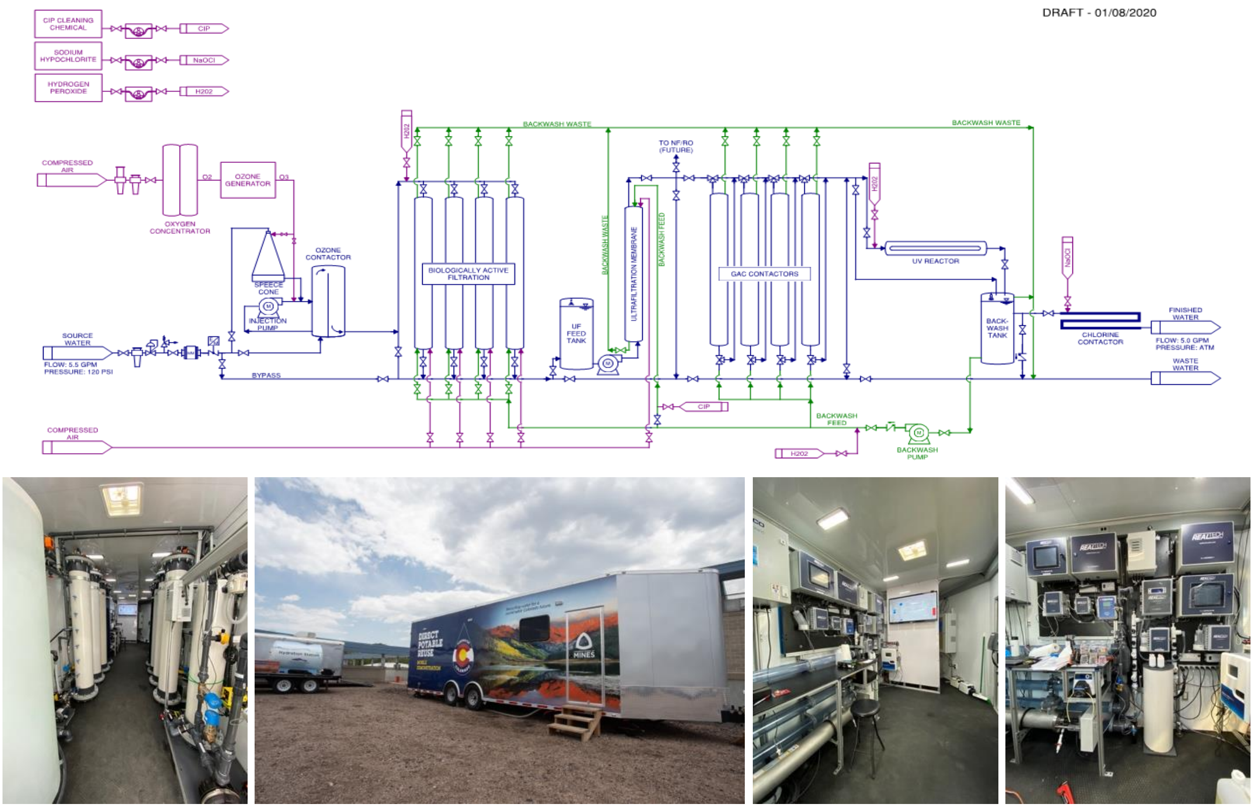


Figure 1: *Scheme of the DPR pilot, including six unit processes: biologically active filtration (BAF), ozonation, ultra-filtration (UF), granulated activated carbon (GAC), UV treatment, and chlorination.*

Colorado State University

Appendix C: ARPA-E ROOTS Plus Up Award

Title: Root genetics in the field to understand drought adaptation and carbon sequestration –
PI: Professor John McKay, Colorado State University
ARPA-E ROOTS Plus Up Award
Colorado State University
CHECRA Grant ($400K over 3 years)

Summary:

We have successfully developed a high-throughput phenotyping platform to measure root system traits at scale in agricultural field experiments. This platform is now being used to identify genetic variation in root traits, and the effect of this variation on drought adaptation, Nitrogen use efficiency and soil carbon sequestration. We are applying this technology to answer basic research questions regarding the genetic basis of how crop roots sense and respond to soil moisture and Nitrogen. In addition, we have funded collaborations to evaluate the root traits in the private sector breeding programs of Corteva, Syngenta as well as public sector breeding programs of the International Maize and Wheat Research Center and national breeding programs across Africa. CHECRA has committed to providing $400K over three years. This grant was funded as a continuation of a previous ARPA-E grant to McKay. The new grant started in May 2022.

Description of the project, the principal persons and the amount of funding:

For the PLUSUP we plan to move forward on commercial use two technology areas:
1) Optimizing the proprietary root and soil sampling technology HTP vehicle and the downstream processing and analysis of root and soil samples. **We will deploy this technology to quantify variation in genotypes of relevance to the Corteva breeding programs**. In particular, we will use time series sampling of roots and soils to quantify Nitrogen Use Efficiency and soil carbon inputs of maize genotypes across soil moisture gradients. This will be led by the John McKay at CSU and Chris Topp at Danforth. We will conduct large scale split plot field trials with varying levels of the factors irrigation and Nitrogen to evaluate germplasm and identify loci controlling variation using the HTP system. Varieties will also be evaluated at Corteva sites in the cornbelt and Danforth farm in Missouri, to establish responses across sites. In year 1 we will initiate transformation and gene editing of identified loci. By the start of year three we will have inbred and hybrid seed containing these edits to evaluate in greenhouse and field studies.

2) Incorporating the MEMS 2.0 soil and ecosystem biogeochemical model into a next generation soil C and GHG computational platform for farm-scale soil carbon and greenhouse gas quantification.

Keith Paustian Lab –Will lead MEMS model implementation, including data assimilation capabilities using remote sensing observations, into the ‘unsupervised’ functionality of the COMET-Farm platform. Tests will involve performance of the model for 30 crop species/ varieties and multiple combinations of management practices (tillage, fertilization, irrigation, etc.), across the full range of soil and climate types within agricultural production regions within the US. A major innovation will be to use the empirical data from the field studies to model genetic variation in nitrogen use efficiencies and soil C input.

Francesca Cotrufo Lab – Will analyze soils derived from the CSU and Danforth field trails for C and N stocks, in the different soil physical fractions represented by the MEMS model, using both physical fractionation with elemental analyses, and Fourier transformed infrared spectroscopy. Data will be used to link crop nitrogen use efficiencies with soil C sequestration and provide data to bridge the field trials (McKay, Topp) with the model development (Paustian), for verification of model predictions.

Funding from CHECRA and allocation:

The CHECRA funds have been used to support PI John McKay, Research Scientist Jack Mullen, and lab manager Stephanie Goldin.

Results Achieved:

Task 9: Genes controlling root traits

In the 2023 field season we used the mechanical root pulling platform to successfully pull up and phenotype nearly 2400 plants. This is an increase in throughput of more than 30% from last year's results. The increased pulling throughput comes as we continue to streamline and upgrade mechanical systems, improve the imaging capabilities to identify plants, and optimize operational procedures. In addition to obtaining measurements of our focal trait of root pulling force (RPF), we now also routinely are extracting and analyzing an additional trait measurement from the pulling data, root pulling distance, RPD. Both of these traits are positively correlated with overall root system size, and we have used this additional measurement to help localize QTL for RPF. However, RPF and RPD themselves are only moderately correlated and this additional trait is more directly related with how root systems are arranged that would effect the magnitude of force before the root system begins to move. Thus the RPD trait can give us additional root system architecture information, over RPF alone, to improve our ability to distinguish root types. For example, in this field season, although the genotypes SF5 and SM5 had similar RPF measurements, we found significant differences between them in RPD. The similarity in RPF is consistent with similar overall root system sizes between the genotypes; however, differences in spacing of roots between the lines appear to underlie differences in RPD, with denser more vertical roots moving less before reaching maximum force. Thus, we expect that this additional trait will continue to improve our ability to evaluate root system architecture variation in maize genotypes of interest.

We created seed for several mutant lines that we planted in the field for this field season. To date we have had the chance to analyze RPF data from one of these, a line with a transposon insertion mutation in a *SLAH2/3* nitrate channel that is expressed in the root stele. This mutant line was identified based on the gene being a candidate from our previous RPF GWAS results (Woods et al. 2022). The mutant line showed an approximately 35% increase in RPF over WT. The increased RPF in the mutant is consistent with our GWAS results in which the minor allele at the gene was the variant with higher RPF.

Task 10: Nitrogen Use Efficiency (NUE) in Elite Germplasm

For this task, we have grown Corteva hybrids this field season in Colorado, as well as two sites in the corn belt. For the Colorado site, we pulled up root systems at two time points and for two nitrogen treatments. For our first time point, we have confirmed significant differences among lines in root investment under low N. We are still analyzing the later root data, and in the next quarter we will also harvest the plots at the Colorado site for grain. We will also obtain yield data across N levels from the corn-belt sites from Corteva. Combined, this will allow us to identify high performing lines across N levels and potential roles for root allocation.

Task 11: Soil carbon and nitrogen modeling

In 2021 baseline time zero soil samples were collected at ARDEC. For that sampling three cores were taken from each plot and split into five depths (0-15, 15-30, 30-45, 45-60, 60-90 cm). The three cores were consolidated per plot and the baseline sampling was done in all 100 plots. All of the baseline samples were 8mm sieved, air-dried, and barcoded. In 2023 we analyzed 20 plots for all 5 depths for a total of 100 samples that spanned a wide area of the field were 2 mm sieved, finely ground, and analyzed for organic C, total N, and the $\delta^{13}C$. We found a significant difference by depth in the organic C and total N with both decreasing in a stepwise manner by depth. The $\delta^{13}C$ of the upper depths has an isotopic signature closer to C3 and that the standard deviation is relatively small indicating that we can detect new soil organic C formed from maize inputs. For the organic C, the coefficient of variation (CV) for the 0-15cm depth for the entire field is reasonable, at 10%, and the CV for the total N for the 0-15cm depth for the entire field is 17%. The CV increases with the deeper depths for both C and N.

In March and April of 2022, the year one samples were collected at ARDEC. Three cores were taken from each of the 100 plots and split into the same five depths and the three cores were consolidated per plot for a total of 500 samples. All these soils have been 8mm sieved like the baseline soils and have been barcoded. In 2023, we analyzed 3 treatments with five plots per treatment for 15 plots total for all 5 depths for a total of 75 samples. We selected the two most extreme maize varieties along with the no-plants blank in this initial analysis. We observed a significant (p=0.006) decline in the surface soil C stocks from baseline to year 1; however, no differences were observed in soil C stocks between the two most extreme varieties, although the varieties differed in amount of coarse root biomass in the soil samples. We also observed a significant increase in soil C (p=0.006) and soil N (p=0.0001) at the 15-30cm depth compared to the baseline possibly due to translocation of C during tillage and fertilization although no significant difference between the treatments.

In 2023 we fractionated the baseline and year 1 soils (from the blank and plots hybrids PH25 and PH7) by size and density to verify if we can detect any difference in soil organic C that cannot be detected on bulk soils. The fractionation isolated a light particulate organic matter (lPOM), a heavy coarse organic matter (hcOM), and mineral associated organic matter (MAOM). Similar to the bulk soil we do see a significant difference in lPOM C and MAOM C between the baseline and year 1 samples with a slight decline in lPOM C (p=0.011) and MAOM C (p=0.047) in 0-15 cm at year 1 and a slight increase in lPOM C (p=0.012) and MAOM C (p=0.029) at 15-30 cm for year 1.

For fraction N, we saw a significant difference between the baseline and year one for lPOM N (p=0.016) and MAOM N (p=0.016) for the 0-15 cm depth with lower N at year 1 in for both fractions. We do not see any significant differences in N at the 15-30 cm depth. We also did not see any significant treatment difference within the fractions.

In 2023 we also focused on the natural abundance of isotopes values from shifting from C3 to C4 crops, to determine the contribution of maize inputs to new soil organic C stocks, as well as the effect of the cropping system conversion from alfalfa to maize on the native soil organic C stocks to see if we can quantify statistically detectable changes in soil organic C and total N from background levels by depth. Preliminary data indicate that up to 16% of the carbon in the soil was derived from corn inputs after one year. However, the corn derived C was quite variable especially in the top soils, and more data analysis is required to finalize these estimates. We did not find a significant difference between corn varieties after 1 year, although the averages at both depths for the larger-rooted line (PH7) were higher than the smaller-rooted variety (PHR25).

Task 12: Technology to Market

In 2023 engaged in a testing agreement with breeding company Syngenta to evaluate a set of 20 of their lines with our root pulling platform to investigate associations between our root trait measurements and plant lodging in the 2023 field season. This is in addition to our collaboration with Corteva, so we are demonstrating the technology and evaluating the germplasm of two of three of the large seed companies in the US. We are also demonstrating the technology and evaluating breeding lines from CIMMYT, the largest public maize breeding program in the world. These collaborations will help communicate our phenotyping to technology to the global crop breeding community. In future years we may have capacity to work with other breeding programs.

We have updated our Technology to market plan based on our continuing experience with the root pulling phenotyping platform and the current policy environment. The document was sent separately from this report. The prioritized situation of use is to improve breeding of corn root traits to enhance NUE, drought tolerance and carbon sequestration. By enhancing corn roots to be more aggressive when searching for nitrogen and/or water in the soil, their root structures will become larger and have more biomass. This increase in biomass size will allow for more carbon to be stored in soil in old rooting structures. Additionally, certain root traits may offer synergistic effects with soil microbes to enhance NUE and foster healthy soil microbiomes.

Future strategies should involve gathering enough data to observe root traits that model improvements of NUE in corn. Once established, a similar crop such as sorghum could act as a second candidate.

The societal benefits are related to the reduction of GHG emissions in carbon and nitrous oxide. By capturing carbon emissions and storing them underground in rooting structures, the global carbon footprint can begin to reduce and will have a positive impact on climate change.

We have been revising our previous T2M efforts. This included the I-Corps Starting Blocks Customer Discovery Workshop that a PhD student in the lab completed this summer. The program components of the Workshop included interviews as an indispensable experience and value of this program that directly connect participates into industry and solving current challenges in industry, fulfilling the 5 potential customer consultations. However, in terms of cost benchmarking, there is no existing commercial technology for comparison. Our increases in throughput are reducing the operational costs from labor. And our testing agreement with Syngenta should inform estimates of the industry's value on such root traits.

We have engaged with the CSU Institute of Entrepreneurship to do an updated and detailed evaluation of the market potential of the RPF system as well as genetics for deeper roots that are more responsive to reduced Nitrogen and water.

Appendix D: Department of Energy National Alliance for Water Innovation (DOE-NAWI) Task 3.25

Title: Optimizing Electric and Water Grid Coordination under Technical, Operational, and Environmental Considerations
PI: Steve Conrad, PhD. Associate Professor, Department of Systems Engineering, Walter Scott, Jr. College of Engineering, Colorado State University
Note: Collaboration between Colorado State University, National Renewable Energy Lab, and Electric Power Research Institute (Nalini Rao, PI)

Project Number: NAWI Task 3.25
CSU PI: Steven Conrad, PhD; Collaboration between Colorado State University, National Renewable Energy Lab, and Electric Power Research Institute (Nalini Rao, PI)
Period of Performance: September 2023 – August 2025
CSU Funding From NAWI: $ 265,661
Total CHECRA Funding: $ 60,222

Summary:

Enabling, renewable energy compatible, alternative water treatment will provide Colorado and the globe capacity to address scarce water resources. Energy compatible water treatment processes provide a significant opportunity to ease the strain on the renewable energy grid and realize co-optimization potential. This project is examining strategies to manage and coordinate water system operations and the electric grid such that desalination treatment processes can be compatible with electrification efforts. These efforts include activities such as (1) load shifting, (2) load shedding, (3) ramping, (4) energy storage, (5) renewable energy generation scheduling, and (5) general demand response activities.

Project Objectives:

CSU and our research partners, the National Renewable Energy Lab and the Electric Power Research Institute, are working to achieve the following objectives and create toolset to help assist water utilities balance their energy and treatment needs against the demands of the renewable energy grid.

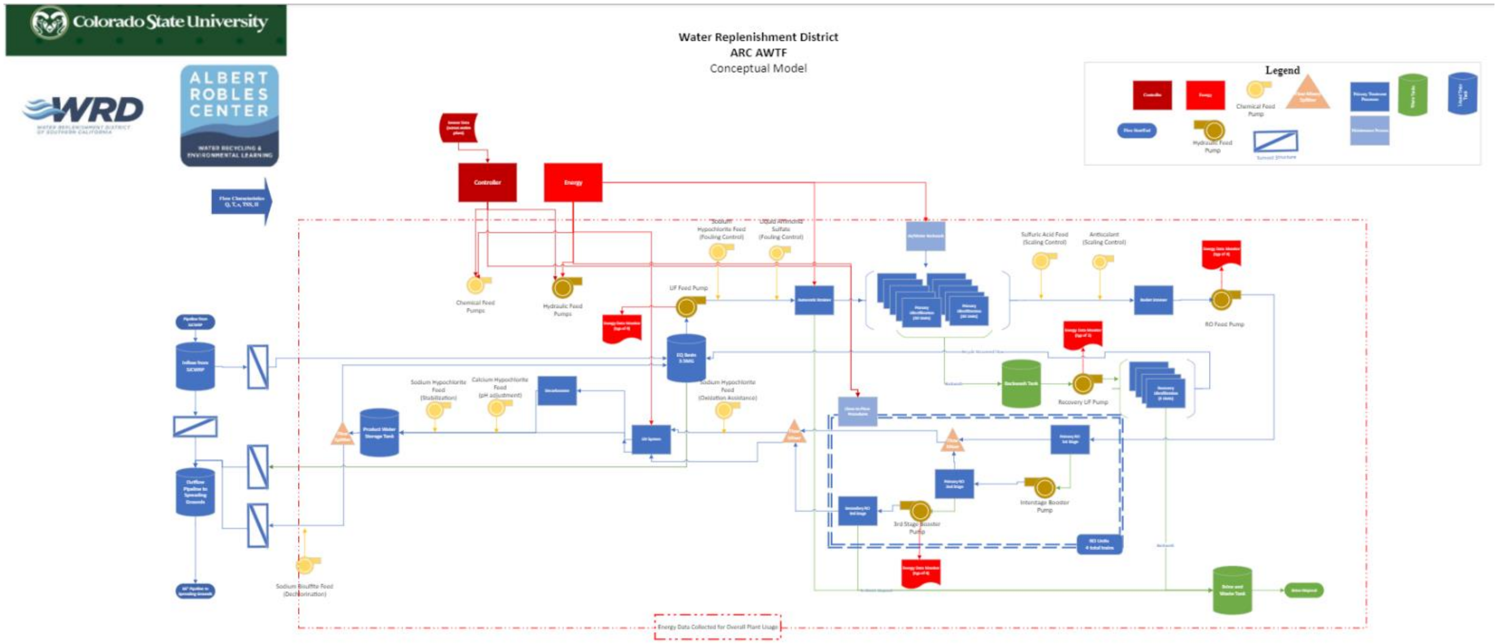
1. *Baseline Assessment and Comparative Analysis:* Perform a stakeholder informed comparative analysis and baseline assessment of selected water treatment processes to develop a research roadmap for optimizing electric and water grid coordination.
2. *Model Development:* Define and develop a water treatment and electrical digital twin to model flexible operations to include grid-renewable hybrid power modeling.
3. *Technoeconomic Analysis*: Interface process modeling and scenario modelling results with the existing NAWI tool WaterTAP to conduct a technoeconomic analysis to understand the impacts that process design and operational variables have on cost outcomes and provide insight from studied scenarios. Document the assessment of potential flexible control strategies.
4. *Framework Review and Application:* Consider the design, treatment, cost, energy use, reliability, adaptability, water impact, and sustainability/scalability as insights to future R&D. Obtain operator and stakeholders assessments for potential future investments in flexible operations and power integration and optimization of water treatment systems.
5. *Coordinated Crosscutting Activities:* Synthesize common challenges and opportunities across three similar NAWI projects to provide foundational and generalizable insights that can be broadly applied, synthesizing examples and demonstrated benefits, barriers and lessons learned in implementing electrification of water treatment processes.

Outcomes of Project over Past Year:

Initial work focused on the conceptualization and development of the digital twin platform and assessment requirements. This digital twin is defined as a digital, dynamic representation of a real-world entity that models its behaviors and physics to enable system analysis and optimization through the bidirectional flow of real-time data. The conceptualized digital twin platform will simulate plant operations and report water quality and energy performance metrics impacted by the studied energy grid scenarios. With this output, the technoeconomic analysis can be performed through WaterTAP to determine the overall cost and technical impact of operating water treatment processes under flexible conditions. The digital twin development and scenario assessment is planned for 2024/2025. After this project, Colorado Utilities will be able to utilize the digital twin platform as a tool to realize their site-specific analysis, control, and optimization assessments. To date:

1. CSU has partnered with host sites and the Electric Power Research Institute to conceptualize the treatment processes and process controls of the study sites when integrated with energy data (Figure 1).
2. This project has provided the opportunity to examine the characteristics and dynamics of digital twins in urban water systems. Using research outcomes from this project, the team at CSU is developing a classification framework for digital twins in urban water systems that will inform the development of the water-energy co-optimization digital twin.
3. This project is currently supporting one graduate student at CSU (Josh Rodriguez) with support for another student planned for 2024.

Figure 1: Conceptual Energy/Water Treatment Model



Appendix E: NSF Engineering Research Center for Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE) - CSU

PI: Jason Quinn, PhD. Professor, Department of Mechanical Engineering, Walter Scott, Jr. College of Engineering, Colorado State University

Colorado Benefits:

The ASPIRE project has delivered significant benefits to Colorado, with its research achievements directly impacting the state through a detailed analysis of environmental health implications and the evaluation of electrified transportation's impact. This work is crucial for understanding and mitigating the environmental and public health challenges associated with transportation in Colorado, supporting the state's transition towards sustainable mobility solutions. A key element of ASPIRE's success in Colorado is its effective collaboration with the University of Colorado Boulder, which has facilitated cutting-edge research and innovation in electrified transportation technologies. This partnership underscores the project's commitment to leveraging local academic expertise to drive advancements in this critical field. Furthermore, ASPIRE's funding has been instrumental in supporting a wide range of educational and outreach activities. These initiatives are preparing Colorado's future workforce for the challenges and opportunities of a sustainable transportation sector, demonstrating ASPIRE's comprehensive approach to benefiting the state through scientific innovation, collaboration, and community engagement.

Scientific Report:

Application of funding: The project is by Jason Quinn with support from funding going to Noah Horesh, the technical lead on the project. The work from CSU has focused on optimizing transportation electrification through an integrated techno-economic analysis (TEA) and life-cycle assessment (LCA) across various vehicle classes and charging systems. An evaluation model that integrates these analyses to guide system-wide optimization and control strategies for infrastructure has been developed and exercised. Collaborating across ASPIRE and leveraging DOE and NSF grants, the work includes assessing environmental, economic, and health impacts, emphasizing equitable electrification solutions. Key deliverables are an open-source integrated assessment model and educational tools, supporting sustainability metrics evaluation and scenario analysis for technology deployment.

Results Achieved:

Project Abstract: ASPIRE, an NSF Engineering Research Center, is spearheading the development of advanced wireless and plug-in charging infrastructure to electrify the transportation sector, aligning with the Biden administration's ambitious goals for electric vehicles (EVs) sales, net-zero greenhouse gas emissions, and a carbon pollution-free power sector by specific future dates. Launched at a pivotal time, ASPIRE addresses the economic and environmental challenges posed by vehicle emissions and the volatility of oil prices through the promotion of EVs. Tackling obstacles related to batteries, range, and charging infrastructure, ASPIRE adopts a comprehensive approach to create a ubiquitous charging experience for all vehicle classes and users. As it enters its fourth year, the Center has transitioned into a phase of growth, securing over $60 million for pre-pilot and pilot projects across four states to test and demonstrate its innovations in real-world settings. These initiatives aim to validate best practices for community engagement and policy development, with upcoming deployments promising significant societal impact and continued stakeholder collaboration across various sectors.

Progress Summary: ASPIRE's multifaceted initiatives encompass pioneering the manufacturing of a 1 MW static wireless charger for electric Class 8 trucks, set for demonstration within the UPS fleet in Utah by 2024, in collaboration with Kenworth, WAVE, Rocky Mountain Power, and local unions. This project aims to overcome barriers to the adoption of battery-electric trucks for urban and regional delivery operations. Additionally, ASPIRE has progressed to the contracting phase for a groundbreaking high-power dynamic wireless charging system, developed in partnership with INDOT and AECOM, integrating this technology into a Cummins Class 8 truck for real-world testing. An integrated evaluation framework has been created to assess the economic, environmental, and equity impacts of EV charging technologies, showcasing the benefits of heavy-duty vehicle electrification. ASPIRE has gained international recognition, leading conferences on wireless charging and infrastructure for electrified transportation, and developing advanced pavement models for integrated solutions on electrified roadways.

On the educational front, ASPIRE has institutionalized its Student Leadership Council (SLC) Cohort Travel Program, exposing students to interdisciplinary research and professional development across various sectors, and launched the Research Experience and Mentoring (REM) program for high school students. Expanded K-12 curricula and a Center-wide Electrified Transportation Systems (ETS) course further ASPIRE's educational outreach, emphasizing inclusivity and environmental justice.

ASPIRE is also fostering a culture of inclusion, with workshops and programs aimed at engaging underrepresented groups in STEM and developing a Transportation Equity Course that explores DEI within the context of electrified transportation.

In the realm of innovation ecosystem, ASPIRE has been designated by the State of Utah for strategic planning in transportation electrification, reflecting a significant expansion and diversification of its membership and partnership base. This encompasses engaging with a broad spectrum of stakeholders, from academia to government, to advance the electrification of transportation infrastructure.

Outcomes and Benefits: Over the past year, the ASPIRE project has yielded significant outcomes and benefits across various domains, from scientific advancements to broader societal impacts. Here's a summary of these achievements:

Scientific and Technological Advancements:

- Development of a 1 MW Wireless Charger: A major technological breakthrough was the industrialized design and manufacturing of the first-ever 1 MW static wireless charger for electric Class 8 trucks, enhancing the practicality of battery-electric trucks for delivery operations.
- Dynamic Wireless Charging System: The transition to the contracting phase for a new pavement integrated solution for high-power dynamic wireless charging represents a pioneering step towards in-motion charging capabilities.
- Integrated Evaluation Framework: The development of an evaluation framework that assesses EV charging technologies against economic, air quality, and equity impacts offers a holistic view of the benefits and challenges of vehicle electrification.

Educational and Outreach Benefits:

- Graduate and Undergraduate Education: Through the ASPIRE Student Leadership Council (SLC) Cohort Travel Program and Research Experience and Mentoring (REM) Program, ASPIRE has significantly contributed to the education and professional development of students at various levels.
- K-12 Outreach: The expansion of ASPIRE-themed curricula and the ASPIRE Air Quality-Climate-Transportation Connections program have engaged hundreds of K-12 students in STEM, emphasizing the importance of electrified transportation and environmental justice.
- Electrified Transportation Systems Course: This course, involving faculty and industry lectures, instills competencies in systems equity, transdisciplinarity, and leadership among participants, expanding ASPIRE's educational impact.

Technology Commercialization and Collaboration:

- Commercialization and Spin-offs: The project's advancements in wireless charging technology have the potential to catalyze technology commercialization and spawn spin-off companies, driving innovation in the electrified transportation sector.
- Collaborations: ASPIRE's efforts this year have been characterized by significant collaborations with industry partners like Kenworth, WAVE, and Rocky Mountain Power, as well as academic and governmental bodies, demonstrating a strong model for multi-sector partnership in advancing transportation electrification.

Cultural and Societal Impact:

- Culture of Inclusion: Regular workshops and programs aimed at engaging underrepresented groups in STEM have fostered a culture of inclusion within ASPIRE, contributing to a more diverse and equitable scientific community.
- International Recognition: Leading international conferences on wireless charging and infrastructure have positioned ASPIRE as a global leader in the field, facilitating cross-border knowledge exchange and collaboration.

In summary, the ASPIRE project has not only made significant strides in the scientific and technological realms but has also made substantial contributions to education, outreach, technology commercialization, collaboration, and the promotion of an inclusive culture. These achievements collectively advance the goals of electrified transportation and have a lasting impact on communities, industries, and the next generation of scientists and engineers.

University of Colorado Boulder

Appendix F: NSF Science and Technology Center on Real-Time Functional Imaging (STROBE)

NSF Award: 1548924
Title: Science and Technology Center on Real-Time Functional Imaging (STROBE)
Period of Performance: 10/01/2016 – 09/30/2026 (~$48M over 10 years, renewed)
Total 2023 CHECRA Funding: $400,000
Award PIs: Margaret Murnane (Director), Jianwei Miao, Markus Raschke, Naomi Ginsberg

Abstract:

Microscopy is critical for discovery and innovation in science and technology, accelerating advances in materials, bio, nano and energy sciences, as well as nanoelectronics, data storage and medicine. Although electron, X-ray and optical nano imaging methods are all undergoing revolutionary advances, no single imaging modality can address critical questions underlying much of science and technology in the 21st century. These grand challenges include: How to capture high-resolution images of functioning nano, energy and quantum systems to guide design? How to rapidly image viruses and vaccines, with molecular-scale information? How to image nanoscale living matter without freezing or labeling? Addressing these major scientific challenges requires the development of the microscopes of tomorrow by integrating state-of-the-art microscopes, new methods, novel sample preparation, fast detectors, big data, advanced algorithms and machine learning - which could not be accomplished without a center.

Progress made over the last year:

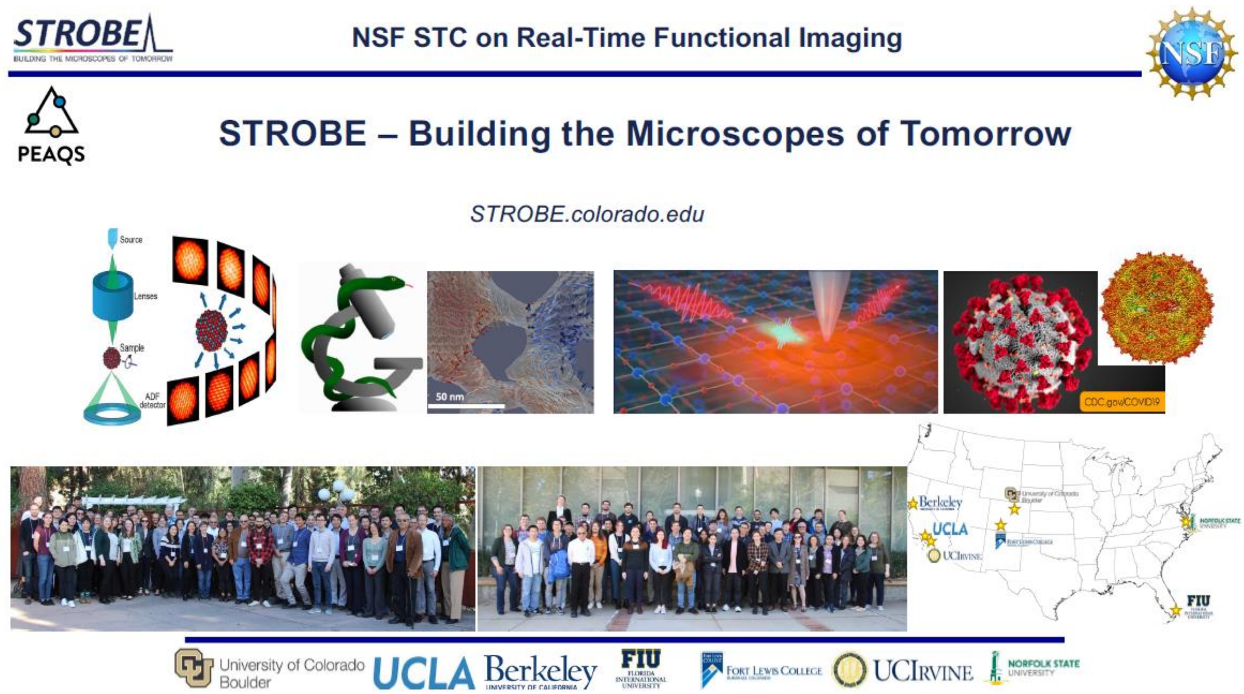
STROBE brings together academia (CU Boulder, UCLA, UC Berkeley, UC Irvine, Florida International University and Fort Lewis College), national laboratories (NIST, LBNL, ORNL) and several US industries to develop and advance microscopy tools and techniques. Major achievements in 2023 include enhanced collaborations with partners who come to STROBE as a resource – institutions such as NIST, 3M, Moderna, Moore Foundation, MRS, DOE LBNL, PPNL, Imec, NSF IPAM, the Penn State NSF MRSEC and elsewhere. STROBE curricula, training and best practices being adopted broadly, within CU Boulder and more broadly by the international Materials Research Society (MRS). A diverse group of >155 graduate student and postdoctoral scientist alumni are impacting the US workforce, and are now working in the US at KLA Tencor, NIST, ASML San Jose, Zoom, Intel, Mitre, the American Physical Society, Applied Materials, HRL, SLAC, Sandia and elsewhere. STROBE has an additional >150 undergraduate alumni. Most notably, STROBE technologies are now either used, are impacting, or will be soon adopted by several national laboratory facilities at NIST (Boulder and Gaithersburg), Lawrence Berkeley Lab, Argonne National Lab, Los Alamos National Lab, industry and elsewhere.

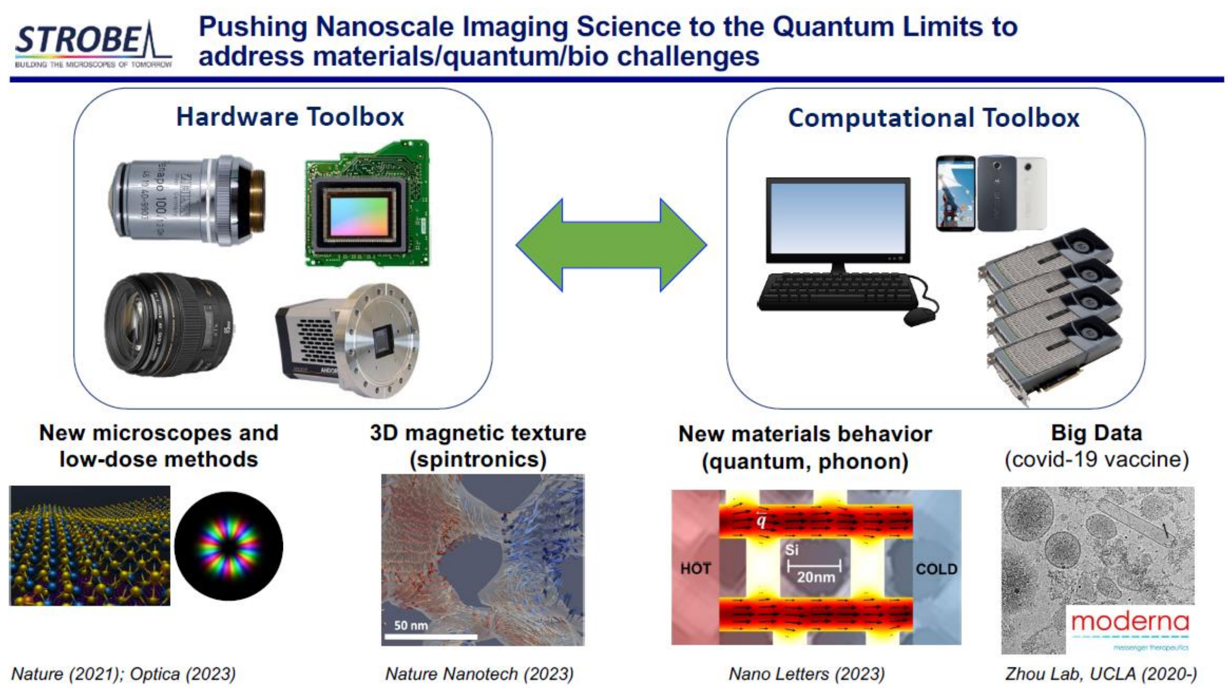
Outcomes/benefits of this project over the past year (2023):

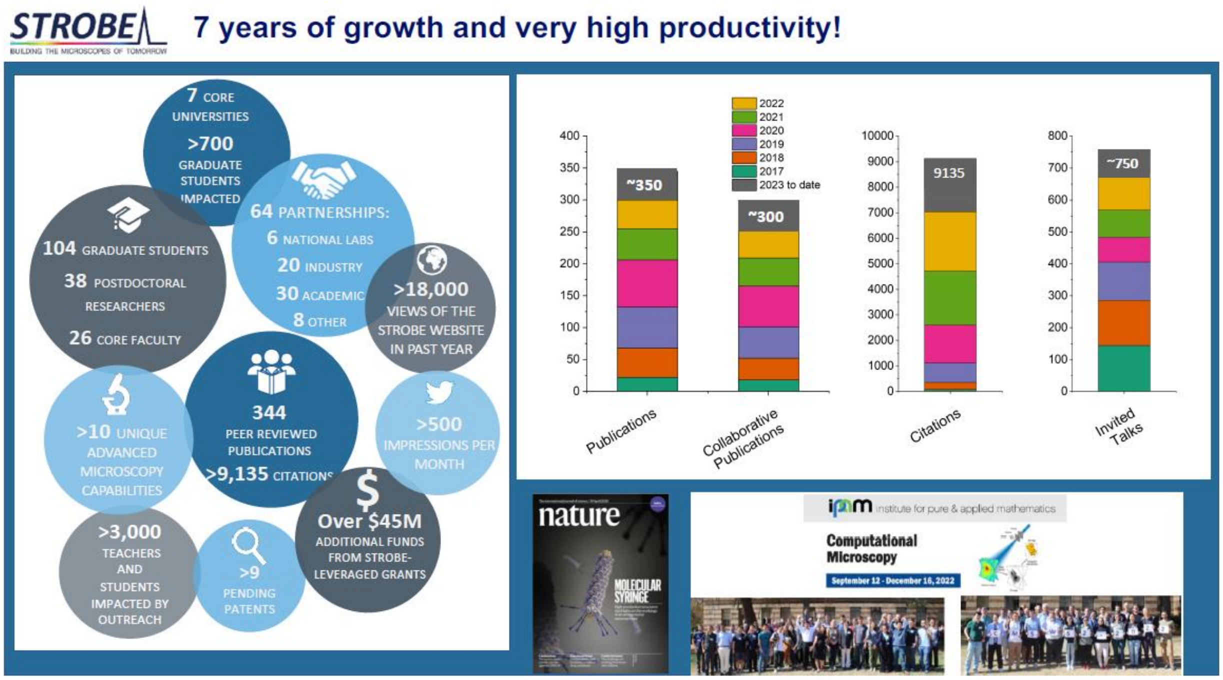
1. STROBE is attracting new collaborations from national labs, academe and industry.
2. >155 STROBE diverse Ph.D. and postdoctoral graduates are impacting the US workforce. Of these, ~33% were women and 12% URM, well above the national averages (20% & 4%). STROBE has an additional >150 undergraduate alumni in multiple career tracks.
3. STROBE partners with Dr. Jeff Jessing at Fort Lewis College (FLC) on a collaborative NSF grant called PEAQS, that is partnering to build research capacity at FLC in Durango, and at Norfolk State University (an HBCU). STROBE's role is to arrange multiple exchange visits for training and research; broaden the research and collaboration network; provide technical and professional training on topics such as resumes, interviewing, software, financial planning, mentoring, tutoring for classes; advise on equipment use and purchasing; and advise on grant administration.

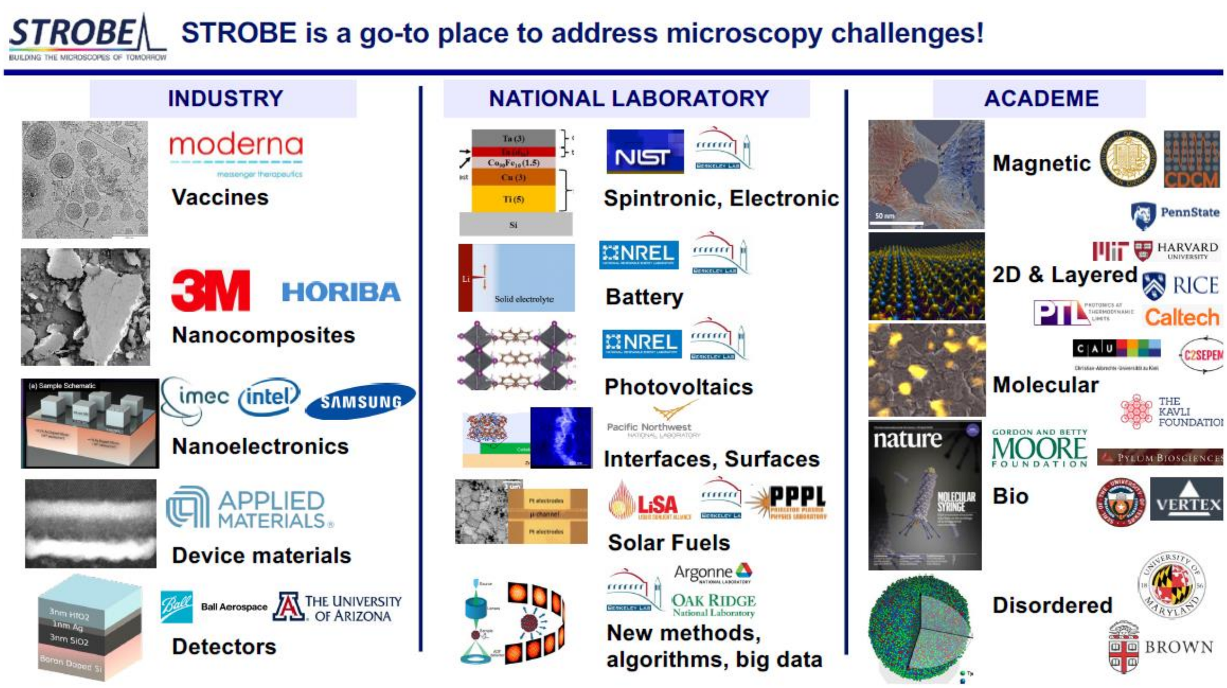
4. UCLA STROBE scientist Hong Zhou continued to provide images of their vaccine to Moderna, as a service spanning ~4 years. For bio-materials, sub-2Å resolution is required to obtain the chemical structure. Only the best electron imaging labs, like Zhou's, have the specialized setups to manage the immense amounts of data required to reach this resolution. STROBE research into advanced algorithms that can extract structural information with less data is key for reaching molecular-level imaging and will have large future impact.
5. STROBE research advances have resulted in >350 papers that are highly cited (please see https://strobe.colorado.edu/ for Publications, News and Awards). The large majority of the papers are collaborative, involving joint university/national lab/industry work.
6. Trainees received multiple awards, including Postdoctoral Fellowships to work at NIST Boulder Labs, graduate fellowships, best papers (see https://strobe.colorado.edu/news-events/awards/)
7. Every year, STROBE collaborates with CU Science Discovery and the teachers in the Four Corners region to develop hands on activities for middle school students. In spring 2023, the activities focused on "Water in the West". STROBE, Science Discovery, and PEAQS undergraduates from Fort Lewis College implemented these workshops in May 2023 for students from middle schools around the Four Corners region, including Tse Bit Tai Middle School on the Navajo Nation and Ignacio Middle School on the Southern Ute reservation. Students learned about how different types of concrete and materials impact water absorption into the land, how clouds form and what causes rain, and how we can use solar energy, water, and gravity to create a renewable hydro-pump energy storage system to power our cities during the day and night. The hydro-pump activity was such a hit with students and teachers, that STROBE Director of Outreach and Broadening Participation and Director of Education, Drs. Sarah Schreiner and Ellen Keister, built 25 hydro-pump boards to provide all teachers with a classroom kit to continue that workshop into their curriculum for years to come. Please see STROBE Newsletter (attached below).
8. Each year, NSF supports a symposium at the Materials Research Society (MRS) conference to welcome undergraduate students from NSF PREM (Partnership for Research and Education in Materials) programs to the materials science community. Dr. Sarah Schreiner collaborated with a team of NSF and PREM faculty members to develop and organize the MRS PREM Research Scholars Symposium at the 2023 MRS Spring Meeting in San Francisco. This symposium hosted almost 100 undergraduate PREM Research Scholars from around the United States for two days (see photo). Scholars participated in professional development and networking activities, and the symposium ended with a poster session for all participants to share their materials research projects with the community. Dr. Schreiner offered two workshops at the symposium on Networking at Conferences and Turning Your Science into a Story. The STROBE- PREM partnership, called PEAQS, supported 10 students from Fort Lewis College and Norfolk State University at the symposium. Please see STROBE Newsletter (attached below).
9. STROBE technologies have been integral to ~10 joint university-industry grants with small and large businesses, and several other industry fellowships/grants in the first 7 years.
10. STROBE-enhanced IR sources are now available to a broad user community at the Department of Energy Synchrotron Source at UC Berkeley.
11. STROBE-enhanced advanced algorithms for X-ray imaging are now available to a broad user community at the Department of Energy Synchrotron Source at UC Berkeley.
12. STROBE-enhanced tabletop X-ray sources are used by NIST Boulder for advanced materials research and will soon be adopted at NIST Gaithersburg.
13. STROBE mentored ~30 undergraduate students for research experiences in the summer of 2023.
14. Multiple outreach activities were implemented, including K-12 school visits, as well as presenting at a Girls in Science Night at the WOW! Children's Museum.

Additional documentation: Please see this webpage for STROBE's Fall 2023 Newsletter.


STROBE
BUILDING THE MICROSCOPES OF TOMORROW
NSF STC on Real-Time Functional Imaging
NSF
PEAQS
STROBE – Building the Microscopes of Tomorrow
STROBE.colorado.edu
Source
Lenses
Sample
ADF detector
50 nm
CDC.gov/COVID19
Berkeley
UCLA
UCIrvine
FIU
University of Colorado Boulder
UCLA
Berkeley
FIU
FLORIDA INTERNATIONAL UNIVERSITY
FORT LEWIS COLLEGE
UCIRVINE
NORFOLK STATE UNIVERSITY

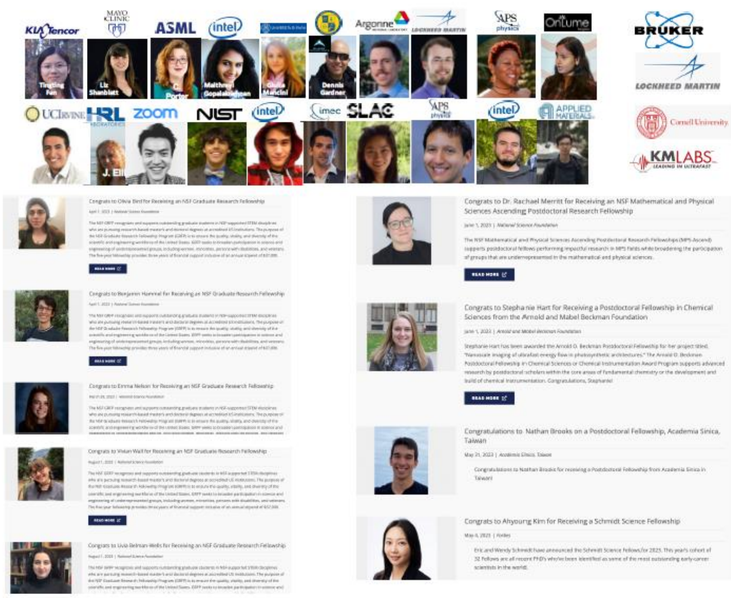

STROBE
BUILDING THE MICROSCOPES OF TOMORROW
Pushing Nanoscale Imaging Science to the Quantum Limits to address materials/quantum/bio challenges
Hardware Toolbox
Computational Toolbox
New microscopes and low-dose methods
3D magnetic texture (spintronics)
New materials behavior (quantum, phonon)
Big Data (covid-19 vaccine)
50 nm
q
HOT
Si
20nm
COLD
moderna
Nature (2021); Optica (2023)
Nature Nanotech (2023)
Nano Letters (2023)
Zhou Lab, UCLA (2020-)

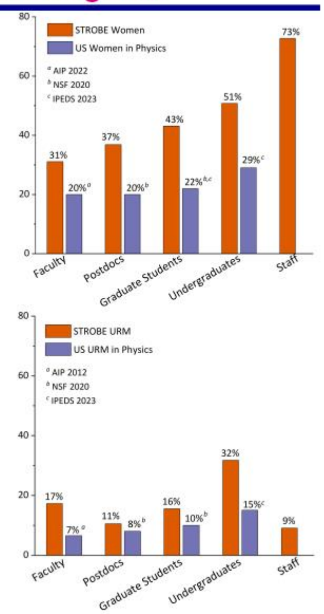

STROBE
BUILDING THE MICROSCOPES OF TOMORROW
7 years of growth and very high productivity!
7 CORE UNIVERSITIES
>700 GRADUATE STUDENTS IMPACTED
104 GRADUATE STUDENTS
38 POSTDOCTORAL RESEARCHERS
26 CORE FACULTY
64 PARTNERSHIPS:
6 NATIONAL LABS
20 INDUSTRY
30 ACADEMIC
8 OTHER
>18,000 VIEWS OF THE STROBE WEBSITE IN PAST YEAR
>10 UNIQUE ADVANCED MICROSCOPY CAPABILITIES
344 PEER REVIEWED PUBLICATIONS
>9,135 CITATIONS
>500 IMPRESSIONS PER MONTH
>3,000 TEACHERS AND STUDENTS IMPACTED BY OUTREACH
>9 PENDING PATENTS
Over $45M ADDITIONAL FUNDS FROM STROBE-LEVERAGED GRANTS
2022
2021
2020
2019
2018
2017
2023 to date
~350
~300
9135
~750
Publications
Collaborative Publications
Citations
Invited Talks
nature
MOLECULAR SYRINGE
ipam institute for pure & applied mathematics
Computational Microscopy
September 12 - December 16, 2022


STROBE
BUILDING THE MICROSCOPES OF TOMORROW
STROBE is a go-to place to address microscopy challenges!
INDUSTRY
moderna
Vaccines
3M
HORIBA
Nanocomposites
imec
intel
SAMSUNG
Nanoelectronics
APPLIED MATERIALS
Device materials
Ball Aerospace
THE UNIVERSITY OF ARIZONA
Detectors
NATIONAL LABORATORY
NIST
Spintronic, Electronic
NREL
Battery
Solid electrolyte
NREL
Photovoltaics
Pacific Northwest NATIONAL LABORATORY
Interfaces, Surfaces
LiSA
PPPL
Solar Fuels
Argonne
OAK RIDGE National Laboratory
New methods, algorithms, big data
ACADEME
Magnetic
CDCM
PennState
2D & Layered
MIT
HARVARD UNIVERSITY
RICE
PTL
Caltech
CAU
C2SEPEM
Molecular
THE KAVLI FOUNDATION
GORDON AND BETTY MOORE FOUNDATION
PYLUM BIOSCIENCES
nature
Bio
VERTEX
Disordered
UNIVERSITY OF MARYLAND
BROWN

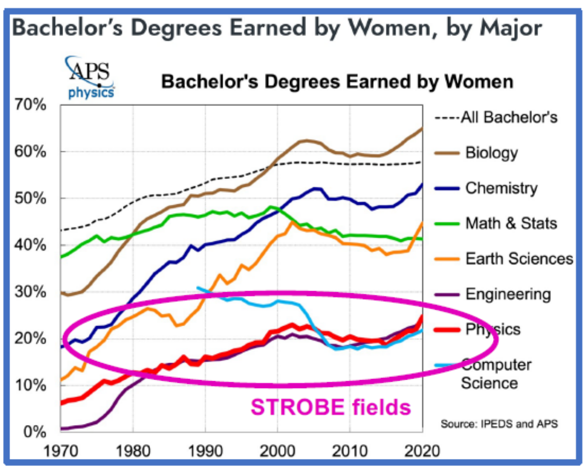
STROBE Stellar award-winning trainees, above center norms

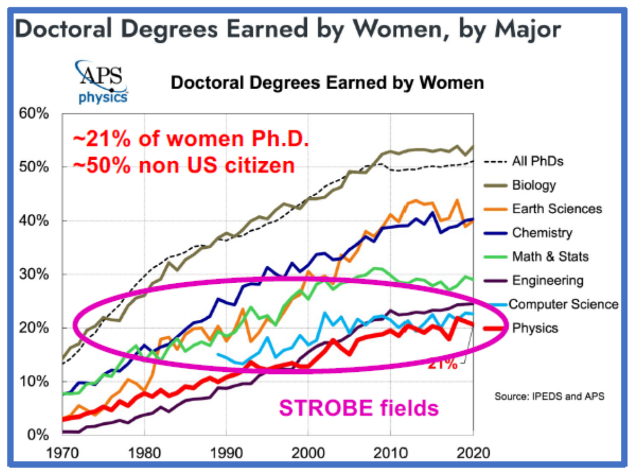
~155 Ph.D. and postdoc alumni since 2017, >150 undergrads

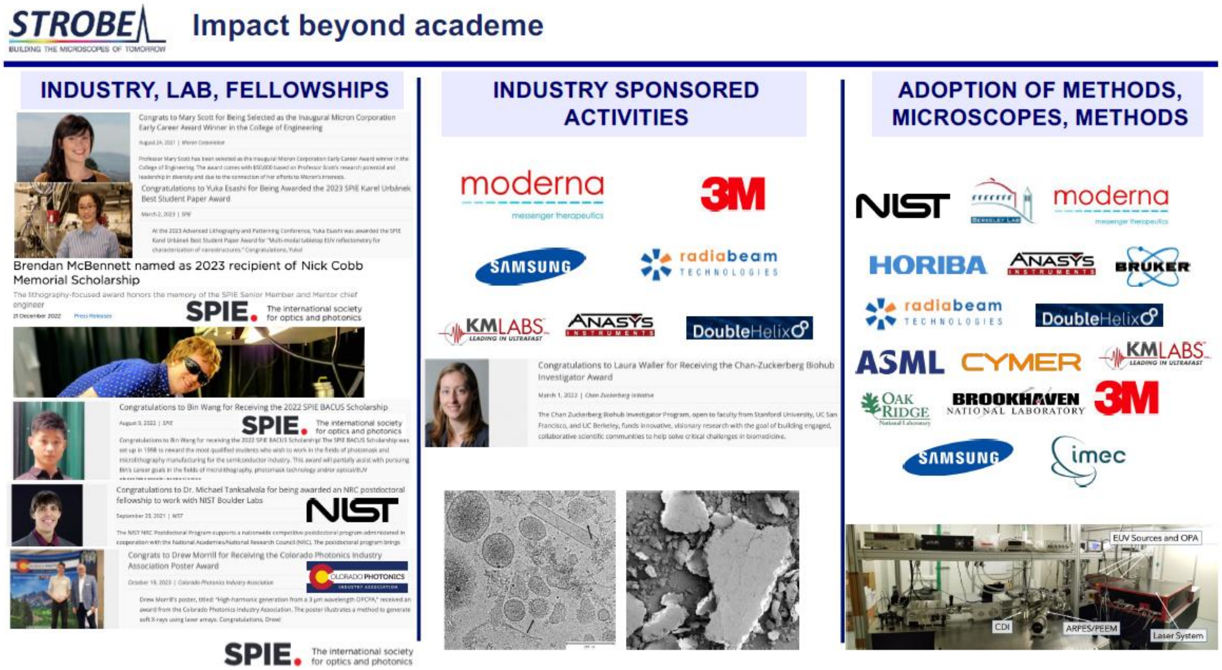


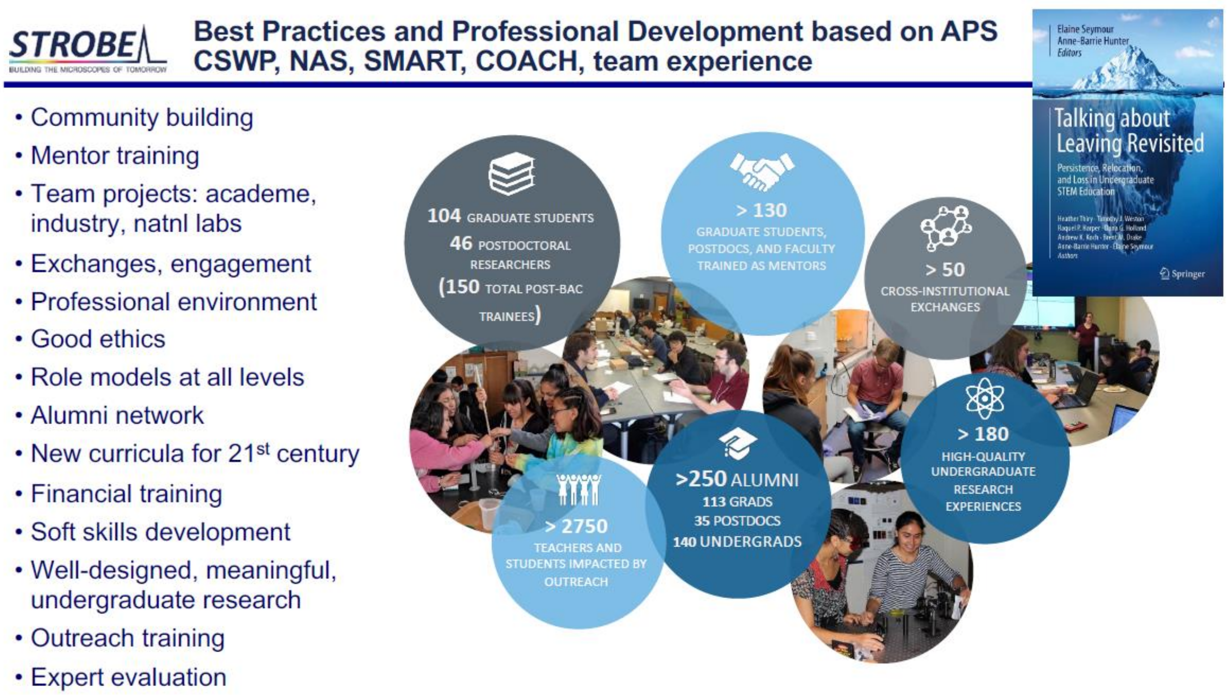


STROBE Grand Challenges for Broadening Participation in STEM






STROBE
BUILDING THE MICROSCOPES OF TOMORROW
Impact beyond academe
INDUSTRY, LAB, FELLOWSHIPS
INDUSTRY SPONSORED ACTIVITIES
ADOPTION OF METHODS, MICROSCOPES, METHODS
Brendan McBennett named as 2023 recipient of Nick Cobb Memorial Scholarship
SPIE. The international society for optics and photonics
Congratulations to Bin Wang for Receiving the 2022 SPIE BACUS Scholarship
Congratulations to Dr. Michael Tanksalvala for being awarded an NRC postdoctoral fellowship to work with NIST Boulder Labs
Congrats to Drew Morrill for Receiving the Colorado Photonics Industry Association Poster Award
Congratulations to Laura Waller for Receiving the Chan-Zuckerberg Biohub Investigator Award
moderna
3M
SAMSUNG
radiabeam TECHNOLOGIES
KMLABS
ANASYS INSTRUMENTS
DoubleHelix
NIST
HORIBA
BRUKER
ASML
CYMER
OAK RIDGE
BROOKHAVEN NATIONAL LABORATORY
imec
EUV Sources and OPA
CDI
ARPES/PEEM
Laser System

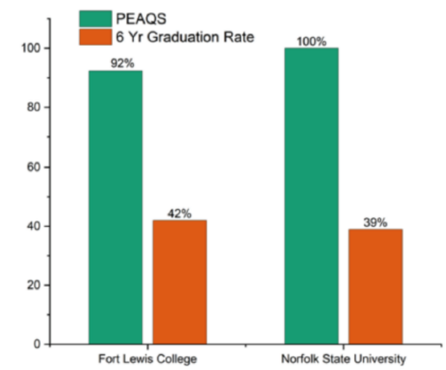

STROBE
BUILDING THE MICROSCOPES OF TOMORROW
Best Practices and Professional Development based on APS CSWP, NAS, SMART, COACH, team experience
• Community building
• Mentor training
• Team projects: academe, industry, natnl labs
• Exchanges, engagement
• Professional environment
• Good ethics
• Role models at all levels
• Alumni network
• New curricula for 21st century
• Financial training
• Soft skills development
• Well-designed, meaningful, undergraduate research
• Outreach training
• Expert evaluation
104 GRADUATE STUDENTS
46 POSTDOCTORAL RESEARCHERS
(150 TOTAL POST-BAC TRAINEES)
> 130
GRADUATE STUDENTS, POSTDOCS, AND FACULTY TRAINED AS MENTORS
> 50
CROSS-INSTITUTIONAL EXCHANGES
> 180
HIGH-QUALITY UNDERGRADUATE RESEARCH EXPERIENCES
>250 ALUMNI
113 GRADS
35 POSTDOCS
140 UNDERGRADS
> 2750
TEACHERS AND STUDENTS IMPACTED BY OUTREACH
Elaine Seymour
Anne-Barrie Hunter
Editors
Talking about Leaving Revisited
Persistence, Relocation, and Loss in Undergraduate STEM Education
Springer

PEAQS STROBE PREM PEAQS-STROBE Partnership

- Help to build a sustainable research capability at FLC and NSU that is mindful of faculty expertise and workloads
- Help to build infrastructure for materials research at FLC and NSU
- Provide students with high-impact, multi-year research experiences leading to technical understanding and broad, transferrable skills that employers seek in 21st century applicants
- Develop student cohorts between FLC, NSU and STROBE that are shown to enhance retention
- Build a strong, diverse network of scientists and students between NSU, FLC and STROBE (and beyond STROBE)
- Provide career preparation, professional development training and through multiple co-mentors: faculty + Drs. Schreiner & Keister
- STROBE role: Train and co-mentor students; Multiple exchange visits for technical & professional training; Advise on equipment use & purchase; Advise on grant administration; Broaden network

Recruitment, retention, mentoring & training of a diverse cohort of undergrads

PEAQS Undergrads have a 96% Graduation Rate compared with institutional averages of ~44%



STROBE NSF SCIENCE AND TECHNOLOGY CENTER Access to STROBE microscopes and methods

User facilities

User proposal:

- COSMIC @ LBL
- NCEM @ LBL
- SINS @ LBL/ALS
- CL @ MoFo
- Materials database
- HyRES @ Boulder
- Free software

Commercial instruments

STROBE industry partners:

- Bruker
- Horiba
- 3M
- KMLabs
- DoubleHelix
- Radiabeam
- NanoElectronic Imaging

Collaborations

STROBE unique instruments:

- X-ray CDI @ Boulder
- Nano-IR @ Boulder
- stroboSCAT @ Berkeley
- Workshops & user training
- KT to MSI's
- Adoption by NIST, DOE, others

Appendix G: NSF Q-SEnSE

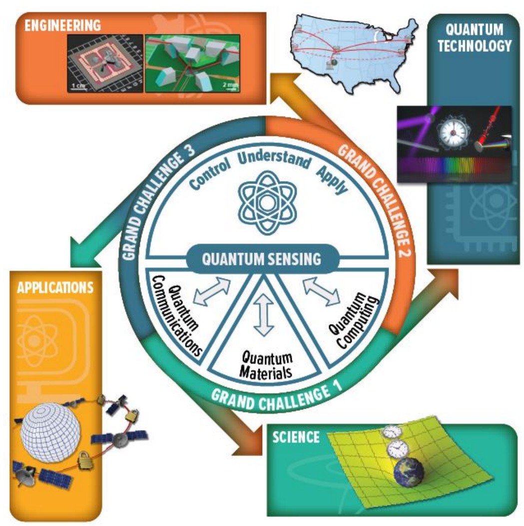
Title: Quantum Leap Challenge Institute for Enhanced Sensing and Distribution Using Correlated Quantum States
PI: Jun Ye (NIST and JILA, the University of Colorado Boulder)

Short description of the project:

As an NSF-sponsored Quantum Leap Challenge Institute, Q-SEnSE has a primary mission of advancing and realizing true quantum advantage in sensing and measurement through collaboration among experts in fundamental physics and applied engineering. Established in 2020 with the leadership of JILA, a joint institute of NIST and the University of Colorado, Q-SEnSE currently comprises 44 senior investigators at 9 universities, 2 National Labs, one National Institute, and one FFRDC. Overall strategy and direction are coordinated through a representative Executive Committee led by Principal Investigator Jun Ye and including a Deputy for Science and Research Convergence, a Director for Education and Workforce Development, and a Director for Operations.

Research projects are organized around three Grand Challenges in a cyclically reinforcing relationship captured in Fig. 1.

Grand Challenge 1: Develop Quantum Advantage in Sensing and Measurement. A unique design feature of our Center is exploitation of the fundamental connection between emerging quantum technology and frontiers of physical sciences, with Center investigators performing pioneering theory and experimental studies on entangled quantum states to demonstrate genuine quantum advantage in quantum sensing and measurement systems. We broadly explore, engineer, and apply many-body quantum states to protect quantum coherence and accuracy, optimize entanglement for measurement, and build inter-system connections for distributed sensing.



Grand Challenge 2: Develop Field-Deployable and Distributed Sensing and Measurement Systems. To facilitate and hasten new quantum technologies for practical applications, we are developing systems with advanced integration, measurement, and interconnectivity capabilities robust enough to be deployed in the field. Examples include integrated systems such as optical atomic clocks, matter-wave interferometers, magnetometers, chip-scale-nonlinear-photonics, optical frequency combs, and distributed sensing networks.

Grand Challenge 3: Create a National Quantum Infrastructure for Sensing and Measurement: Case Study – Strontium. To provide a lasting impact for a quantum ecosystem, a unique Center goal is development of robust, cost-effective, and standardized tools that provide synergy across multiple practical implementations. With multiple leading research groups working with alkaline earth atoms such as Sr, we exchange information to allow rapid tool development, technology maturation, and dissemination. We aim to develop and distribute these tools to a broad user community through coordinated partnerships among universities, National Laboratories, NIST, and industry partners.

Spanning those Grand Challenges is a fourth major goal: Design and establish mechanisms to introduce undergraduate and master's level students to the principles and practices of quantum science and engineering in a team setting and prepare those individuals for productive entry into an economy that has begun to recognize, pursue, and take advantage of, the promise of those fields. This ambitious research program has the potential for transformative extensions of quantum sensing for new basic physics (detection and characterization of dark matter, dark energy, and matter-antimatter asymmetry); for applications of quantum technologies to areas of practical importance (quantum communications and networking); and for establishing, and hastening use of, standards for quantum tools for academia and industry. We also seek strong impact of quantum technology on many different scientific fields, including some of which are yet to be imagined.

We are implementing concrete ideas to train the next generation of the quantum workforce, spanning new undergraduate and postgraduate degrees, new educational modules for two-year colleges, and internships or summer schools with emphasis on introducing underserved minorities to the educational and professional opportunities in quantum science and engineering.

Summarize progress made over the last year, focusing on key objectives or milestone reached, challenges encountered, and/or other particularly noteworthy highlights.

Representative Milestones over Year 3:

- Delivery of quantum advantage in sensing is most directly shown in the use of emerging quantum technology for the probing fundamental physics. Q-SEnSE continues to lead this effort with individual groups and cross-group collaborators.
- We describe a space mission concept by placing a state-of-the-art optical atomic clock in an eccentric orbit around Earth.
- Various quantum metrology algorithms are investigated, and a new broadband dynamical decoupling algorithm proposed to improve signal sensitivity while suppressing noise, with numerical simulations of scalar dark matter searches having realistic noise sources.
- Experiments are beginning to probe interactions of quantum particles with a gravitational field considered as a superposition state.
- Q-SEnSE has made remarkable progress in delivering quantum entanglement for sensing and leads the entire field with outstanding results on generating and applying squeezed states of atomic spins for sensing applications.
- Performance of a quantum sensor network is limited by technical challenges and inherent noise associated with quantum states used to realize the network. For networks with only local entanglement at each node, the noise performance improves at best with square root of the number of nodes.
- By implementing an effective time-reversal protocol in an optically engineered many-body spin Hamiltonian, we demonstrate a quantum measurement with non-Gaussian states with a signal amplification through a time-reversed interaction to achieve the greatest phase sensitivity improvement beyond the standard quantum limit.
- Building on the pioneering work of Center investigators at MIT and Stanford, the recent JILA efforts achieve direct optical clock comparison at the 10^{-17} level enabled by spin squeezing.
- Our integrated photonics work spans a wide range of efforts, such as the interface for micro-fabricated ion traps for quantum information and sensing, the development of scalar-vector magnetometers, chip-scale optical lattice clocks, frequency combs for sensing and timing distribution networks, nonlinear optical devices for wavelength conversion and generation of squeezed state of light, and the construction of a new quantum source for a quantum network linking the CU Boulder and NIST campuses.

- The connection of quantum sensing to quantum many-body physics has provided a rich playground to guide experiments in a quest to learn how to harness interactions to generate entanglement and protect quantum coherence. Center work has impact in optical lattice clocks, optical tweezer clocks, polar molecules, trapped ions and cavity QED systems.
- Microscopic Control of Atoms and Ions is an important research component in Q-SEnSE to achieve high fidelity entanglement generation and readout in sensing applications, which cuts across Grand Challenges 1 and 2. We combine technologies for controlling individual atoms or ions to demonstrate larger scale sensor-qubit and clock technologies and enable scientific research benefitting quantum computing, sensing, and communication beyond what can be done today with smaller systems.
- One important Center theme is motional state control of trapped ions, especially on the use of 2-mode squeezing to implement SU(1,1) interferometry. For the first time, 2-mode squeezing in trapped-ion motion has been demonstrated.
- Fruitful collaboration across theory and experiment has been established, yielding joint projects such as search for ultralight dark matter with optical clocks and satellite-based observations. One team is developing a concept for flying a cluster or formation of small satellites in low Earth orbit to use frequency combs and optical links for two-way time and frequency transfer and ranging.
- A high-precision optical atomic clock (OAC) on an Earth-orbiting space station is a major thrust of quantum technology with many exciting scientific opportunities. We propose a pathfinder mission to compare space-based OAC with ultra-stable terrestrial OACs to search for space-time-dependent signatures of dark scalar fields, opening possible probes of new physics that are inaccessible to purely ground-based OAC experiments.
- Portable Quantum Sensors are a major goal of Grand Challenge 2 and a portable Yb optical lattice clock has now been constructed and is in full operation. After initial characterization, it was involved in comparison with clocks at a remote location. New laser cooling techniques and robust optical reference cavities are also part of the technology development to support portable lattice clocks. Q-SEnSE development of stable lasers, atomic ovens, cryogenic systems, and integrated atomic physics packages represents a broad scope advance for alkaline earth-based quantum sensing infrastructure.

Provide outcomes/benefits of this project over the past year, including both scientific advancements as well as other benefits. Examples of the latter include contributing to graduate and undergraduate education; K-12 or other outreach; technology commercialization and/or spin-off companies; collaboration with others.

Convergence and Communications:

Q-SEnSE incorporates activities to foster convergence and coordination in its geographically dispersed team of 44 senior investigators, including:

- *Convergence Seminars*: monthly events structured as brief presentations by senior investigators to highlight what is working well and what impediments have been encountered and might be addressed by new collaborations. A complete list of recent Convergence Seminars is on the Community page of the Q-SEnSE website.
- *Executive Committee Meetings* scheduled as needed to discuss significant strategic matters such as the selection of proposed new projects and the allocation of funds to individual investigators.
- *Center-wide Annual Meeting*, which was remote in 2022 but in-person in Boulder for 2023, with participation of Senior Investigators and students from all Partner Organizations and one full session on strategic planning for Award Year 4 and beyond.

- *Communications with other scientists and the public*, is accomplished through the flood of research papers highlighted on the Publications page of our website, each with its abstract, and through the numerous talks delivered by our investigators.
- *Fourteen-Minute Video*, available on the home page of our comprehensive website, describing the goals, impact, and public benefit of our Center and, by implication, of the QLCI program generally. See https://www.colorado.edu/research/qsense

Catalysis of Related Quantum Initiatives:

Q-SEnSE is the original core, and remains a primary focus of CUbit, an umbrella administrative unit at the University of Colorado Boulder that seeks to coordinate quantum research and education across departments and colleges. https://www.colorado.edu/initiative/cubit/ Q-SEnSE was a spark for the formation of the Quantum Engineering Initiative (QEI), a new unit in the CU College of Engineering, jointly staffed by Engineering faculty and accomplished quantum scientists and engineers from NIST Boulder Labs.

Education and Workforce:

Our Center has matured initial plans for Education and Workforce Development into several concrete programs:

- *The Q-SEnSE Research Exchange* (QRX) is well underway as an internship program in which students from predominantly minority-serving institutions join a yearlong cohort of professional development focused on industry enculturation and preparation for internships. In Year 3, QRX launched a dedicated online community via a commercial vendor, Mobilize, to offer and coordinate on-demand quantum and professional development content. To export the model to regions outside Boulder, we submitted an NSF ExLENT proposal to expand QRX into a national model for cohort-based quantum internships, initially partnering with Cal State San José, U.T. Dallas, and Worcester Polytechnic Institute. That proposal is pending.
- *Undergraduate Research Assistantships* are an excellent mechanism for inspiring early engagement with quantum and are offered to all Partner organizations, with early uptake from exchanges among MIT, Stanford, JILA, CU Engineering, Innsbruck, and Oregon.
- *Graduate Student Exchange Program*, in which a graduate student from one Partner spends from a few days to a week in the lab of another Partner. The benefit of these exchanges can flow in either direction: exchanging students sharing knowledge of specialized techniques with a host lab or gathering knowledge from a host lab to bring back to their home labs. Existing examples include multiple exchanges of students from the Blumenthal group, UCSB, bringing integrated laser technology for testing and measurements in the Ye and Thompson labs.
- *Quantum Forge* has emerged as a successful and attractive quantum education course implemented as hands-on capstone lab projects to train upper-division undergraduates or 1st year master's students in the conceptual and practical aspects of working in a team environment to address an industry-provided, quantum-relevant, appropriately scoped technical project. At the end of its 1st year, the corporate sponsor, Maybell Quantum, retained one of that year's student participants and committed to sponsoring a 2nd project in Award Year 4, where Maybell has been joined by a second corporate sponsor, the very early-stage startup Mesa Quantum Systems.

Additional documentation:

Fourteen-Minute Q-SEnSE Highlights Video, available on the home page of our comprehensive website, describing the goals, impact, and public benefit of our Center and, by implication, of the QLCI program generally. See https://www.colorado.edu/research/qsense

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Appendix H: NSF Center for Integration of Modern Optoelectronic Materials on Demand

Title: STC: Center for Integration of Modern Optoelectronic Materials on Demand (IMOD)
NSF Award No.: DMR-2019444
PI: Seth Marder (PI at CU Boulder)

Enter a short description or abstract of the project:

The NSF Center for Integration of Modern Optoelectronic Materials on Demand, or IMOD, was announced in September of 2021. IMOD is an NSF Science and Technology Center (STC), one of a class of six funded in 2021. The NSF STC programs support exceptionally innovative, complex research and education projects that require large-scale, long-term awards. The stated goals of NSF STCs are to conduct world-class research through partnerships among academic institutions, national laboratories, industrial organizations, and other entities, both domestically and internationally and to undertake significant investigations at the interfaces of disciplines and/or using fresh approaches within disciplines. More specifically, IMOD is driven with the vision of incorporating colloidal quantum dot technology into both conventional (e.g., quantum light sources) and unconventional (e.g., quantum light emitting diodes). In this regard, our Center is focused more on quantum materials focused than quantum compilers.

IMOD consists of 24 core faculty-led research groups based across 11 US academic institutions, and includes over 100 graduate student, postdoctoral research fellows, and research scientists. The lead institute is the University of Washington, which subcontracts to the other academic institutions in the network, which includes:

- The City University of New York
- Columbia University
- Georgia Institute of Technology
- Lehigh University
- Northwestern University

- University of Chicago
- University of Colorado Boulder
- University of Maryland
- University of Maryland, Baltimore County
- University of Pennsylvania

IMOD issued five new seed awards and three renewal seed awards in Year 3. Five of the eight seed awards went to CU Boulder, and one award went to Rice University as a new subaward, increasing IMOD's US academic institutions to 12.

Summarize progress made over the last year, focusing on key objectives or milestone reached, challenges encountered, and/or other particularly noteworthy highlights (limit answer to 1/2 page).

Our Center has had many accomplishments to report to date through the first two years. We developed a Strategic Plan in Year 1 that outlines our 10-year vision and goals, as well as details performance indicators and metrics for achieving our 5-year milestones. We are planning to submit a renewal proposal in early Year 4 (around Jan. 2025). IMOD has made impressive progress on its research, education, broadening participation, and knowledge transfer goals, and has established a center culture and identity that has been recognized through our programs' evaluation. Highlights of these activities, including a summary of the activities funded by CHECRA support, are described below.

- Successfully hired multiple positions at CU Boulder to support the Center, including Managing Director, Director of Communications, Director of Research Integration, Research Operations Manager, and more recently Director of Education and Human Resource Development. The Research Operations Manager position is partially funded through CHECRA funding. CU PI Marder serves as the Deputy Director, and his time in this capacity is supported through CHECRA funding. About 1 month per calendar year of STROBE's Director of Education, Dr. Keister, is supported through CHECRA to work on IMOD activities. Positions were also filled at University of Washington, including the hiring of Director of Diversity, Equity, and Inclusion, and a partially supported Operations Manager.
- In Year 2, IMOD continued to focus on encouraging collaborative capabilities amongst the team and had 32 publications as of September 2023. These publications were largely drawn from the improved integration across our dispersed teams through a yearly Publication Plan that defines active projects and collaborations in a way that is transparent and actionable. At this time, there are over 30 publications being planned that include 10 which have been submitted or accepted, and 7 manuscripts in preparation. Figure 1 shows the number of IMOD publications since IMOD's inception in 2021.
- IMOD has conducted three open Seed proposal calls for Year 1-3. Proposals funded include 3 seed proposals (at CUNY, UW/UMBC, and CU Boulder) in Year 1, 4 seed proposals (at UW, 2x at CU Boulder, and Georgia Tech), and 8 seed proposals (at UW, UMBC, Rice, and 5x at CU Boulder). The CU Boulder projects were supplemented with CHECRA funding to allow for additional student support on the seed awards, thereby allowing the seed awardees to focus more effort on their IMOD projects. In particular for the last round of seed awards, leveraging CHECRA support was critical in our Center's ability to issue 5 seed awards to CU Boulder. The IMOD Seed Program has focused on increasing theory efforts and diversity across the Center, with over 60% of the seed awards going to MSIs and individuals from groups underrepresented in STEM.
- UW IMOD staff hosted STC STROBE staff in Seattle in Fall 2023 to strengthen our relationship with members of their team and look for opportunities for IMOD-STROBE partnering. This engagement is also leading to the development of an NSF PREM proposal, joint with STC STROBE, in response to a call for proposals (due March 2024), that involves MSIs NSU and Fort

Lewis College. IMOD is also working on developing another PREM proposal the Center's MSI partner UC Merced.

Provide outcomes/benefits of this project over the past year, including both scientific advancements as well as other benefits. Examples of the latter include contributing to graduate and undergraduate education; K-12 or other outreach; technology commercialization and/or spin-off companies; collaboration with others.

- One of IMOD's signature programs is a center-wide, cohort-building, week-long, in-person Trainee Course (OMS^3) that is held annually in person before the Center's Annual all-hands Meeting. The Year 2 OMS^3 Course, which was held on the UW Seattle campus in July 2023, and included 30 participants representing 19 of 23 senior personnel's research groups, with 25% of the participants from our MSI partners. Trainees received foundational technical skills, learned best practices in team science including cross training and reflexivity, developed communication skills, and knowledge transfer training.
- We held our second IMOD REU program with a national applicant pool, placing 8 IMOD REU students participating at multiple sites across the center (including 4 REUs at UW) in summer 2023 (50% female, 25% first generation college students, 12.5% self-identify as URM, 37.5% from MSI or 2 yr. college). The application portal for the 2024 Summer REU program just closed, with over 200 applications. We are also launched an RET program at UW in Summer 2023 and recruited three teachers to participate. In Year 3, we plan to expand the RET program to other sites.
- IMOD is both making progress on long-term synthetic materials and integration challenges, while also performing the first rounds of highly collaborative synthesis/processing/structure/device/function/theory loops that we will need to iterate through over the coming years to have the center level impact. As an example of a Year 2 highlight, IMOD facilitated the development of giant SiO2-shelled II-VI quantum dots that were tailored to enable their deterministic placement to sub-wavelength precision of the emitting core across microfabricated wafers in collaboration across research thrusts, and verification of their behavior as arrays of single-photon emitters across large areas. In Year 3, IMOD introduced new Working Groups to support cross-center collaboration and strategic goal-focused research planning. One of the signature outcomes from these groups thus far is the progress toward the scalable integration of Quantum Dot (QD) emitters, showing that QD emitters can be positioned with high fidelity, in a scalable fashion.
- We have developed a number of tools within the Center to enhance the community and engagement. This includes an IMOD Integrated Travel Program, which supports both center members and new external collaborations (with several awards being made to CU students and postdocs), the use of Basecamp leveraged through CU's RASEI as a project management tool, and an internal IMOD SharePoint site for sharing documentations and Center resources.

Appendix I: NSF Engineering Research Center for Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE) - CU

Title: NSF Engineering Research Center for Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE)
PI: Qin Lv

Enter a short description or abstract of the project:

The ASPIRE NSF ERC is the first of its kind in the world to take a holistic approach to eliminate range and charging as barriers to electrifying all vehicle classes, from passenger cars to heavy duty trucks. The center is pursuing innovative wireless and plug-in charging and infrastructure technology solutions that bring the power to the vehicles—where they drive and park. The result will be smaller and longer lasting batteries on vehicles, effectively unlimited range, and a seamless charging experience. Users will no longer be concerned with when, where, or how they will charge, and electric vehicles will be less expensive to purchase and operate than their gasoline and diesel counterparts. Electric vehicles will become a resource to decarbonize the electric grid and an ideal companion to connected and autonomous vehicles. The ASPIRE team will serve as a trusted guide for society and as a champion for inclusive pathways from varied aspects of life into a diverse engineering workforce specially trained to support the ensuing cross-industry transformations. ASPIRE has grown to over 350 participants, recruited 31 industry and 21 innovation members, received commitments for more than $50M in pilot demonstration projects, formed and actively engaged its boards and councils, and significantly advanced engineering workforce development and diversity and culture of inclusion initiatives, including multiple workshops, training sessions, recruitment programs, and development of joint courses addressing convergent research across the center and diversity, equity and inclusion in transportation.

Summarize progress made over the last year, focusing on key objectives or milestone reached, challenges encountered, and/or other particularly noteworthy highlights.

We have continued work on better understanding the interdependencies between transportation and power infrastructure and how people from different communities use these systems. We have completed phase 1 of the project, which analyzed the adoption of electric vehicles (EVs) and infrastructure health in the Colorado Front Range and San Francisco Bay Area. Our analysis found noticeable differences in adoption trends between these two areas, demonstrating the importance of a regional approach for modelling the impact of EV adoption on infrastructure. In phase 2 of the project, we are exploring demographic factors, including socio-economic variables and electric vehicle adoption, to understand how specific areas are more or less susceptible to changes in travel behavior in response to weather conditions and power disruptions.

To understand the air quality, health, and environmental justice implications of vehicle electrification, we have leveraged fine spatial scale emissions input data and the use of a reduced complexity model (RCM) to improve the accuracy and specificity of ASPIRE's air quality modeling efforts related to vehicle electrification scenarios. We have initiated efforts to incorporate more realistic adoption and charging scenarios by leveraging ASPIRE-created EV adoption curves and power system models. We have analyzed six months of particulate matter elemental and organic carbon data using source apportionment and machine learning methods to understand the spatiotemporal distribution of particulate matter sources. A case-study approach is designed to investigate the specific impacts of EV adoption on power systems, and therefore on local air quality and health.

Provide outcomes/benefits of this project over the past year, including both scientific advancements as well as other benefits. Examples of the latter include contributing to graduate and undergraduate education; K-12 or other outreach; technology commercialization and/or spin-off companies; collaboration with others.

We successfully hosted the 2023 ASPIRE ERC Annual Meeting and NSF Site Visit on the University of Colorado Boulder campus. Over 200 participants attended the week-long event. The participants included faculty, staff, and students across different ASPIRE campuses, as well as the NSF site visit team, state and campus representatives, and ASPIRE industry and innovation partners.

Two students working on phase 1 of the project have graduated with MS degrees. Phase 2 is currently being developed by a PhD student. In addition to the educational outcomes, we have produced a conference paper from phase 1 of the project. This paper will be presented at the Construction Research

Conference, organized by the American Society in Civil Engineering in March 2024. We expect to have two papers derived from phase 2 of the project.

We have submitted a journal manuscript assessing the spatial distribution of traffic related air pollutants in a near highway environment using air quality monitors and small unmanned aircraft. We have also collected sensor and reference data to assess gas phase pollutant concentrations. The methods we are developing to model emissions scenarios and understand sources of air pollution are flexible and can easily be implemented in other areas, like Denver, which may aid local and state agencies—such as the CDPHE and DDPHE—in understanding air pollution sources and potential avenues to reduce emissions.