COLORADO
Higher Education Competitive
Research Authority

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, 2023

Honorable Members of the House and Senate Education Committees
State Capitol
200 East Colfax
Denver, Colorado 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 2022. This includes multi-year projects that received continued funding in 2022, and new initiatives funded for the first time in 2022.

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 almost $1.69 million in 2022 to support nine multi-year research grants, and support the purchase of five Major Research Instruments, that collectively have brought over $50 million in federal research dollars to the state. Following is a list of the multi-year research grants that received CHECRA funding in 2022:

University of Colorado (CU)

- 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. CHECRA has pledged $400,000 for a renewal of five years; 2021 was the first year of funding for the second renewal.

- 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; 2021 was the second year of funding.

- **DOE Desalination Hub: NAWI Road mapping project**, led by University of Colorado Boulder, the project engaged in the baseline evaluation and roadmap development of water reuse practices supporting NREL and the NAWI team in the areas of industrial reuse, agricultural reuse, oil and gas wastewater reuse and mining wastewater reuse. The CHECRA board has authorized a contribution of $40,000.00.

Colorado School of Mines (CSM)

- The **National Alliance for Water Innovation (NAWI)** is a research consortium that was formed in 2017 to partner with the U.S. Department of Energy to create the Energy-Water Desalination Hub. In 2019 the DOE announced that NAWI will manage the new Desalination Hub. NAWI vision is to support the develop affordable, energy-efficient, and resilient water supplies from unconventional resources (e.g., oil and gas, mining, agriculture, seawater/brackish water, power industry, and general industries). Research under NAWI focused on enhancing the U.S. economy through decentralized, small-scale, fit-for-purpose desalination. The CHECRA board has authorized a contribution of $123,188.00.

Colorado State University (CSU)

- **Colorado State University's Industrial Assessment Center (CSU IAC)**, funded by the U.S. Department of Energy, provides industrial energy audits by engineering students to small and medium sized manufacturing facilities. The CHECRA has committed to providing a total of $131,634 to the IAC over three years. CHECRA made the final of three payments in 2021 for $43,878.00.

- The **CSU ROOTS** is contributing to technological innovation in high throughput sampling of roots and soil and soil carbon modeling and demonstrated the values of these innovations to established and emerging industry partners. 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.

- A **Novel Electro-dialytic Crystallizer (EDC) for Energy Efficient Zero-liquid Discharge** led by Colorado State University. This project investigates a new brine management process called electro-dialytic crystallization (EDC). The core innovation of EDC is the use of the electrodialysis phenomenon to maintain a saturated brine stream for continuous salt precipitation. The CHERCA board authorized a contribution of $89,275.00.

In addition to the payments listed above, CHECRA provided $346,800 as a cost share for the following Major Research Instrumentation (MRI) grants received from NSF in 2022. These one-time grants provide higher education institutions with major instrumentation that supports the research and research training goals of the institution and are also used by other researchers regionally or nationally.

- **CU MRI Consortium: Development of Fiber-coupled stimulated emission depletion microscopy (STED).** With this grant, CU is developing a unique miniature optical fiber-coupled microscope that will enable flexible imaging at unprecedented spatial resolution. Developed with a diverse team that includes engineers, physicists, and neuroscientists, this cutting-edge microscope will yield far-reaching impacts through intellectual property development and future commercialization and deployment in industry. The research team will use the new instrument to expand ongoing efforts to mentor and inspire young students from groups underrepresented in Science Technology Engineering and Mathematics (STEM) fields.

- **CU MRI: Acquisition of a High-Performance Computing Cluster for Next-Generation Computational Science in Southern Colorado.** This project will enable the acquisition, deployment, and maintenance of a high-performance computing (HPC) cluster (to be called INCLINE). This instrument will provide much-needed computational resources to the UCCS campus and the Southern Colorado scientific and academic communities.

- **CSU MRI: Acquisition of an Open Access Shared-Use MALDI-TOF/TOF Mass Spectrometer.** This project provides partial cost share support for a National Science Foundation Major Research Instrumentation Grant awarded to Colorado State University in August 2021, to fund the acquisition of a high-resolution Matrix Assisted Laser Desorption/Ionization Tandem Time-of-Flight Mass Spectrometer (MALDI-TOF/TOF). This will serve as a shared resource for CSU faculty and students with open access to users from the surrounding Rocky Mountain region.

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 programs include industry partners and often drive new venture creation in the state. Many of the CHECRA supported programs have a triple helix ecosystem of partners (research universities, industry, and government). A most recent example is support for projects at Colorado School of Mines and at CSU through NAWI (National Alliance for Water Innovation), which is led by a U.S. Department of Energy national lab (Lawrence Berkeley), has multiple participating companies in the sector, and includes open opportunities to all of Colorado's public research institutions.

- The future is bright for CHECRA and includes opportunities to amplify our impacts to contribute to the science and technology infrastructure of the Front Range and beyond across several areas. These include new investments in a hydrogen hub, in climate resilience, and general investments in our state science and technology infrastructure.

- These opportunities will remain linked to large federal investments that will enable our state to remain competitive and collaborative in generating important science and technology solutions to our most pressing problems as well as to attract students to our state contributing to our economy and workforce development efforts.

Due to the State budget impacts of the pandemic, the annual distribution of Limited Gaming Funds in the amount of $2.1 million to the Authority was suspended for two years, so CHECRA did not receive that revenue in 2021. Interest earnings on the Authority's funds totaled $18,455 in 2022. Expenses totaled $1,690,000.

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

Cc: Dr. Alan Rudolph, Vice President for Research, Colorado State University, and Chair, CHECRA
Dr. Jeri-Ann Lyons, Associate Vice President for Research, University of Northern Colorado, and Vice Chair, CHECRA
Dr. Walter Copan, Vice President for Research and Technology, Colorado School of Mines
Dr. Massimo Ruzzene, Vice Chancellor for Research, University of Colorado Boulder

CHECRA Appendices:

University of Colorado Boulder

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

First and last name of the primary investigator (PI) for this project (or PI's):
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 (limit answer to 1/2 page).

We have analyzed electric vehicle (EV) adoption trends and infrastructure health in the Denver, CO, and San Francisco, CA metropolitan areas. We identified various demographic factors that impact EV adoption in these areas and assessed how increased EV adoption may adversely affect road and power infrastructure quality in nearby areas. We also found that lower-income communities who may not directly benefit from the ownership of electric vehicles may face unfavorable impacts from adjacent, higher-income communities. We hope to use these results in the next year to inform models that will be used to predict EV adoption, and analyze how compounding effects from reduced fuel tax revenue and strained power infrastructure may disproportionately affect certain neighborhoods.

Over the last year, we have made progress on our three primary objectives: (1) establishing an air quality monitoring network in Salt Lake County (SLCo), (2) beginning to conduct a modeling study estimating the health and environmental justice (EJ) impacts of vehicle electrification in SLCo, and (3) making connections with SLCo-based researchers and community organizations that enable this work. We analyzed the existing air quality monitoring network and identified target areas for sensor deployment based on existing gaps in sensor coverage, proximity to point and non-point (road) sources pertinent to our investigation of electrification of the inland port, and the location of SLCo schools, where we plan to host our sensors. We are hoping to improve on past ASPIRE-led health analyses by using more recent spatially downscaled air quality emissions data, which has a resolution of 1 km x 1 km. We have begun pre-processing the emissions data that is compatible with our reduced complexity air quality model—InMAP. We have begun creating vehicle electrification scenarios and are working with our local research partner—who also specializes in community-engaged research in SLCo's historically disadvantaged Westside communities—and community organizations such that community groups can inform selection of additional electrification scenarios.

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 have submitted an abstract, with the intention of publishing a peer-reviewed conference proceeding, to the American Society of Civil Engineers (ASCE) CI CRC Joint Conference 2024 titled "TRENDS IN EQUITABLE ELECTRIC VEHICLE ADOPTION AND IMPACTS ON PAVEMENT QUALITY AND ELECTRIC POWER RELIABILITY." This is based on the work performed by two undergraduate students (one of which has continued on in this project as a graduate student), a postdoctoral researcher, and Professors Kyri Baker and Cristina Torres-Machi at the University of Colorado Boulder. For both students, this was their first research project, and first time working towards a publication.

Our research has produced—or is on the way to producing—several beneficial outcomes, including: established community relationships with local researchers and community groups, an improved air quality monitoring network in terms of pollutant and spatial coverage, and increased spatial resolution of emissions data for use in scenario modeling. All of these goals are in service of ultimately understanding the air pollution, health, and EJ implications of vehicle electrification. While our research has to date been conducted in SLC, our research approach could be replicated in other areas and our findings from our SLC-based research provides valuable findings for other communities. As SLC and Denver face many similar issues with regard to air quality—including elevated levels of ozone and particulate matter—our research into electrification can help inform how Denver transitions to electric vehicles, ensuring that the transition delivers optimal air quality and health benefits. Additionally, 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.

Appendix B: MRI - Acquisition of a Direct Detection Electron Energy Loss Spectrometer for Fast, Low- Dose, and High Resolution Spectroscopic Imaging of Hard and Soft Materials

First and last name of the primary investigator (PI) for this project (or PI's):
Gordana Dukovic

Enter a short description or abstract of the project:
This project aims to acquire a high-speed electron energy loss spectrometer (EELS) equipped with a direct electron detection (DED) camera for use at the University of Colorado Boulder. This instrument is integrated into an aberration-corrected transmission electron microscope recently installed at the University of Colorado Boulder. The science enabled by the new spectrometer will span many fields and include collaborations across diverse departments, institutes, universities, national labs, and industry. The EELS/DED system will enable researchers to **(a)** develop and apply multidimensional STEM techniques for measuring small electric, magnetic, and strain fields in nanomaterials and small phase contrast in beam-sensitive soft materials, **(b)** probe optical and electronic properties of materials in UV, visible, and IR regions down to 80 meV with high spatial resolution, **(c)** fully exploit the elemental composition, chemical bonding, and oxidation state information contained in the electron energy loss near edge structures (ELNES) with atomic resolution, **(d)** carry out high resolution electron imaging and spectroscopy on beam-sensitive and low-contrast materials.

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).
After receiving the award, we realized that the CEOS company has also completed its electron spectrometer development, and its system has become available on the market. Therefore, Gatan is not the only manufacturer of high-energy electron spectrometers anymore. This development allowed us to renegotiate the initial quotation we received from Gatan for the proposal. After six months of intense negotiation with both Gatan and CEOS, we leveraged this NSF award significantly and purchased the instrument from Gatan but with a better system. In addition to what we proposed in our proposal, the new system has a Stela camera, a hybrid pixelated direct electron detector camera which is a complementary detector to the K3 camera, a highly stable cryo-transfer holder, and a piece of software for phase analysis. We placed an order for this EELS system in early March 2022. At the time of writing this report, the system is physically installed on our aberration-corrected microscope, and work is in progress to fully align the system and bring everything up to spec. Unfortunately, due to the supply chain issues, we experienced a delay in the final alignment of the system because we had to wait for a scanning board/chip that must be installed on the microscope before the alignment procedure can be carried out.

Appendix C: STC - Center for Integration of Modern Optoelectronic Materials on Demand (IMOD) NSF Award No. DMR-2019444

First and last name of the primary investigator (PI) for this project (or PI's):
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 23 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

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 had a successful first year with many accomplishments to report to date. In Year 1, IMOD developed a Strategic Plan that outlines our 10-year vision and goals, as well as details performance indicators and metrics for achieving our 5-year milestones. IMOD has made impressive progress on its research, education, broadening participation, and knowledge transfer goals, and has begun to forge a center culture and identity. 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, and Research Operations Manger. The Research Operations Manager position is partially funded through CHECRA funding. Positions were also filled at University of Washington, including the hiring of Director of Diversity, Equity, and Inclusion, and Director of Education and Human Resource Development.

In Year 1, IMOD focused on building collaborative capabilities amongst the team, and had 4 publications and 4 pre-prints. In Year 2, we are working to improve integration across our dispersed teams and developed a 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 4 which have been submitted or accepted, and 8 manuscripts in preparation. This also includes 2 IMOD-led review articles for Chem. Rev. and ACS Nano. The topics represented in the Publication Plan span all Research Theme areas including efforts focused on materials synthesis, systems and integration, and measurement and properties.

IMOD conducted two open Seed proposal calls for Year 1 and Year 2 funding, including to establish formal review processes, and funded 3 seed proposals (at CUNY, UW/UMBC, and CU Boulder) in Year 1 and 4 seed proposals (at UW, 2x at CU Boulder, and Georgia Tech). 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.

IMOD staff conducted a site visit with one of our MSI partners, UC Merced, to better understand their needs and opportunities for local and IMOD engagement. This engagement is also leading to the development of an NSF PREM proposal, joint with STC STROBE, in response to a call for proposals anticipated later in 2023, that involves MSIs UC Merced, NSU, and Fort Lewis College.

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.

Developed, from the ground up, a signature, center-wide, cohort-building, week-long, in-person Onboarding Course that is held annually on the UW Seattle Campus. The Year 1 Onboarding Course trainees, which was held on August 15-19, 2022, included 32 participants, representing 23 of our 24 senior personnel’s research groups, and members 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.

IMOD held an REU program in Year 1 with a national applicant pool, placing 8 REU students participating at multiple sites across the center (including 1 REU at CU) in summer 2022. The cohort consisted of 50% female, 25% first generation college students, 12.5% self-identify as URM, 25% from MSI or 2 yr. college. We are currently accepting applications for the 2023 Summer REU program. We are also launching an RET program at UW for Summer 2023.

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.

Established an online onboarding process for distributed participants from PIs to trainees, including surveys, training materials, and for students, and selection of dual mentors for all postdoc and PhD student participants. We are also developing a number of tools within the Center to enhance the research experience. This includes the launch of the IMOD Integrated Travel Program, which supports both center members and new external collaborations (with 4 of the 6 awards being made to CU students and postdocs), the use of Trello as a project management tool, and an internal IMOD SharePoint site for sharing documentations and Center resources.

Additional documentation:
IMOD YR1 Annual Report

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

NSF award to University of Colorado, Boulder (UCB) NSF Award: 1548924
Period of Performance: 10/01/2016 – 09/30/2026 (~$48M over 10 years, renewed)

Total 2021 CHECRA Funding: $400,000

Award PI's: 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? What is the 3D atomic structure of glasses and how do the atoms rearrange themselves during the glass transition? 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 (LBNL, ORNL, NIST) and several US industries to develop and advance microscopy tools and techniques. Major achievements in 2022 include enhanced collaborations with partners who come to STROBE as a resource – institutions such as Moderna, 3M, Moore Foundation, MRS, DOE LBNL, PPNL, PPPL, NIST, 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 >140 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 and elsewhere. Most notably, STROBE technologies are now either used, or are impacting, several national laboratory facilities at NIST Boulder Labs, Lawrence Berkeley Lab, industry and elsewhere. Finally, UCLA STROBE scientist Professor Hong Zhou continued to work with Moderna in 2022, to provide high resolution images of their vaccines.

Outcomes/benefits of this project over the past year:
STROBE is attracting new collaborations from national labs, academe and industry.
>140 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%).

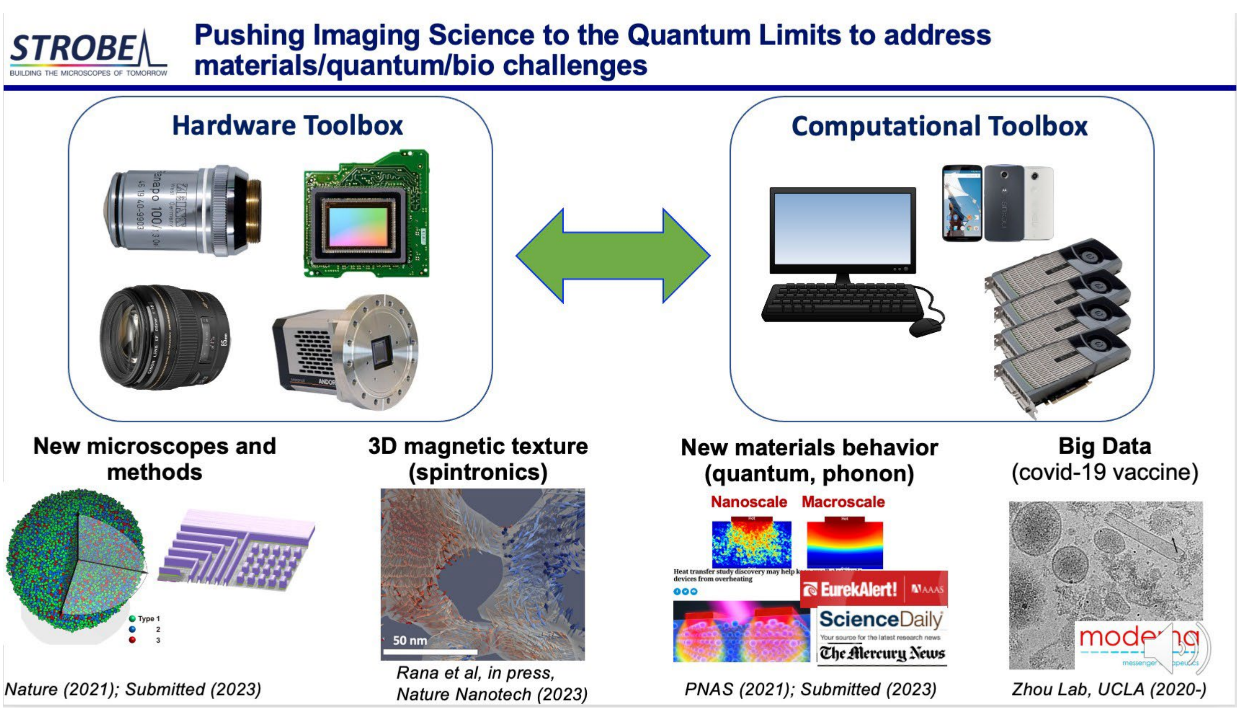
UCLA STROBE scientist Hong Zhou continued to provide images of their vaccine to Moderna, as a service spanning ~3 years. For bio-materials, sub-2Å resolution is required to obtain the chemical structure. Only the best electron imaging labs, like Zhou's, have the specialized setups to manage the immense 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.

STROBE research advances have resulted in >280 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.

1. Trainees received multiple awards, including National Research Council Postdoctoral Fellowships to work at NIST Boulder Labs, graduate fellowships, best papers (see https://strobe.colorado.edu/news- events/awards/)
2. STROBE continued to partner with CU Science Discovery (CU Boulder) and the middle school teachers in the rural Four Corners Region to provide materials in support of NGSS (Next Generation Science Standards). STROBE provides hands on workshop for over 200 students at Ignacio Middle School on the Southern Ute Reservation and Tse Bit Ai Middle School in the Navajo Nation. STROBE is working with Mr. Anil Chopra, the prior STEM education coordinator for Ignacio Middle School, to assist with planning and refinement.
3. 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 6 years.
4. STROBE-enhanced IR sources are now available to a broad user community at the Department of Energy Synchrotron Source at UC Berkeley.
5. 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.
6. STROBE-enhanced tabletop X-ray sources are used by NIST Boulder for advanced materials research.
7. STROBE mentored ~30 undergraduate students for research experiences in the summer of 2022.
8. 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.

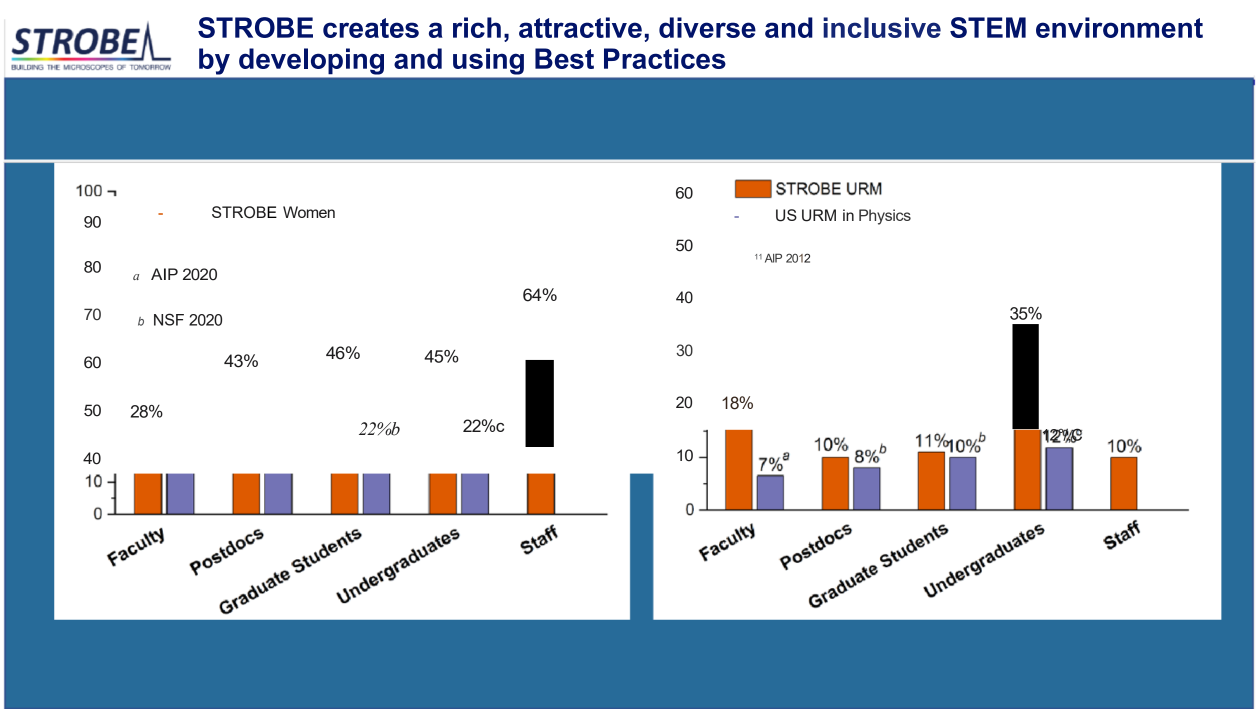
Please see the slides below for data and further information.

Attachment A

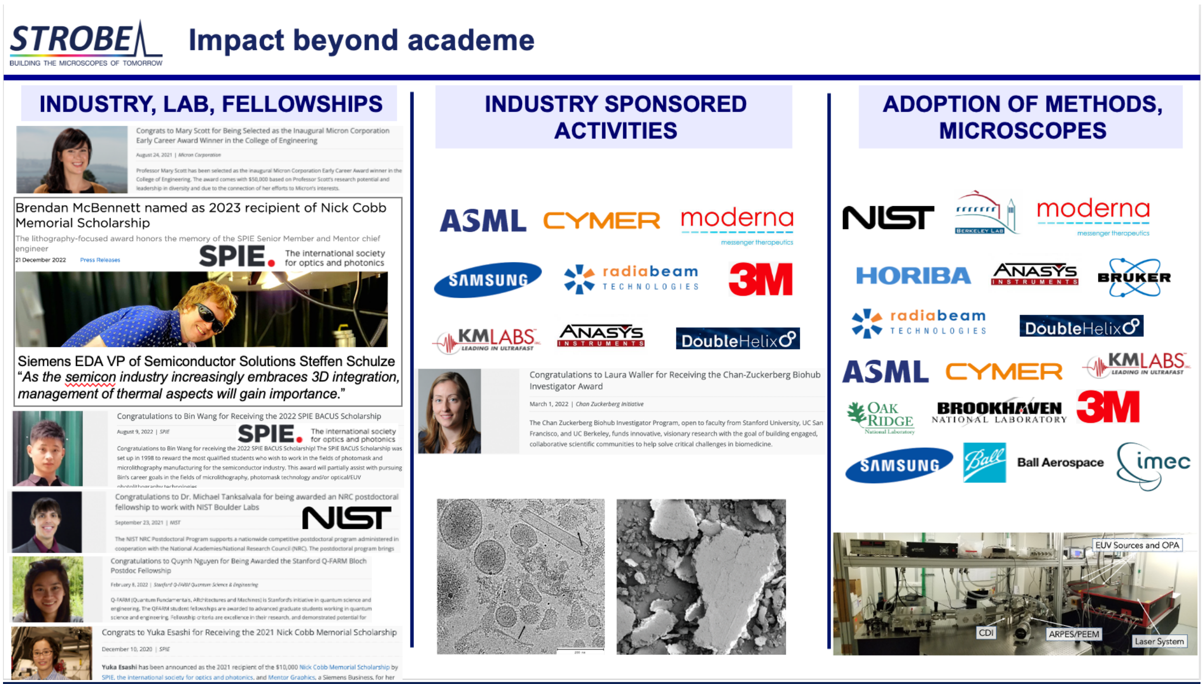


Attachment B

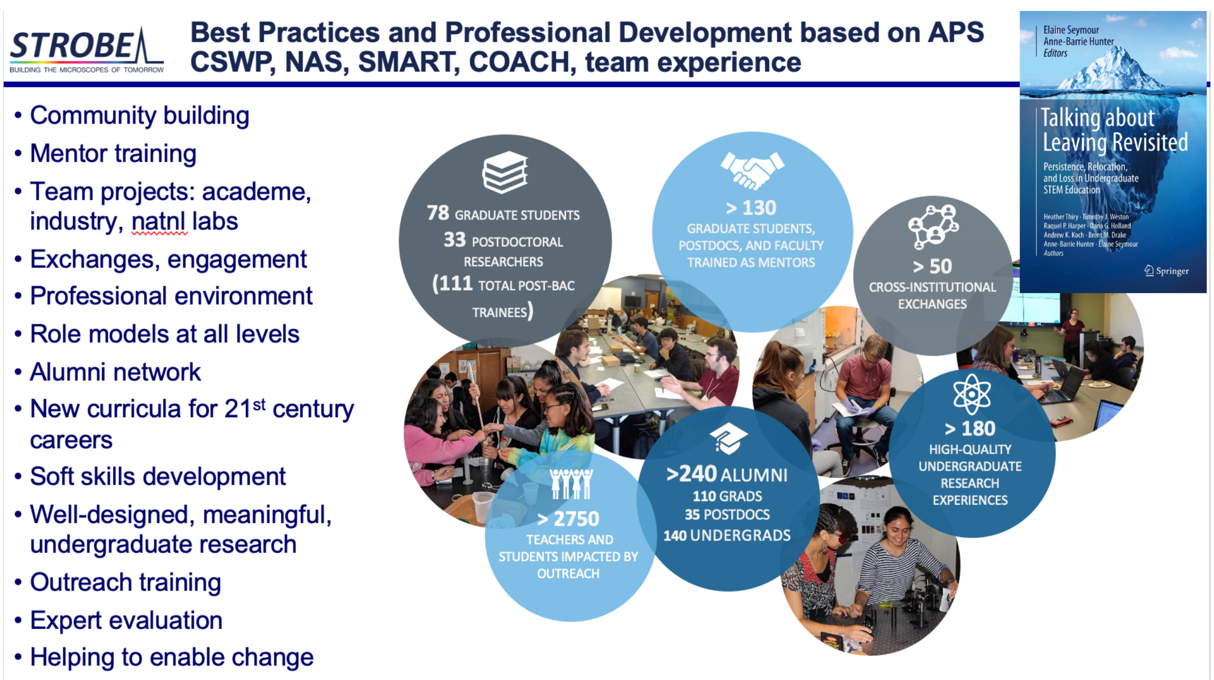
Attachment C



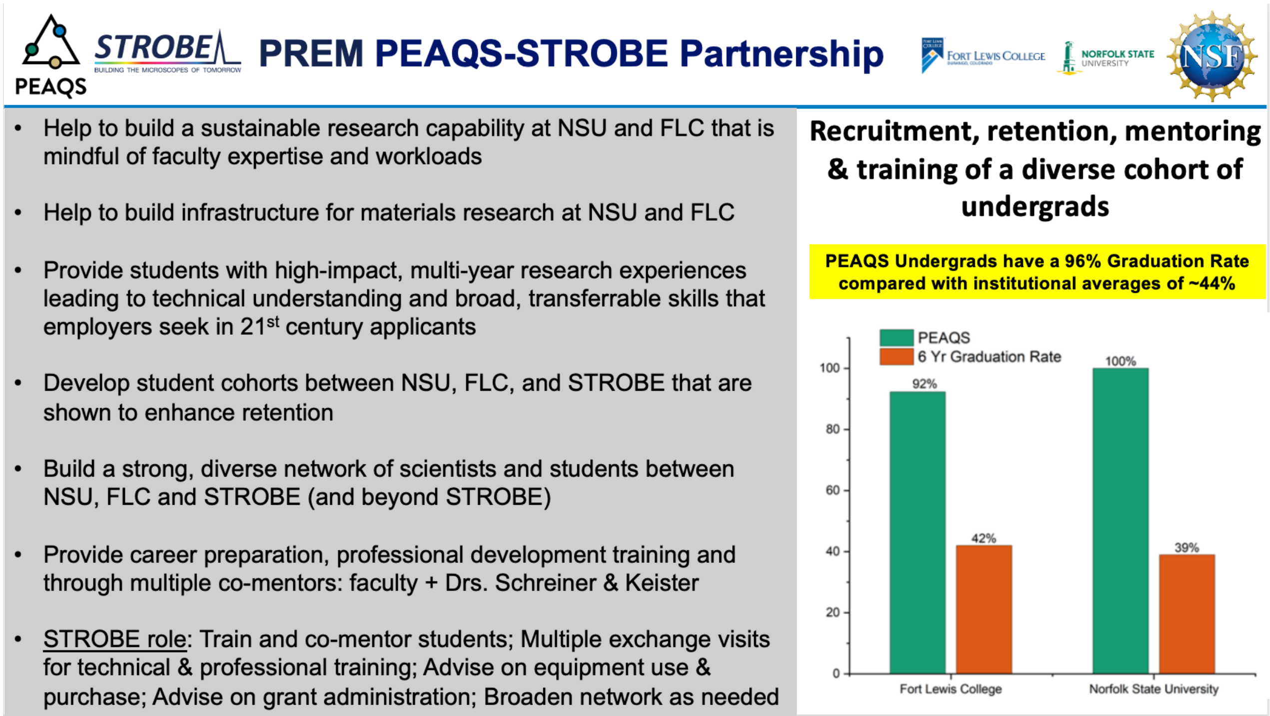
Attachment D



Attachment E



Attachment F



Appendix E: NSF Quantum Leap Challenge Institute for Enhanced Sensing and Distribution Using Correlated Quantum States

First and last name of the primary investigator (PI) for this project (or PI's):
Jun Ye (NIST and JILA, the University of Colorado Boulder)

Enter a short description or abstract of the project:
The Institute will design, build, and employ quantum sensors based on high-performance atomic, molecular, and optical systems. The Institute is designed around three ambitious Grand Challenges to significantly advance fundamental science, technology integration, and practical application of quantum-based technologies:

> *Grand Challenge 1*: Perform basic research and enable technology to achieve "quantum advantage" in sensing and measurement: clear supremacy over classical or "Quantum 1.0" methods
> *Grand Challenge 2*: Develop field-deployable quantum sensors and interconnections
> *Grand Challenge 3*: Develop the experimental and technical tools to establish atomic strontium (Sr) as the industry standard in quantum sensing, thus facilitating more rapid advances by the wider academic and industry communities.

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 (limit answer to 1/2 page).

Since the previous report, we updated operational components in four broad areas: Infrastructure, Education and Training, Research and Collaboration, and Communications (internal and public facing).

- *Infrastructure accomplishments*
  - Designed, authored, and maintained a database of all Q-SEnSE publications, searchable by author, institution, and keyword. This is useful, for example, in assessing two metrics of high significance to the NSF QLCI program that sponsors our Center: i) the number of joint author collaborations among our Center's Senior Investigators, and ii) the number of Q-SEnSE projects forged from two or more Q-SEnSE Partner organizations.
  - Expanded our External Advisory Board to include three new members:
    - John Bowers (UCSB), an expert in photonic integrated circuits and quantum photonics
    - Holger Müller (UC Berkely), who focuses on atomic, molecular, and optical physics, including use of atom interferometry as a precision probe for measuring gravity, fundamental constants, and the laws of physics
    - Jon Simon (Stanford), who researches quantum & classical matter
    - *For full EAB listing, see Org Chart in Attachment A.*
  - Added UCLA as13th Partner organization, maintaining Senior Investigator status for Dr. David Leibrandt, formerly of NIST Boulder Labs.
  - Leveraged our Q-SEnSE Institute to help form the Quantum Engineering Initiative in the CU Boulder College of Engineering. We anticipate that QEI's continued growth will substantially amplify the critical linkage between quantum physics and quantum engineering.
- *Education and Training accomplishments*
  - Collaborated with the CU Boulder Vice Chancellor for Research Massimo Ruzzene to recruit Prof. Noah Finkelstein of UCB Physics to lead and help implement coordinated, campus-wide programs in quantum education at the undergraduate and graduate levels.
  - Mentored and trained 16 postdoctoral students, 61 PhD graduate students, and 10 undergraduate students in the fields of quantum science and engineering across the Institute's 13 partner organizations (*see Attachment B*).
  - In addition to linking with the new Quantum Engineering Initiative, continued to foster integration of traditionally separate disciplines of Physics and Engineering, as will be necessary for success in meeting the

Institute’s ambitious technical goals

  - Secured and equipped lab space and offered the 1st run of a new joint Physics- Engineering course for Quantum Forge, which provides upper division undergraduates with hand-on experience in quantum-related projects relevant to industry.
  - Under the leadership of Dr. Michael Bennett, Q-SEnSE Director of Education and Workforce Development, established Q-SEnSE Research Exchange (QSRX), a program that facilitates internships for two-year college students at host companies and national labs, coaches students on preparing applications for those opportunities, and provides support as students transition into their internship placements.

- *Research and Collaboration accomplishments*
  - Used CHECRA funds for new support of:
    - Prof. Scott Diddams, who was recruited to lead the new Quantum Engineering Institute at CU Boulder from his previous position in NIST Boulder Labs. Since moving, Scott has taken on leadership of the QEI, a role for which he is amply prepared, with his decades-long experience in applying physics perspectives and techniques to engineering problems of significant impact.
    - Prof. Shuo Sun, a new Q-SEnSE Senior Investigator who adds expertise in atomic & molecular physics, nanoscience, quantum information science & technology
    - Prof. Dana Anderson, who mentors a graduate in JILA on a Q-SEnSE project even as he helps expand the CU spinoff ColdQuanta that he founded in 2007.
  - Continued to foster team communications and collaborations among our three Grand Challenges by exploring and goals and identify paths and teams for specific research projects (*see Attachment E*)
  - Continued monthly “Research Convergence” seminar series to foster cross- disciplinary and multi-institution collaborations among the Institute’s 41 Senior Investigators and their graduate students and postdocs (*see Attachment C*)
- *Communications: (Internal and Public facing) accomplishments*
  - Continued development of a website[11] dedicated to sharing results and plans among the Senior Investigators, students, and more broadly to the public; established and populated a Dropbox folder hierarchy with access-controlled sub- folders for specific groups; established Slack channels for communications among Institute investigators and students
  - Planning our second Annual Meeting to highlight early scientific progress, re- enforce collaborations, and give graduate students and postdocs an opportunity to present their projects and directly engage with the entire Institute community. This year we hold the Annual Meeting and NSF Site Visit with substantial in- person participation, inviting one Senior Investigator from each Partner to come to Boulder, along with several graduate students who can present their projects,

[1] https://www.colorado.edu/research/qsense/

network with peers, and tour Q-SEnSE labs in JILA, CU Engineering, and NIST Boulder Labs.

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.

Further examples of noteworthy outcomes in Year 1 include:

- *Research and Collaboration*
    - Produced multiple outstanding results including a systematic survey among quantum industry partners and ensuing data analysis/research on quantum education; setting the most stringent constraints on the ultralight dark matter with the use of a state-of-the-art optical atomic clock – and example of precision metrology meeting cosmology; generating new molecule-based quantum systems and exploring quantum entanglement between molecules; and investigating the connection between quantum complexity and quantum information by studying quantum chaos in strongly-correlated many-body systems. *For details, see Attachment D.*
    - Expanded our External Advisory Board to elicit suggestions that would increase the Institute's impact on science, engineering, and the public. For full EAB membership, see Org Chart in Attachment A.
    - Used the successful NSF QLCI award to leverage establishment of a new Quantum Engineering Institute (QEI) at CU to better realize the benefits of Physics-Engineering deep collaborations in quantum.
- *Education and Training*
    - Established Quantum Forge as an education platform to provide hands-on training of undergraduate students to prepare them for quantum research and industry positions, and established Quantum Forge as an official class at CU. The initial semester (fall, 2022) attracted 10 students, and their hands-on project was designed in collaboration with Maybell Quantum, a young Colorado company. Maybell sponsored the course with funding, and its CEO and other senior individuals grounded the project in concrete practicality through lectures to the class.
    - Continued design and preparation of a simulation module in the internationally recognized PhET[22] system at CU to translate the idea of quantum superposition and coherence in an intuitive way to pre-college students and the public. We plan to present an initial static (non-interactive) draft at the NSF Site Visit in early August.
    - Launched the Q-SEnSE Research Exchange program (QSRX) to provide undergraduate students with quantum-related laboratory experience; initiated contact with internship program directors at LANL, Sandia National Labs and Boeing.

[2] https://phet.colorado.edu

Additional documentation:
(Additional documentation may include additional artifacts, reports, or content that should be included as an appendix or addendum to the content supplied in this form.)

Attachment A: An updated Organization Chart for our NSF Quantum Leap Challenge Institute (Q-SEnSE, for "Quantum Sensing through Entangled Science and Engineering")

Attachment B: Universities and National Laboratories partnering in the Institute

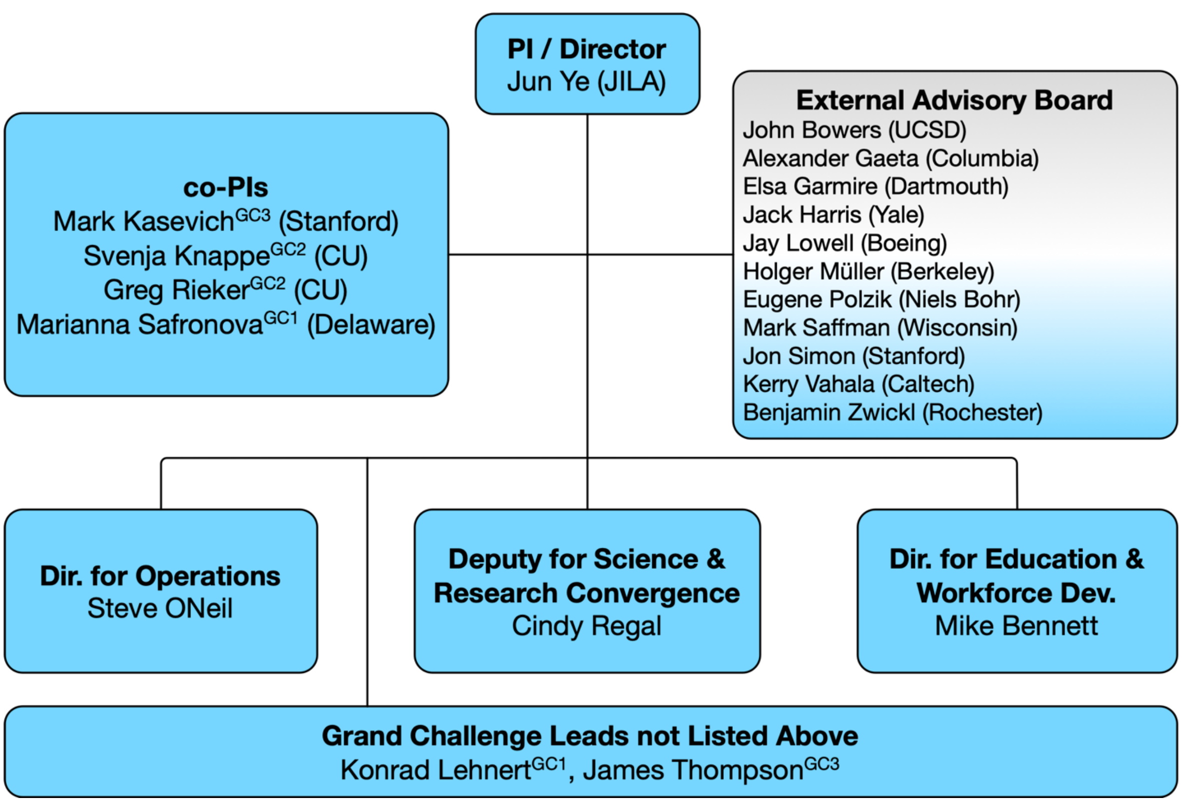
Attachment C (PDF): Copy of "Community" page of the Institute website, listing meetings, seminars that foster coherence and collaboration among the Institute's senior investigators and across its 12 participating organizations, and presentations of Institute work to a wider audience

Attachment D: (PDF): Publications by Institute Researchers

A full list, with a drop-down abstract for each publication, is on our web site at https://www.colorado.edu/research/qsense/publications

Attachment E: Working Groups

Attachment A: Organizational Chart of NSF QLCI



Principle Investigator & Director:

- Jun Ye, NIST and JILA, University of Colorado Boulder

Co-PIs:

- Prof. Mark Kasevich, Stanford (Applied Physics)
- Prof. Svenja Knapp, University of Colorado (Engineering)
- Prof. Greg Rieker, University of Colorado (Engineering)
- Prof. Marianna Safronova, University of Delaware (Physics & Astronomy)

Deputy for Science & Research Convergence**:** Prof. Cindy Regal, JILA and University of Colorado (Physics)

Director for Education and Workforce Development**:** Michael Bennett, PhD

Director for Operations: Stephen ONeil, PhD, MBA

Attachment B: Universities and Laboratories Partnering in the Institute

- JILA and University of Colorado Boulder (lead)
- Harvard University
- Los Alamos National Laboratory
- Massachusetts Institute of Technology (MIT)
- MIT Lincoln Laboratory
- National Institute of Standards and Technology (NIST)
- Sandia National Laboratories
- Stanford University
- University of California, Los Angeles
- University of Delaware
- University of Innsbruck (Austria)
- University of New Mexico
- University of Oregon

Attachment C Copy of Community Page

Community | Q-SEnSE: Quantum Systems through Entangled Science and Engineering | University of Colorado Boulder 2/1/23,

University of Colorado **Boulder**

12:36 PM

Community

On this page:

From individual researchers and laboratories to departments, institutes, and organizations, **modern science and engineering are team efforts**. Communities large and small coordinate to expand our understanding of the world and apply that new understanding to **inform**, **involve** and **advise** colleagues and the public, and help develop novel products and services for the economy.

Q-SEnSE investigators are involved with the community in many ways, with recent examples included below.

Q-SEnSE Convergence Seminar Series

1:15 - 1:30pm Mountain Time reserved for Senior Investigators; 1:30 - 2:45pm Mountain Time open to all Q-SEnSE investigators, collaborators, students, and postdocs

Thursday, Jan 26, 2023: All Q-SEnSE Convergence Seminar (Ye & Bennett)

Next Up: Thursday, Feb 16, 2023: All Q-SEnSE Convergence Seminar (Safronova & Newbury)

Fall 2022 Convergence Seminar Dates & Speakers

Thursday, Dec 8, 2022: All Q-SEnSE Convergence Seminar (**Industry Roundtable on "National Quantum Infrastructure for Sensing and Measurement: Case Study - Strontium**"); 15 Q-SEnSE Investigators; 19 collaborators, students & postdocs; 9 Industry experts

Thursday, Nov 3, 2022: All Q-SEnSE Convergence Seminar (**Sun** & **Wineland**); 12 Q- SEnSE Investigators; 64 collaborators, students & postdocs

Thursday, Oct 6, 2022: All Q-SEnSE Convergence Seminar (**Knap pe** & **Vuletic**); 18 Q- SEnSE Investigators; 19 collaborators, students & postdocs

Spring 2022 Convergence Seminar Dates & Speakers

Wednesday, May 25, 2022: All Q-SEnSE Convergence Seminar (**Regal** & **Huang**); 19 Q- SEnSE Investigators; 10 collaborators, students & postdocs

Wednesday, Apr 27, 2022: All Q-SEnSE Convergence Seminar (**Jau** & **Hollberg**); 16 Q- SEnSE Investigators; 22 collaborators, students & postdocs

Wednesday, Mar 2, 2022: All Q-SEnSE Convergence Seminar (***Education & Workforce Special Edition***); 12 Q-SEnSE Investigators; 23 collaborators, students & postdocs

Wednesday, Feb 23, 2022: All Q-SEnSE Convergence Seminar (**Gopinath & Diddams**); 17 Q-SEnSE Investigators; 17 collaborators, students & postdocs

Wednesday, Jan 19, 2022: All Q-SEnSE Convergence Seminar (**Hogan** & **Allcock**); 23 Q- SEnSE Investigators; 32 collaborators, students & postdocs

2021 Convergence Seminar Dates & Speakers

Tuesday, Dec 14, 2021: All Q-SEnSE Convergence Seminar (**Martin** & **Combes**); 18 Q- SEnSE Investigators; 8 collaborators, students & postdocs

Tuesday, Nov 30, 2021: All Q-SEnSE Convergence Seminar (**Axelrad**); 21 Q-SEnSE Investigators; 11 collaborators, students & postdocs

Tuesday, Oct 19, 2021: All Q-SEnSE Convergence Seminar (**Stick** & **Yelin**); 23 Q-SEnSE

Investigators; 45 collaborators, students & postdocs

Tuesday, Sep 21, 2021: All Q-SEnSE Convergence Seminar (**Doyle** & **Rieker**); 16 Q- SEnSE Investigators; 18 collaborators, students & postdocs

Tuesday, Jun 8, 2021: All Q-SEnSE Convergence Seminar (Deutch & Rey); 18 Q-SEnSE Investigators; 21 collaborators, students & postdocs

Tuesday, May 4, 2021: All Q-SEnSE Convergence Seminar (Chiaverini & Nam; 22 Q- SEnSE Investigators; 22 collaborators, students & postdocs

Tuesday, Apr 20, 2021: All Q-SEnSE Convergence Seminar (Kasevich & Kaufman; 22 Q- SEnSE Investigators; 28 collaborators, students & postdocs

Tuesday, Mar 23, 2021: All Q-SEnSE Convergence Seminar (Pap p & Newbury; 17 Q- SEnSE Investigators; 20 collaborators, students & postdocs

Tuesday, Feb 23, 2021: All Q-SEnSE Convergence Seminar (Monteleoni & Lehnert; 21 Q-SEnSE Investigators; 21 collaborators, students & postdocs

2022 SQuInt Workshop, October 20-22, 2022 at Berkeley.

Q-SEnSE partner University of New Mexico's SQuInT Center will hold its 2022 workshop at Berkeley, October 20-22, 2022. The full program is available online.

Collaboration Builders for Grand Challenges 2 & 3

Informal lunches to spark novel pair-wise collaborations among Investigators in Grand Challenges 2 & 3. Currently scheduled for noon in Boulder, with highlights presented in the next Convergence Seminar chat session.

Collaboration Builder Dates & Times

Tuesday, May 24, 2022, Noon Mountain Time •

Monday, Apr 11, 2022, Noon Mountain Time

Wednesday, Mar 2, 2022, Noon Mountain Time

Thursday, Jan 27, 2022, Noon Mountain Time -- **CANCELLED** for Covid Restrictions •

Thursday, Nov 18, 2021, 12:30pm Mountain Time

Grand Challenge Crystallization (Team-building) Meetings

Crystallization Dates & Times

- Feb 23, 2021: Grand Challenge 2 Crystallization Workshop II (**Axelrad, Knappe,** & **Rieker** organizers; 20 Q-SEnSE Investigators)

- Oct 23, 2020: Grand Challenge 3 "Crystallization Workshop" (14 Q-SEnSE Investigators)
- Oct 22, 2020: Grand Challenge 2 "Crystallization Workshop" (25 Q-SEnSE Investigators)
- Oct 13, 2020: Grand Challenge 1 "Crystallization Workshop" (26 Q-SEnSE Investigators)

NSF Site Visit 2022

NSF Site Visit 2022

- **Tuesday, August 16 -- *ALL TIMES MOUNTAIN*; All sessions via Zoom**

9:00am ***Private*** -- *For NSF Site Visit Panel Only*

10:00am *Welcome and Overview* (Ye, 20 min + 10 Q&A)

10:30am *Education & Workforce Development* (Bennett, 15 min + 10 Q&A) 10:55am *Quantum Sensing 1: Quantum sensors in space and fundamental physics* (Safronova, 15 min + 10 Q&A)

11:20am *Break* (10min)

11:30am *Quantum Sensing 2: Precision sensing and fundamental physics* (Lehnert, 15 min + 10 Q&A)

11:55am *Computing Applications & Sensing: Quantum algorithms and machine learning for sensing* (Holland & Monteleoni, 20 min + 10 Q&A)

12:25pm *Lunch Break* (40 min)

1:05pm *Convergence* (Regal, 10 min + 5 Q&A)

Student & Postdoc Research "Quick Views" (each 2 min + 3 Q&A)

- 1:20pm *Experimental progress in trapped-ion motional state control for quantum sensing* (Jeremy Metnzer, Oregon, Allcock group)

- 1:25pm *Interacting spin-orbit coupled fermions in Wannier-Stark optical lattice clock* (Anjun Chu, JILA, Rey group)

- 1:30pm *Ultracold SrOH molecules for quantum sensing of ultrlight dark matter*

(Zack Lasner, Harvard, Doyle group)

- 1:35pm *Towards programmable quantum sensors with alkaline earth atom arrays* (Aaron Young, JILA, Kaufman group)

- 1:40pm *Toward quantum-enhanced atom interferometry* (Guglielmo Panelli, Stanford, Kasevich group)

  - 1:45pm *Break* (15 min)
  - 2:00pm *Private visit with University Administration* (Ruzzene *(until 2:30)*, Bright, Molenaar,

Farmer, Wilson, Lehnert, Ritzwoller; 30 min)
2:30pm *Private visit with Center management other than PI & Co-PIs* (Regal, Bennett, ONeil, Pryzgocki; 30 min)

3:00pm *Wrap-up and Adjourn Day 1*

- **Wednesday, August 17 -- *ALL TIMES MOUNTAIN*; All sessions via Zoom**

9:00am *Industry Engagement: Status and Outlook* (Makotyn, 10 min + 10 Q&A) 9:20am *Quantum Sensing 3: Photonics for quantum sensing* (Diddams, 20 min + 10 Q&A)

9:50am *Spin squeezing for clocks & interferometers* (Thompson, 20 min + 10 Q&A) 10:20am *Break* (20 min)

10:40am *Microscopic control of entanglement* (Martin, 20 min + 10 Q&A) 11:10am *Grand Challenge 3: Status and outlook* (Kasevich, 20 min + 10 Q&A) 11:40am *Lunch Break* (40 min)

12:20pm *Private Visit: Representative Grad Students* 45 min; Emily Caldwell (NIST, Newbury), Annika Lunstad (Harvard, Doyle), Jeremy Metzner (Oregon, Allcock), Maya Miklos (JILA, Ye), Sean Muleady (JILA, Rey), Guglielmo Panelli (Stanford, Kasevich), Emily Haoyue Qiu (MIT, Vuletic), Enrique Segura (LANL, Martin), Jacob Siegel (NIST, Ludlow), John Wilson (JILA, Holland), Aaron Young (JILA, Kaufman) 1:05pm *Private Visit: Representative Postdocs,* 45 min; Tori Borish (JILA, Lewandowski), Simone Colombo (MIT, Vuletic), Zack Lasner (Harvard, Doyle), Garrett Mathews (CU Engineering, Rieker)

1:50pm *Break* (15 min)

2:05pm *Private Visit: Representative Senior Investigators* (Deutsch, Diddams, Doyle, Lehnert, Leibfried, Rey, Stick, Thompson; 30 min)

2:35pm *Private Visit: QLCI Leadership* (Ye, Kasevich, Knappe, Rieker, Safronova (unless mid-flight), Regal, Bennett, ONeil; 60 min)

3:35pm *Wrap-up and Adjourn Site Visit*

Special Event: Summer School on Many Body Physics for Quantum Information and Sensing

Summer School on Many Body Physics

Student-organized Summer School (1 Day, Virtual, Friday, August 19, 2022). This summer school, organized by Q-SEnSE students, will focus on Many Body Physics for Quantum Information and Sensing at a level accessible to everyone in Q-SEnSE

Schedule (Friday, August 19, 2022, all times Mountain) *Sign up by 5:00pm Mountain on Tuesday, August 16*

9:30-11:45am *Lecture* by Prof. Ana Maria Rey (theory)

Lecture by Prof. James Thompson (experiment)

11:45am - 1:00pm *Lunch Break*

1:00-2:00pm *Career Panel* Q&A

Featuring postdoc researchers and early-career scientists with PhDs in AMO physics The career panel will include a scientist from Quantinuum, a postdoctoral researcher in physics education research, a postdoctoral researcher in AMO physics, and a scientist from Apple

- 2:15-3:15pm Interactive computational workshop by Prof. Josh Combes

We will go over exercises on spin squeezing on a Jupyter notebook followed by a group discussion.

Registration is free and open for everyone including those whose PIs aren't directly funded by Q-SEnSE.

Sign up by 5:00pm Mountain on Tuesday, August 16

2022 Annual Meeting

2022 Annual Meeting Agenda

- 2022 Q-SEnSE Annual Meeting, June 29-30

Wed June 29 -- All times Mountain; All presentations delivered via Zoom

- 10:00am ***Private Session:*** *Executive Committee and External Advisory Board*

(15 min + 5 Q&A)

10:25am *Center overview and update* (Ye, 15 min + 5 Q&A)

10:50am *Education & Workforce overview and update* (Bennett, Deutsch, Lewandowski, 20 min + 5 Q&A)

- 11:20am *Clocks in space, precision sensing, and contributing science and technologies* (Lehnert, Safronova, Axelrad, 35 min + 5 Q&A)

- 12:05pm *Quantum algorithms and machine learning for sensing* (Holland, Yelin, Monteleoni, 35 min + 5 Q&A)
- 12:45pm *Lunch break* (30 min)
- 1:15pm *Student Council Overview* (Na Narong, 10 min + 3 Q&A) 1:31pm Student talks (each 12

min + 3 Q&A), all from JILA X317

- 1:31pm Lasner (Harvard, Doyle)

1:49pm Rege (CU Engineering, Monteleoni) 2:07pm Metzer (Oregon, Allcock)

- 2:25pm Panelli (Stanford, Kasevich) 2:43pm Young (JILA, Kaufman)
- 3:01pm *Industry Overview* (Makotyn, 10 min + 5 Q&A)
- 3:19pm *Photonics for quantum sensing* (Rieker, Diddams, Combes, 35 min + 5 Q&A)

Thu June 30 -- All times Mountain; All presentations delivered via Zoom

- 10:00am *Spin squeezing for clocks and interferometers* (Thompson, Rey, Kasevich, 35 min + 5 Q&A)
- 10:45am Student talks (each 12 min + 3 Q&A), all from JILA X317 except as noted

  10:45am Chu (JILA, Rey)

  11:03am Kiehl (JILA & CU Engineering, Regal & Knappe) 11:21am Lunstad (Harvard, Doyle)

  11:39am Na Narong (Stanford, Hollberg) 11:57am Poggi (UNM), presented from UNM

- 12:15pm *Lunch break* (30 min)
- 12:45pm *Grand Challenge 3 update and discussion* (Kasevich, Thompson, Kaufman, Ye, 30 min + 5 Q&A)
- 1:20pm *Microscopic control of entanglement* (Leibfried, Doyle, Martin, 35 min + 5 Q&A)
- 2:00pm *External Advisory Board*

  2:00pm Closed Session (30 min)

  2:30pm with Executive Committee (30 min) ▪ 3:00pm Annual Meeting Adjourns

Earlier Community Events

Earlier Community Events

- Aug 16-17, 2022: NSF Year 2 Site Visit (**Investigators, Collaborators, Students, Postdocs, Staff**)
- Aug 11-12, 2021: NSF Year 1 Site Visit (**Investigators, Collaborators, Students, Postdocs, Staff**)
- Jul 20-21, 2021: NSF Q-SEnSE Annual Meeting (**Investigators, Collaborators, Students, Postdocs, External Advisory Board**)

- Dec 18, 2020: Social Intelligence Workshop for Q-SEnSE Leadership (attendees **Ye, Regal, Thompson, Lehnert, ONeil** et al.)
- Nov 5, 2020: Q-SEnSE Executive Committee Meeting (9 XC Members)
- Oct 8, 2020: Q-SEnSE Executive Committee Meeting (9 XC Members) Sep 10,
- 2020: Q-SEnSE Executive Committee Meeting (9 XC Members)

Invited Talks

- Jul, 2022: "Entanglement-Enhanced Matter-Wave Interferometry in a High-Finesse Cavity," ICAP International Conference on Atomic Physics, invited talk, Toronto, Canada (**Thompson**)
- Jun, 2022: "Entanglement for Quantum Sensing in Matter-wave Interferometers, Clocks, and Molecules," Q-SENSE Annual Meeting, Boulder, CO (**Thompson**)
- Jun, 2022: "Towards Realizing a Quantum Repeater based on a Spin-Photon Quantum Interface", invited talk at DAMOP, Orlando, Florida (**Sun**)
- Jun, 2022: "Towards Realizing an All-Photonic Quantum Repeater Based on a Spin-Photon Quantum Interface", invited talk at Quantum 2.0, Boston (**Sun**)
- Jun, 2022: "Entanglement-Enhanced Matter-Wave Interferometry in a High-Finesse Cavity," DAMOP Invited talk, Orlando, FL (**Thompson**)
- May, 2022: "Approaching the Solar Planck Limit with Dual-Comb Passive Thermal Light Spectroscopy" Invited Talk, CLEO 2022 (**Diddams** et al.)
- Apr, 2022: "Deterministic Single-photon Optical Nonlinearity Enabled by a Quantum Dot Spin", invited talk at Photonics and Electromagnetics Research Symposium (PIERS) 2021, Hangzhou, China (Hybrid) (**Sun**)
- Mar, 2022: "Optical lattice clocks: From Timekeepers to Spies of the Quantum Realm", School of Physics Colloquium (virtual presentation), Georgia Institute of Technology, Atlanta, GA (**Rey**)
- Mar, 2022: "Spin squeezing with finite range spin-exchange interactions", invited talk. 85th Annual Conference of the DPG and DPG Spring Meeting (virtual presentation), Erlangen, Germany (**Rey**)
- Feb, 2022: "Optical lattice clocks: From Timekeepers to Spies of the Quantum Realm", CCQ/CQOM Colloquium (virtual presentation), Center for Complex Quantum Systems, Aarhus University, Aarhus, Denmark (**Rey**)

- Jan, 2022: "Experiments in Many-body Cavity QED: Entangled Matterwave Interferometers, Superradiant Lasers, and Dynamical Phase Transitions", Quantum Science Seminar Mainz, Virtual (**Thompson**)

- Dec, 2021, "How Does Laser Cooling of Molecules Work?", lab presentation to high school students by graduate students Justin Burau, Kameron Mehling, and Parul Aggarwal in **Ye** group.

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  - Nov, 2021, "Preparing for the Quantum Revolution: What Is the Role of Higher Education?" 2nd European Quantum Technologies Conference (virtual) (**Lewandowski**)

  - Nov, 2021: "Quantum nanophotonics: engineering atom-photon interactions on-a-chip", Rice University, Quantum Seminars (**Sun**)

  - Oct, 2021: "Quantum nanophotonics: engineering atom-photon interactions on-a-chip", Indiana University–Purdue University Indianapolis (IUPUI), Physics Department Seminar (**Sun**)

  - Sep, 2021: "Single-photon level nonlinear optics with nanophotonic cavity QED", invited talk at Annual Meeting of the APS Four Corners Section, Virtual Meeting (**Sun**)

  - Oct, 2021: "Preparing to enter the quantum workforce," Southwest Quantum Information and Technology Workshop, (virtual) (**Lewandowski**)

  - Sep, 2021: "Twists, Gaps, Dynamical Phases, and Supperadiant Emission on Ultra-Narrow Optical Transitions," COSCALI Collective Scattering of Light, Porqerolles, France (**Thompson**)

  - Sep, 2021: "Preparing to enter the quantum workforce," Co-design Center for Quantum Advantage: Quantum Career Fair, (virtual) (**Lewandowski**)

  - Aug, 2021: "Hiring Challenges in Quantum Information Science", Keynote address, Quantum Workforce Recruitment in Government Workshop, (virtual) Laboratory for Physical Sciences (**Lewandowski**)

  - Aug, 2021: "QED-C Workforce TAC Webinar: NSF Quantum Centers and their engagement with industry" (**Regal**)

  - Jul, 2021: "Cavity QED systems: metrology with collective states," Boulder School for Condensed Matter and Materials Physics: Ultracold Matter, Virtual (**Thompson**)

  - Jun, 2021: "Preparing for the Quantum Revolution: What Is the Role of Higher Education?" Software-Tailored Architectures for Quantum Codesign (STAQ) Virtual Summer School, Duke University (virtual) (**Lewandowski**)

  - Jun, 2021: "Preparing for the Quantum Revolution: What Is the Role of Higher Education?" QUEST: Quantum Undergraduate Education & Scientific Training Workshop, Cal State San Marcos (virtual) (**Lewandowski**)

- Apr, 2021: “Preparing for the Quantum Revolution: What Is the Role of Higher Education?” Physics Colloquium, University of Utah, Salt Lake City, Utah (virtual) (**Lewandowski**)

- Mar, 2021: “Cavity-enhanced non-destructive measurements for determination of the strontium clock transition linewidth with 30 microhertz resolution,” SPIE Photonics West Optical and Quantum Sensing and Metrology (**Thompson**)

- Mar, 2021: “Preparing for the Quantum Revolution: What Is the Role of Higher Education?” DOE Office of Science’s Quantum Information Science Education Working Group, (virtual) (**Lewandowski**)

- Mar, 2021: QED-C Quantum Industry Workforce Needs Survey: Preliminary Results”, 2021

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- Feb, 2021: “Preparing for the Quantum Revolution: What Is the Role of Higher Education?” NSF Workshop on Quantum Engineering Education, (virtual) (**Lewandowski**)

Jan, 2021: Aerospace Corporation Distinguished Speaker Series (**Ye**)

Dec, 2020: “Breaking Quantum and Thermal Limits with Collective Physics,” Physics Colloquium, ETH, Zurich, Switzerland (**Thompson**)

- Dec, 2020: USAF Virtual Quantum Collider 2.0, panel member (**Lewandowski**)Dec, 2020: NSF
- Project Scoping Workshop: "Does the QISE Community Need a Goal- Oriented Distributed User Facility?" (**Ye**)

- Dec, 2020: NQI Community Meeting: NSF, NIST, DOE (**Ye**, **Lewandowski**)

- Dec, 2020: Overview of Q-SEnSE, CUbit, and JILA for the Missile Defense Agency Advanced Technology Directorate (**Regal**)

- Nov, 2020: Overview of CUbit and Quantum for CO-Labs and U.S. Congressman Joe Neguse (**Ye**)

- Nov, 2020: OSA High Brightness Virtual Conference (**Ye**)

- Nov, 2020: 2020 Chicago Quantum Summit, hosted by the Chicago Quantum Exchange (**Ye**)

- Oct, 2020: Quantum 2020, hosted by IOP Publishing, Chinese Physical Society and the University of Science and Technology of China (**Ye**)

- Oct, 2020 onwards: National Quantum Initiative Advisory Committee, organized by the White House Office of Science and Technology Policy (OSTP) and the U.S. Department of Energy (**Ye**)

- Oct, 2020: ColdQuanta announces public availability of Albert, a remote acess platform for students anywhere to form, manipulate, and study Bose-Einstein Condensates (**Anderson**) Oct, 2020: IEEE Quantum Week, Quantum Workforce Track, Chair (**Lewandowski**)

Sep, 2020: NSF QLCI Grantees' Meeting (**Ye**)

Sep, 2020: DOE OSA Quantum 2.0 Conference (**Ye**)

Aug, 2020, Virtual Photonics for Quantum 2 Workshop, hosted by Rochester Institute of Technology (**Regal**)

Archived Entries

2019 Community Outreach & Engagement

November 2019

- Kavli Futures Symposium: Achieving a Quantum Smart Workforce (**Lewandowski**) IEEE
- Quantum Initiative Sessions at IEEE Rebooting Computing Week 2019 (**Lewandowski**)

University of Colorado Boulder

Attachment D (Publications, cumulative)

A full list, with a drop-down abstract for each publication, is on our web site at

https://www.colorado.edu/research/qsense/publications

(Senior Investigators of the Institute are in **boldface**)

M. F. J. Fox , B. M. Zwickl, and H. J. **Lewandowski**, "Preparing for the quantum revolution: What is the role of higher education?", Physical Review Physics Education Research 16, 020131 (2020), DOI: 10.1103/PhysRevPhysEducRes.16.02013

C. J. Kennedy, E. Oelker, J. M. Robinson, T. Bothwell, D. Kedar, W. R. Milner, G. E. Marti, A. Derevianko, and J. **Ye**, "Precision Metrology Meets Cosmology: Improved Constraints on on Ultralight Dark Matter from Atom-Cavity Frequency Comparisons", Phys. Rev. Lett. 125, 201302 (2020),

DOI 10.1103/PhysRevLett.125.201302

K. Matsuda, L. De Marco, J-R. Li, W.G. Tobias, G. Valtolina, G. Quéméner, J. **Ye**, "Resonant collisional shielding of reactive molecules using electric fields", Science, Vol. 370, Issue 6522, pp. 1324-1327 (2020), DOI: 10.1126/science.abe737

S. Kelly, A. M. **Rey**, and J. Marino, "Effect of active photons on dynamical frustration in cavity QED", Physical Review Letters 126, 133603

(2021), 10.1103/PhysRevLett.126.133603

R. J. Lewis-Swan, D. Barberena, J. R. K. Cline, D. Young, J.K. **Thompson**, and A.

M. **Rey**, "Cavity-QED quantum simulator of dynamical phases of a BCS superconductor", Phys. Rev. Lett. 126, 173601 (2021),
DOI 10.1103/PhysRevLett.126.173601

T. Bilitewski, L. De Marco, J. Li, K. Matsuda, W. Tobias, G. Valtolina, J. **Ye**, and A.

M. **Rey**, "Dynamical generation of spin squeezing in ultra-cold dipolar molecules", Phys. Rev. Lett. 126, 113401 (2021). DOI 10.1103/PhysRevLett.126.113401

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Attachment E, Workgroups within the Grand Challenges

Working groups within individual Grand Challenges or spanning several. Regular meetings of these working groups established several effective collaborative projects within the center.

- Spin squeezing collaboration between The University of Colorado (CU), MIT, and Stanford
- Tweezer collaboration between CU, The University of New Mexico (UNM), and Los Alamos National Laboratory (LANL)
- Integrated photonics and trapped ion collaboration between CU/NIST, MIT Lincoln Lab, Sandia National Lab, and University of Oregon
- A portal for atomic structure calculation that is relevant for fundamental physics search has been established, along with effective collaboration between U. Delaware, CU/NIST
- A cross-center collaboration on the connection between quantum information science, quantum sensing, and machine learning between CU, UNM, Harvard, U. Innsbruck
- Phase-stabilized fiber network collaboration between CU and NIST
- Magnetometer-based quantum sensing collaboration within CU
- Portable atomic clocks and integrated photonics

collaboration between CU, NIST, and external partners such as U. California Santa Barbara

- Sr quantum information infrastructure collaboration between Stanford and CU
- Cold molecule-based quantum sensing platform between Harvard and CU
- Quantum Clocks in Space for Precision Astrophysics, among University of Delaware, UCLA, and CU

Colorado School of Mines

Appendix F: Department of Energy National Alliance for Water Innovation (DOE-NAWI) Task 6.10

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. Berkely has synthesized six new PPNs for PFAS and selenium uptake which have been evaluated at Mines. PFAS uptake by PPNs was shown to be hundreds of times better than commercially available sorbents such as activated carbon and ion-exchange resin.
3. Methods were developed at Mines that allows for speciation and quantification of selenium at sub-ng/L concentrations in water samples. This is allowing for assessment of PPNs developed by Berkeley at Mines for the removal of selenium species.
4. This project is currently supporting one PhD student at Mines (Bahareh Tajdini) who recently completed her PhD qualification exam.

Attachment A Figures and Graphics

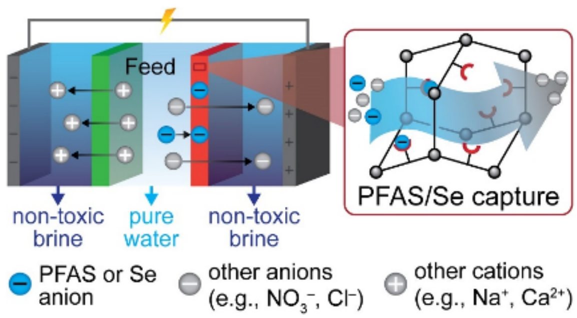

Figure 1. Overview of project including collaborators

Appendix G: Department of Energy National Alliance for Water Innovation (DOE-NAWI) Task 5.8

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

Mines Funding From NAWI: $811,235

Total CHECRA Funding: $162,247

Summary:

Today's operations in water treatment and production 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 will be the core of the project; we are using a very unique mobile lab the demonstrate 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, Colorado Springs Utilities, and the National Science Foundation. The system is comprised of six processes, including ozonation, biologically active filtration (BAF), ultrafiltration (UF), carbon adsorption (GAC), ultraviolet irradiation with advanced oxidation (UV-AOP), and chlorination. Influent into the DPR systems, generated by water reclamation facilities, can have highly variable quality due to daily and seasonal original source water quality changes, 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, inCtrl Solutions Inc., IntelliFlux Controls Inc., and Rockwell Automation. Most importantly, they will provide advice, next to other in-kind contributions:

1. Colorado Springs Utilities and Aurora Water: Access to data of the upstream plant, maintenance of a **direct potable reuse (DPR)** system.
2. inCtrl Solutions Inc.: Access to SIMBA# modelling and control software
3. IntelliFlux Controls Inc.: Access to software and industrial insights
4. 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 will be tested on at least three full-scale plant managed by Colorado Springs Utilities (past, 2021-2022), Aurora Water (current, 2022-2023), and Littleton/Englewood South Platte Renew (future, 2003-2024).

Outcomes of Project over Past Year:

5. The DPR mobile lab was operational in Colorado Springs from 2021 to 2022 (12 months), at which time we have both conducted research but also conducted substantial public outrich to demonstrate that potable reuse is possible and feasible:
   a. 49 tours
   b. 945 people attending (85% tasted the purified water)
   c. 3 community events in which we served 760 soda tastings (soda made of the reclaimed water…)
   d. 4 public presentations with 101 public attendees
   e. 11 school and college tours
   f. 2 media events
   g. 10+ media stories and 2 videos.
6. Since June 2022 we are operating the mobile lab at the Sand Creek water reclamation facility in Aurora. The demonstration in Aurora brough more companies to invest in our research, including a recent generous donation of $100,000 from Hach (water sensors)
7. 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).
8. The project won a prestigious award: 2022 WateReuse Awards for Excellence in Outreach

Attachment A 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]()

Attachment B Figures and Graphics

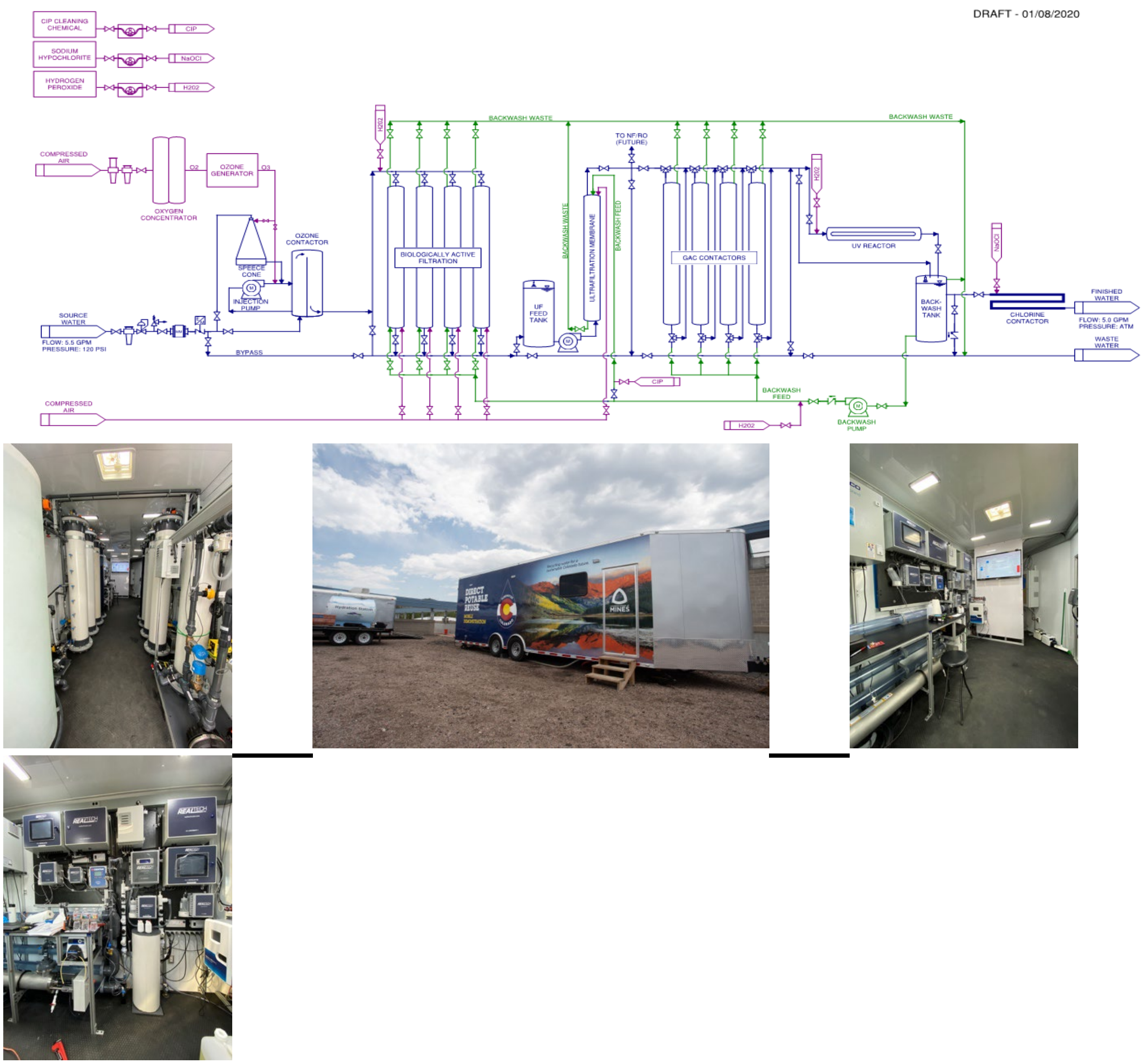

Figure 1: Scheme of the DPR pilot, including six unit processes: biologically active filtration (BAF), ozonation, ultra-filtration (UF), granulated activated carbon (GAC), UV treatment, and chlorination.

Colorado State University

Appendix H: Colorado State University Extension Industrial Assessment Center

Appendix I: 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:

The CSU ROOTS made substantial technological innovation in high throughput sampling of roots and soil and soil carbon modeling and demonstrated the values of these innovations to established and emerging industry partners. For the PLUSUP we plan to move forward on commercial use in 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. 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 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 as represented by the current COMET-FARM system for farm-scale soil carbon and greenhouse gas quantification. SoilMetrics will then market the use of this model for supporting companies develop

environmentally sustainable supply chains and product branding and as a component of carbon registry-compliant quantification systems to market carbon removal credits.

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:
We will utilize a diverse set of maize lines to examine for root structure and composition under full and limited irrigation in Colorado and Arizona. They will be phenotyped with our existing approaches as well as newly developed root (root pulling force) and soil HTP approaches. The understanding derived from these experiments and the data on root and soil response variables will be used to develop and evaluate a new generation process-based model, to be used to enhance translation and improve throughput of breeding as well as a tool to quantify the impacts of root parameters across ideotypes on soil C sequestration and GHG emissions in different environments. For category 2 we will develop novel sensors, incorporating them into our already functioning field HTP systems. The most promising methods and sensors will be used to identify genomic regions that influence root and soil traits and their sensitivity to drought by screening large mapping populations in the field. Data from this larger field effort will be used to validate the new model. The principal persons involved at Colorado State University are PI John McKay, as well as Co-PIs Francesca Cotrufo, and Keith Paustian.

Funding from CHECRA and allocation:
The CHECRA funds have been used to support personnel conducting the research including PI John McKay, Research Scientist Jack Mullen, and lab manager Stephanie Goldin. The CHECRA funds have also enabled purchase of computational time and other expenses that are essential to achieve the project milestones but are difficult for universities to charge to federal grants.

Results Achieved

Task 9: Genes controlling root traits

In this past field season, we phenotyped root traits in the B73 x CML69 maize NAM RIL population to validate the biological significance of root QTL identified in our previous GWAS study (Woods et al. 2022), using the mechanical root pulling HTP platform. With the mechanical puller, in addition to our usual trait root pulling force (RPF), we also analyzed a second trait, root pulling distance (RPD). Roots from the RILs were pulled at two time points during the field season, first at mid-flowering in early September and then again post-flowering in early October. We found substantial variation in RPF in this population at both times as well as a significant though moderate correlation between times.

QTL mapping on the root traits identified 6 QTL. We have further identified a deletion of one of the two genes that are within 10 kpb of the GWAS hit in the parental line CML69. We have also found that the RPF QTL on chromosome 3 co-localized with one of our previous GWAS hits. This hit is within the transcription factor Zinc finger CCCH domain-containing protein 5. We have confirmed the sequence differences between the parental lines at this site. The direction of the root effect is similar in both the mapping population and GWAS results and interesting in that the less common allele found in the smaller-rooted CML69 parent is associated with larger roots.

We have also used mutants to better characterize the effect size for our candidate gene of interest PHO1;2a (Woods et al 2022). In the 2021 field season we were able to grow an existing mutant line for this gene, *ZmPho1;2a-m1.1* (Salazar-Vidal et al 2016) and phenotype it for root traits. We also have created a homozygous line for an additional mutant, UFmu-10407. This past field season we grew and phenotyped this new mutant line. For both mutants, we observed an approximately 25% decrease in root traits relative to WT.

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

Trials for genetic variation in NUE were successfully completed in Y1 and will be repeated in Y2 at the same Corteva locations. A brief description of the experiment was to evaluate 20 modern Pioneer-brand hybrids across 3 nitrogen levels at two Corteva research locations in the mid-west corn belt. Fourteen of the hybrids overlapped with the RPF and/or the biomass studies and included PH11 and PH15 to PH27. The hybrids were evaluated under RCB design with applied nitrogen treatments of 0, 50, 200 lbs/ac UAN and 4 replicate blocks per location. Collected metadata applicable for Y3 MEMS modeling included soil sampling prior to planting and fertilizer applications, management and previous crop information and local weather. Preliminary analysis indicates that both hybrid and the applied nitrogen rate and the interaction were significant both within and across locations. Follow-up analysis to examine hybrid specific nitrogen responses and changes to NUE between the 200N and 50N nitrogen treatments is proceeding.

Task 11: Soil carbon and nitrogen modeling

In April and May of 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 for a total of 500 samples. These baseline samples were 8mm sieved and air-dried for storage. A subsample of these baseline soils will be 2mm sieved, finely ground, and analyzed for total C and N and 13C. These samples are currently being barcoded and included into our lab management software, eLabJournal. 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 depth 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 2022 our field was expanded, and we collected an additional set of baseline soils in the expanded area in May of 2022. These additional baseline soils have been 8mm sieved and air-dried and are currently being barcoded and incorporated into our lab management software. We have finished quantifying the root biomass in the baseline samples.

Task 12: Technology to Market

We have updated our T2M plan and have submitted it to ARPA-E. Additionally, the Soil C Solutions Center has been engaging with key stakeholders in soil carbon sequestration, from the approach of customer discovery.

Appendix J: MRI - Acquisition of an ultrahigh resolution mass spectrometry system to enable metaproteomics experiments to support microbiome research

Award Date: 8/15/21

Project Period: 10/01/21 to 09/30/24

Award Amount: $1,167,241

Status of Instrumentation: This award provided funds to acquire a Thermo Scientific Orbitrap Eclipse Tribrid Mass Spectrometer (Orbitrap Eclipse) system with a nLC and a FAIMS-Pro ion mobility interface. Language from last status update: The instrument was received in March 2022 and installed in June of 2022, immediately followed by onsite training. The instrument is now fully operational, and it being heavily utilized by both the CSU and regional non-CSU research communities. Additionally, a post-doctoral scientist was hired in November 2022 to focus on the development and optimization of metaproteomics informatics and applications. Finally, to promote the capabilities of the new instrument we have launched a new seminar series. The seminars are virtual to enable remote presenters and to maximize participation. To date we have hosted 4 speakers, including an application specialist on proteomics from Thermo Fisher (Kevin Schauer), a CSU Microbiologist with extensive proteomics experience (Karen Dobos), a metaproteomics informatics specialist (Jagtak Pratik) and an expert on soil metaproteomics (Mary Lipton). Additionally, we hosted an open forum during installation of the Orbitrap Eclipse, where proteomics experts from ARC-BIO and Thermo Fisher were available to answer questions from the local research community. Seminar registration has ranged from 24-64 people per seminar.

Appendix K: A Novel Electro-dialytic Crystallizer (EDC) for Energy Efficient Zero-liquid Discharge

PI: Tiezheng Tong, CSU

Description of the project: In this project, we aim to investigate a new brine management process called electro-dialytic crystallization (EDC). The EDC process integrates electrodialysis, which is a desalination technology driven by electricity, and crystallization into a single system to enable brine crystallization without evaporation or large temperature swing. The core innovation of EDC is the use of the electrodialysis phenomenon to maintain a saturated brine stream for continuous salt precipitation. We plan to perform experiments in order to prove the concept and acquire fundamental understanding of the system behavior. In addition, we will perform system-scale modeling to guide system design and optimization of EDC, which includes understanding the tradeoffs between system performance, longevity, scale, treatment cost (CAPEX and OPEX) through techno-economic analysis (TEA). Lastly, we will perform lifecycle assessment (LCA) and market analysis to evaluate the potential of the proposed technology for future practical adoption and the consequent environmental impacts. This is a collaboration with Vanderbilt University, and CSU is mainly responsible for understanding membrane scaling and fouling during brine treatment using EDC, performing system-scale modeling to guide system design and optimization, as well as TEA and LCA analyses.

Project progress: During this reporting period, the two graduate students recruited by this project have performed the experiments and modeling work as described in the proposal. Especially, we performed experiments that successfully proved the concept of EDC by using a single salt Na_2SO_4 (**Figure 1**). This result demonstrates that we are able to achieve salt crystallization and precipitation that is solely driven by an electric field without evaporation. Also, we have tested the performance of EDC for a diverse set of salts and elucidated the criteria of achieving salt crystallization using EDC (**Figure 2**). Further, we have tested the effects of mineral scaling on the performance of EDC, demonstrating that EDC is not affected significantly by the presence of mineral scalants in the feedwater (**Figure 3**). Additionally, we performed preliminary TEA and LCA on the EDC technology that we developed. Our results show that the energy consumption and life-cycle impacts of EDC are lower than those of mechanical vapor compressor, the state-of-the-art brine crystallization technology (**Figures 4 and 5**). Based on the results we obtained during this period, we have written a manuscript in collaboration with our research partners from Vanderbilt University, which has been submitted to the journal *Nature Water* (Zhang, X., Yao, Y., Horseman, T., Wang, R., Yin, Y., Zhang, S., Tong, T.*, and Lin, S.* (2023) Electrodialytic crystallization. *Nature Water*, under review).

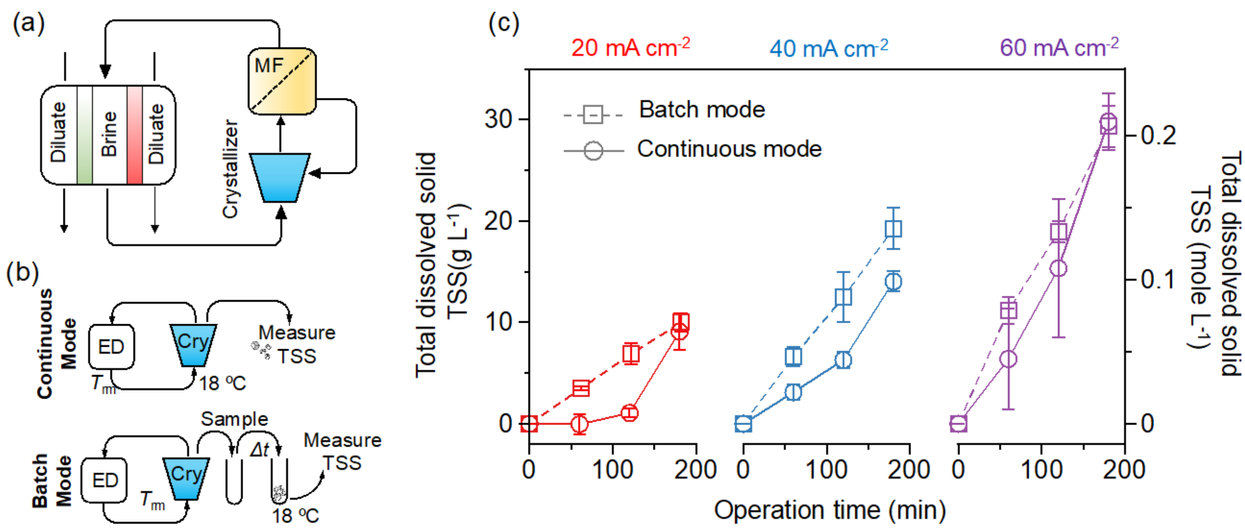

Figure 1. Proof of concept for EDC with experiments of Na_2SO_4 crystallization. **(a)** Schematic of the experimental setup for EDC experiments, integrating an ED cell, a crystallizer, and a microfiltration (MF) unit. **(b)** Comparison between continuous mode, where crystallization occurs within the EDC system, and batch mode, where crystallization occurs external to the EDC system. **(c)** TSS in both g L^{-1} (left) and mole L^{-1} (right) as a function of operation time with different operating modes and current densities (20, 40, and 60 mA cm^{-2}). In the continuous mode, the brine temperature in the crystallizer was maintained at 18°C and crystals were *in-situ* produced and measured; while in the batch mode, the EDC system was operated at room temperature and crystals were produced in an 18°C water bath and then measured. The ED cell comprises 2 pairs of the standard IEMs. The initial diluate was 2 L of 6 wt% (63.5 g L^{-1}) Na_2SO_4, while the initial brine was 1 L of saturated Na_2SO_4 (174 g L^{-1}, corresponding to Na_2SO_4 solubility at 20°C).

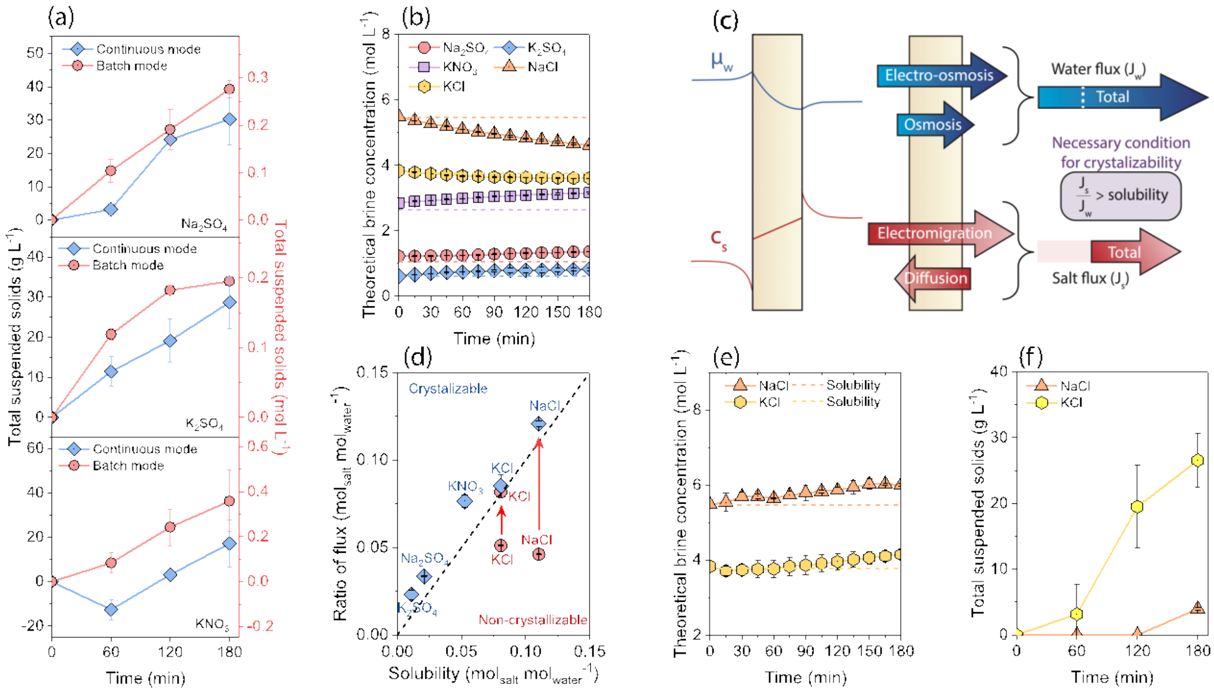

Figure 2. Crystallization of different salts in EDC. **(a)** Total suspended solids (TSS) production rates of Na_2SO_4, K_2SO_4 and KNO_3 with continuous and batch modes. The ED cell configured with 5 pairs of the standard ion exchange membranes (IEMs). The applied current density was 40 mA cm^{-2}. The initial diluate was 4 L of 0.6 M of each salt. The initial brine was 1 L of saturated solution of the respective salt (at 20°C). **(b)** Theoretical brine concentration, i.e., TDS plus TSS (if any), for five different salts. **(c)** Schematic illustration of salt crystallization mechanism in the EDC system. **(d)** Molar ratio of salt to water as calculated from the salt solubility at 18°C (x axis) as compared to the ratio of salt flux to water flux in continuous mode (y axis). Blue rhombuses represent successful crystallization whereas red circles represent unsuccessful crystallization. **(e)** Theoretical brine concentration and **(f)** TSS for NaCl and KCl as a function of operation time with low-water-uptake IEMs and different operating conditions.

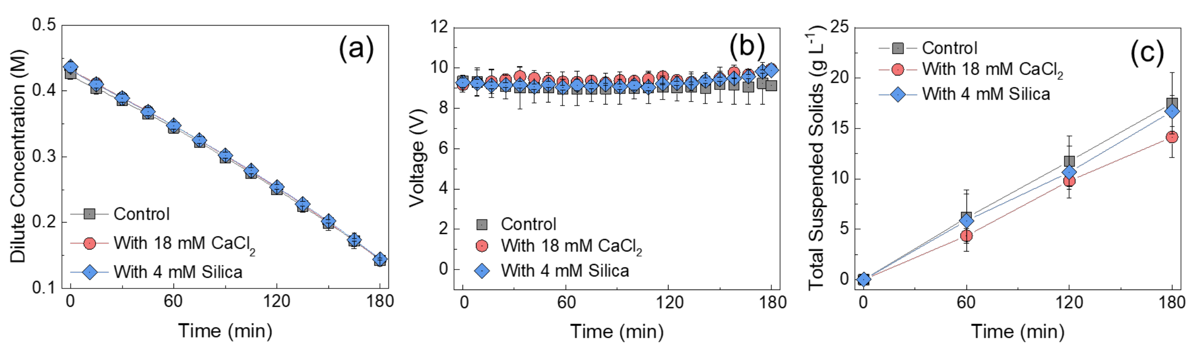

Figure 3. **(a)** The conductivity of the diluate as a function of operation time. **(b)** The voltage as a function of operation time. **(c)** The TSS as a function of operation time. The initial diluate contains 6 wt% (63.5 g L^{-1}) without (control) and with 18 mM $CaCl_2$ or 4 mM silica. The initial brine contained saturated Na_2SO_4 (174 g L^{-1}) corresponding to Na_2SO_4 solubility at 20 °C regardless of whether $CaCl_2$ or silica was added.

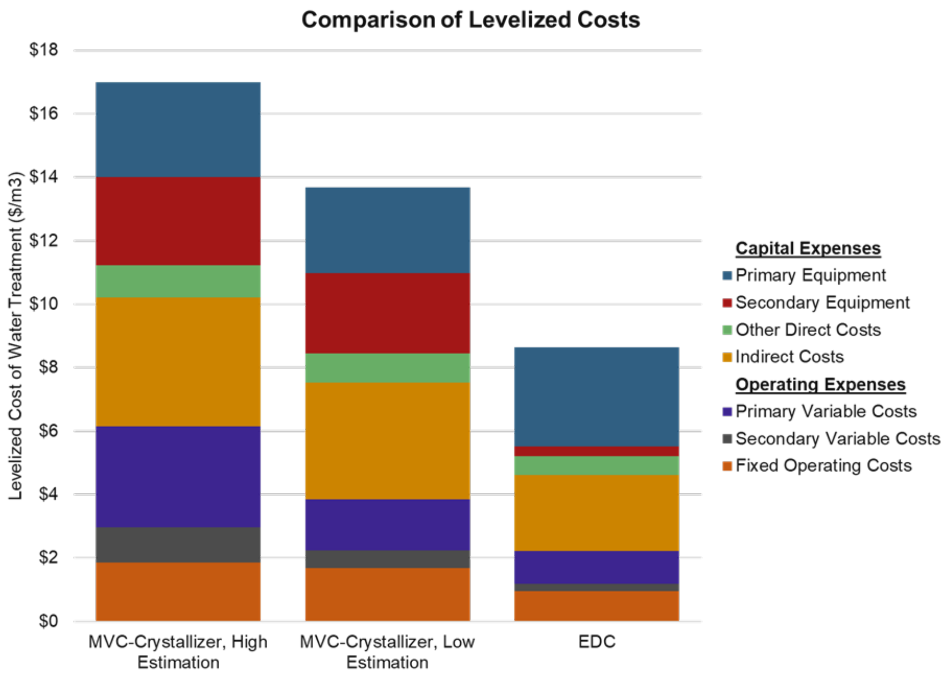

Figure 4. Techno-economic analysis that compares the levelized cost of EDC with that of mechanical vapor compressor.

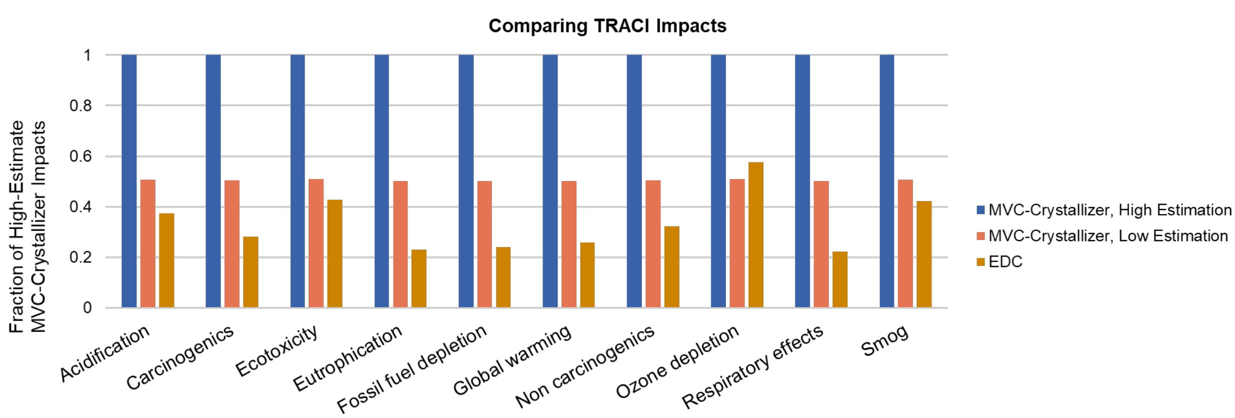

Figure 5. Life-cycle assessment that compares the reduction and assessment of chemical and other environmental impacts (TRACI) of EDC with those of mechanical vapor compressor.

Outcomes/benefits of this project: This project is a collaboration with Vanderbilt University supported by Department of Energy Innovation Hub (National Alliance for Water Innovation). This project provides an opportunity to promote research on desalination and water treatment at CSU and has been supporting two PhD students. Key outcomes/benefits of this project are summarized below.

- A novel EDC technology with the potential of revolutionizing hypersaline brine treatment has been developed, with the concept of the technology proved.
- We have obtained the fundamental understanding of ion/water transport during brine treatment using EDC, which will guide us for further improvement of EDC.
- We have analyzed the economic cost and life-cycle impacts of EDC and other state-of-the-art brine crystallization technologies, providing a methodological framework to assess the benefits and commercialization potential of brine management technologies.
- The TEA and LCA results show that EDC is able to reduce the cost and energy consumption of brine treatment, thereby contributing to achieving a circular water economy that is resilient to the changing climate.

One manuscript has been written and submitted to the journal *Nature Water.*