Accelerator Stewardship Program
Collaborative Accelerator Research Teams (CARTS) -- Letters of Intent

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Digital Twin Guided Controls and Optimization Addressing the Frontiers of Beam Creation and Manipulation

Letter of Intent for the DOE DE-FOA-0003620
Collaborative Accelerator R&D Team (CART) Program
Topic 2.1: Advanced Beam Dynamics and Accelerator Control Systems

PI: Gerard Andonian
Institution: UCLA Department of Physics and Astronomy
Phone: (310) 206-5584
Email: gerard@physics.ucla.edu
Co-Investigators / Senior Personnel: James Rosenzweig (UCLA), Brian Naranjo (UCLA), Monika Yadav (ODU), Gwanghui Ha (NIU), John Power (ANL), Sami Tantawi (ASU)

Specific Research Interests and 5-Year Vision

Digital twins have been an essential part of the landscape of accelerator design, optimization and operation for at least two and a half decades, with the most prominent initial example being the use of start-to-end simulations for frontier facilities such as the LCLS X-ray free-electron laser. This concept has matured through introduction of machine learning techniques closely tied to benchmarking through experimental measurements. Indeed, automated tuning of X-ray FELs using ML-enabled digital twins is now a well-diffused technique in the field, permitting tuning and optimization of extremely complex systems with vast available parameter spaces.
As we advance in complexity, the need for digital twin-based tools is rapidly increasing. In the nucleus of this emerging collaboration, we are dealing with extremely intricate experimental beam manipulation environments exemplified by two current scenarios:

- The use of high charge beams that simultaneously undergo emittance compensation and pulse compression through velocity bunching. These beams, now being utilized at the UCLA MITHRA laboratory for an array of next-generation wakefield and radiation generation experiments (*e.g.* inverse Compton scattering, FEL) emphasizing orbital angular momentum (OAM) production, possess plasma-like dynamics due to space-charge that must be understood at the microscopic level for experiments to succeed, as beam characteristics are strongly imprinted onto wakefields and radiation production

- At a yet higher level of complexity, a campaign is being mounted by a UCLA/NIU/ANL/ASU collaboration to test the proposed nano-bunching concept which utilizes the emittance exchange (EEX) process. This scheme proposes to convert a transverse modulation at the sub-µm level to bunching at the few nanometer scale. This approach underpins the ASU CXFEL project, but as yet is untested. The current experiment at the AWA is very challenging from many points of view: µm transverse measurements, notably nonlinear beamlines and strong collective effects such as coherent synchrotron radiation (CSR) which limit the beam phase to the pC level, yielding a strong constraint on the coherent radiation production available. The nonlinearity and extreme sensitivity of the beam transfer function in *full 6D phase space* make experimental optimization an unprecedented challenge, not addressable by human expertise. Any error in these small phase space volumes can lead to failure of experiment

As one may appreciate, to address these state-of-the-art scenarios, one need to introduce both experimental and computational methods at new levels of sophistication. The experimental challenges of EEX nano-bunching are now addressed in the context of a BES-funded project. Similar support is available for the velocity bunching studies at MITHRA through other funding sources. While each project contains advanced computational elements, in order to robustly proceed, we must develop deployable digital twins for the experiments. This requires use of the appropriate codes, with GPT (now in wide use inside the field) providing the initial, highly capable environment for nonlinear optical elements, space-charge and CSR.

The code suites involved will be utilized to train surrogate models that predict output beam properties and phase-space features. Once the surrogate model exists, we can use optimization tools to tune the EEX and short pulse, intense beam experiments efficiently, iterating use to converge performance to a ML-enabled peak, with new strategies emerging. We note that this project will also be leveraged off concurrent efforts of a UCLA/RadiaSoft project at the AWA to place a hardware-enabled AI scheme for optimizing longitudinal phase space using a unique multi-leaf collimator.

This CART, if successful, would utilize the power of the digital twin in much more challenging environments than addressed before. This will enable essential new physics understanding by opening up a much more sophisticated understanding of beam dynamics in nonlinear collective effect-dominated environments in 6D with few nanometer resolution. This in turn will enable the development of new paths to advanced light sources and high field acceleration techniques. These would not exist without such a dedicated effort over the next years.

For potential collaborators, this project offers a strong, energetic nucleus of existing collaborators with expertise in advanced experimentation with high brightness beams and attendant computational methods. This nucleus is already strongly engaged in the experiments at both UCLA and ANL. This laboratory infrastructure would be made available to CART team members.

We are actively seeking new collaborators in areas related to implementation of the digital twins in the accelerator context, and their integration into effective control and optimization methods. Agentic AI can naturally be incorporated as part of the workflow, including surrogate-model-based optimization, diagnostic interpretation, and feedback control. Collaborators are also sought with strengths in beam dynamics, collective effects and coherent radiation production.

It should be noted that the research programs at UCLA, ASU and the AWA (notably through NIU) have very strong workforce development components, particularly in the experimental programs described. Graduate student research is emphasized in all the programs, and a long, successful track-record the production of the next generation of accelerator and beam scientists. It is expected that new student engagement opportunities will be offered using the Tigner Fellowship and the SCGSR programs.

This CART will be managed in a mode developed over time in UCLA-centered collaborations, with weekly Zoom meetings to coordinate research priorities and execution, and diffusion of results at conferences and through publication. In this way, resource allocation and real-time management of the project and progress evaluation may occur.

Computational and Theoretical Foundations for Predictive Accelerator Science

2.1 Advanced Beam Dynamics and Accelerator Control Systems
Béla Erdélyi, Professor, Northern Illinois University
(815) 753-6484, berdelyi@niu.edu

Central idea: Treat charged particle beams as complex, controllable states of matter, and build the theory, computation, and AI/ML infrastructure needed to understand behavior, predict, shape, transport, accelerate, control, and use custom-tailored beams.

Research Vision

I seek to help form a Collaborative Accelerator Research Team centered on predictive accelerator science. My starting point is that charged particle beams should be understood not simply as particles passing through hardware, but as complex, controllable states of matter. Their production, transport, acceleration, shaping, stability, control, and use can be studied at a fundamental level and then engineered for specific scientific, industrial, medical, security, and national-laboratory applications.

The long-range objective is a research program that connects first-principles beam physics with modern computation and data-driven methods. The practical goal is to design and operate accelerators with greater confidence, fewer empirical corrections, and a clearer understanding of where models are reliable, where they fail, and how to improve them. This requires a team that can combine classical accelerator physics with applied mathematics, nonlinear dynamics, symplectic geometry, topological methods, high-performance computing, and scientific machine learning.

Expertise and Capabilities

I would bring expertise in nonlinear beam dynamics, symplectic methods, high-order maps, dynamic aperture analysis, integrable and near-integrable systems, accelerator modeling, deep expertise in relevant areas of pure and applied mathematics, and large-scale scientific computing. These areas form the technical core of my research program and would be central to my CART contribution rather than peripheral interests.

At Northern Illinois University, I can connect accelerator research with broader institutional capabilities through the Northern Illinois Accelerator and Detector Development Center and the Center for Research Computing and Data. As director of both centers, I can contribute a platform that links beam physics, detector and accelerator expertise, research computing, data infrastructure, AI/ML workflows, and student training. This combination is useful for a CART because the hardest problems now require not only ideas, but reproducible workflows, robust software, scalable computation, shared benchmarks, and people trained across disciplinary boundaries.

I anticipate a substantial effort commitment, potentially on the order of 40% academic-year effort and 100% summer effort, depending on the final scope and team structure. This reflects the fact that the proposed themes are my main research direction: fundamental beam physics, predictive modeling, and the computational methods needed to make accelerator science more quantitative and transferable.

SciML and Emerging Computational Directions

I believe the convergence of modern AI/ML, high-performance scientific computing, differentiable programming, and, where appropriate, emerging quantum-computing approaches is creating a qualitatively better way of doing accelerator science. The useful shorthand is SciML, but the important point is not generic AI on accelerator data. The goal is physics-informed, structure-preserving learning: models and workflows that respect Hamiltonian structure, symmetries, constraints, conservation laws, uncertainty, machine layout, and accelerator design logic.

Promising directions include graph neural networks and graph transformers for accelerator lattices, differentiable beamline models, high-order map-based surrogate models, operator learning, active learning for simulation campaigns, autonomous optimization, and hybrid workflows that connect expert physics codes with trainable components. Accelerator physicists have used high-order maps, automatic differentiation, differential algebra, sensitivity analysis, and surrogate-like representations for decades, long before the current terminology became fashionable. The opportunity now is to join that mature accelerator-specific infrastructure with modern foundation-model ideas, GPU/HPC workflows, uncertainty-aware learning, and AI-assisted design and control.

Illustrative Research Thrusts

One thrust would focus on single-particle nonlinear dynamics and dynamic aperture estimation based on methods that span several time scales. On the one-turn scale, the work would use high-order one-turn maps and their generating functions. On the few-turn and intermediate-time scale, it would explore orbit classifiers based on topology, geometry, and homological signatures of phase-space transport. On long time scales, it would advance geometric integration and stability estimation, including opportunities created by newer results on self-force, radiation reaction, and nonsingular point-particle electrodynamics where they are relevant to accelerator modeling.

A second thrust would aim to bring multi-particle beam dynamics closer to the maturity level now available for single-particle dynamics. The ambition is to make collisional and collective simulation methods practical for difficult beam-dynamics problems such as intrabeam scattering, electron cooling, beam-gas scattering, halo formation, 3D coherent synchrotron radiation, and other realistic radiation effects. The desired endpoint is a framework in which microscopic multi-particle effects are not appended as semi-empirical patches, but treated as first-class physics in predictive accelerator design and control.

Workforce Development and Collaboration Fit

Workforce development would be an integral part of my contribution. NIU has an active graduate curriculum in accelerator and beam physics, and we have participated in and hosted USPAS and CAST activities. Our graduates have moved into faculty positions, national laboratory staff roles, and industry positions ranging from intellectual property technical advising to data science and AI management. The future accelerator workforce must be fluent in beam physics, modern computation, AI/ML, software discipline, experimental awareness, and cross-sector translation.

Within a CART, I would support graduate courses, short modules, research rotations, student and postdoc exchanges, computational tutorials, shared code and benchmark projects, and training activities that connect nonlinear dynamics and beam physics with AI/ML and scientific computing. I am especially interested in collaborators with complementary expertise in foundation models, graph learning, scalable AI/ML on HPC platforms, differentiable programming, uncertainty quantification, controls, collective-effects simulation, radiation and self-force theory, experimental diagnostics, and benchmark datasets from operating machines.

The best CART would not be a loose federation of unrelated projects. It should be a coordinated team where mathematical structure, simulation, AI/ML, experiments, and workforce development reinforce one another. If successful, it would move accelerator science from case-by-case modeling and expert tuning toward a more predictive and transferable discipline: tools and people capable of controlling charged particle beams as complex engineered states of matter.

Letter of Intent

Unlocking the Powers of HPC and Differentiability in Nonlinear and Polarized Beam Dynamics Simulations for AI/ML Optimization of Future Accelerators

Topic number and name: Track 2.1—Advanced Beam Dynamics and Accelerator Control Systems
PI: Georg Hoffstaetter de Torquat, Cornell University, +16072555197, georg.hoffstaetter@cornell.edu
Lead institution: Cornell University
Proposed CART type: Tier 2, five years, $1.5M / year.

Co-PIs: Klaus Heinemann (UNM), Daniel Ratner (ODU), Matthew Signorelli (BNL), Auralee Edelen (SLAC), Axel Huebl (LBNL), Oleksii Beznosov (LANL).

Key and Senior personnel: James Ellison (UNM), Leon van Riesen-Haupt (ODU), Yue Hao, Kevin Brown, Lucy Lin, Eiad Hamwi (BNL); Ryan Roussel (SLAC), Thorsten Hellert (LBNL).

There currently is an urgent, timely, and revolutionary opportunity in accelerator science: AI/ML methods can dramatically increase the efficiency of design, commissioning, and operations of particle accelerators. However, their effectiveness depends on simulation codes that provide derivatives; run efficiently on CPU/GPU platforms; propagate beam distributions, uncertainties, and parameter sensitivities; and form digital twins by connecting naturally to experimental data streams. The proposed CART will address that gap by bringing together leading US expertise in nonlinear orbit and spin-orbit dynamics, AI/ML for accelerator design and operations, and high-performance computing to realize the full potential of AI/ML in accelerator science.

The effort will be organized around SciBmad, an emerging framework that extends Bmad's scientific strengths into a computational ecosystem for parallel execution, automatic differentiation, digital twins, and AI/ML workflows. Supported by previous Stewardship funding, SciBmad provides CPU/GPU-parallelized, fully differentiable 6D symplectic tracking with spin and radiation; nonlinear parametric normal form analysis (to, e.g., compute gradients of nonlinear orbit and spin-orbit resonance driving terms w.r.t. parameters); and batched parameter evaluation enabling parallel tracking across hundreds of thousands of accelerator designs on a single CPU/GPU simultaneously. Such capabilities uniquely position SciBmad as the foundation for next-generation AI/ML-driven accelerator design, commissioning, and operations.

The five-year research vision has four tightly connected thrusts.

1. Differentiable nonlinear beam dynamics and high-dimensional optimization. Cornell, ODU, BNL, and SLAC will develop differentiable methods for nonlinear tracking, dynamic-aperture studies, map-based modeling, lattice optimization, model calibration, and uncertainty quantification. SciBmad will be interfaced to modern optimizers and AI/ML frameworks so that gradients, sensitivities, and uncertainty information can be used directly in accelerator design and operations.

2. Integrated nonlinear spin-orbit dynamics and polarization kinetics. UNM, Cornell, LANL, and LBNL will develop kinetic spin-orbit methods that propagate particles, distributions, stochastic processes, and parameter sensitivities within the same SciBmad-centered framework used for nonlinear orbital dynamics. Traditionally, polarized lepton beams are studied by the Derbenev-Kondratenko formulas, which can fail at high energies such as those in the FCC-ee. We will solve this problem by including all key physical effects (radiative depolarization, Sokolov–Ternov, and kinetic polarization) into two equivalent kinetic approaches. A 9-dimensional Fokker-Planck-Equation approach propagates full phase-space and spin distributions and will explore both low-rank tensor methods and random Fourier neural network machine learning methods. An equivalent Stochastic Differential Equations approach will propagate particles by Monte Carlo tracking. Our approaches and differentiable SciBmad implementations will naturally include usually-neglected effects on polarized beam distributions, such as beam-beam physics and intrabeam scattering.

3. Digital twins, model calibration, tomography, and AI/ML integration. SLAC, Cornell, BNL, LBNL, and ODU will connect SciBmad to digital-twin and online-model workflows, including LUME-based interfaces, differentiable phase-space tomography, uncertainty quantification, and model calibration from machine data. These tools will enable AI/ML systems not merely to optimize black-box accelerator settings, but to learn from physics-informed, uncertainty-aware, differentiable accelerator models. The spin-orbit kinetic models developed with UNM and LANL will be incorporated into this same digital-twin framework so that polarization observables, depolarization mechanisms, and nonlinear orbital dynamics can be optimized together. Model calibration, accelerator tuning, uncertainty quantification, and AI/ML optimization will then be able to utilize polarization measurements. Agentic workflows, as enabled by the Osprey Framework, will connect Large Language Models (LLMs) to our digital twin implementations.

4. Parallel and heterogeneous computing for complex accelerator processes. LANL and LBNL will contribute expertise in modern high-performance accelerator modeling, including connections to WarpX for strong-strong beam-beam physics and GPU-enabled simulation techniques. The CART will develop SciBmad capabilities for differentiable parallel computing on hybrid CPU/GPU shared memory architectures, supporting computationally intensive processes such as beam-beam interactions, collective effects, stochastic spin-orbit dynamics, uncertainty propagation, and large ensembles of lattice and machine configurations.

The team offers complementary and mutually reinforcing capabilities, with all partners being integrally involved in the overall project. The proposed work will focus on beam dynamics with broad impact across major research and industrial accelerators. For the Electron-Ion Collider, Fermilab's neutrino program, and the FCC-ee the CART will provide reliable modeling and optimization, precise nonlinear dynamics, injector performance, beam-beam effects, and polarization preservation. For industrial accelerators, including xLight's accelerator-driven chip-production the CART aims for complete agentic control based on a digital twin. This CART will provide generic accelerator-science foundations that are not tied to a single facility and will be available to many stakeholders.

Workforce development will be central. Students and postdocs will be trained at the intersection of accelerator physics, spin dynamics, scientific computing, differentiable programming, HPC, and AI/ML. The CART will create cross-institution mentoring, shared software projects, short courses, tutorials, user-friendly examples, and open documentation. The goal is to educate accelerator scientists who can move fluently between theory, simulation, machine data, and operational optimization. The team has a long history of educating leaders in this field.

Progress will be evaluated through quantitative milestones from the following areas: differentiable SciBmad modules, validated nonlinear and polarized benchmarks, CPU/GPU scaling demonstrations, user-friendly optimizer interfaces, digital-twin demonstrations, public tutorials, peer-reviewed publications, and adoption by facility and industrial accelerator users.

This CART will seize the current opportunities of AI/ML for accelerators and will strengthen U.S. leadership in accelerator science, support national-priority projects, incl. the EIC, LCLS, PIP-II, and FCC-ee; and it enables automation of industrial accelerator applications in areas such as advanced chip production. This effort directly addresses the CART goal of long-term, generic, cross-cutting accelerator R&D and the NOFO's emphasis on multi-institutional teams, workforce development, and AI/ML-enabled accelerator science.

Intelligent Control and Mitigation of Particle Beams with High-Energy-Density

Topic 2.1: Advanced Beam Dynamics and Accelerator Control Systems

PI: Dr. Dongwook Lee, Professor of Applied Math, UC Santa Cruz, (831) 502-7708, `dlee79@ucsc.edu`
Co-PIs: Dr. Jeffery Dooling (Argonne National Laboratory); Dr. Nathan Cook (RadiaSoft); Dr. Aparna Chandramowlishwaran (UC Irvine)
Senior Personnel: Dr. Austin J. Dick (Postdoc, ANL); Dr. Akash Dhruv (Staff Scientist, ANL); Dr. Klaus Weide (Consultant, former Flash-X Staff Scientist)

1. Statement of Specific Research Interests

Five-Year Research Vision & Core Questions. Accelerator facilities worldwide are pursuing higher beam brightness by lowering transverse emittance and raising stored current. The same brightness that enables transformative science creates a machine-protection problem: unplanned beam losses can deposit energy densities exceeding the high-energy-density (HED) threshold of $\sim 100\,\mathrm{J/mm^3}$ within collimators or insertion devices in under a millisecond. Assessing the risk to a given device for a given beam and operating mode demands high-fidelity multi-physics modeling coupled with beam-dynamics and control-systems expertise, and designing machine protection systems (MPS) to mitigate it is a community-wide challenge. Our CART will address the fundamental physics of collimator damage, the optimal MPS design philosophy at high intensity, and the integration of specialized MPS into controls infrastructure using modern, AI-enabled frameworks. Our five-year goals are threefold: (1) establish *HED-Melt* as a validated, predictive tool for MPS studies, continuously advanced through AI-enabled code updates; (2) release *HED-Melt* to the broader HED community as an open, extensible framework; and (3) train the next generation of accelerator scientists by fostering Ph.D. students into postdoctoral leaders. Our vision is a software framework that embeds dynamic MPS into an intelligent accelerator design and control ecosystem.

Proposed Approaches and Methods. We will leverage our simulation toolset, *HED-Melt*, developed under the previous ARDAP awards DE-SC0023152 (9/1/22 - 12/31/25) and the supplemental award corresponding to DE-FOA-0003432 (12/31/25 - 8/31/26), to model the multi-physics interaction of a beam or radiation source with a collimator, absorber, or insertion device. Coupling beam-dynamics models with radiation–material interaction and magnetohydrodynamic expansion (including phase change), we estimate a material insert's evolution under a beam strike across diverse beam, lattice, and geometry conditions. This approach has shown good qualitative agreement with loss patterns and structural damage observed at the APS and APS-U following beam aborts [1]. Operational systems with diverse working points require comprehensive material-response and beam-dynamics models under varied abort scenarios. Operational use further requires lightweight, responsive surrogates that integrate into a conventional controller or an AI-enabled infrastructure; we have identified a neighborhood-attention, mixture-of-experts architecture to expedite surrogate training and inference for active-control environments, and will apply AI-assisted code updates to evolve *HED-Melt*'s physics and surrogate modules.

Anticipated Transformative Impact. Predictive MPS modeling in this regime is a priority computational need identified in the *Basic Research Needs Workshop on Compact Accelerators for Security and Medicine* (DOE/SC, 2019), the 2022 *Accelerator and Beam Physics Roadmap* (HEP-AAC), and *Accelerators for America's Future* (DOE/SC, 2009). Success will give future DOE user facilities a predictive, AI-enabled MPS capability that protects high-brightness beamlines and accelerates their design and commissioning.

2. Capabilities and Offerings for Collaboration

Available Expertise and Level of Effort. UCSC brings unique expertise in the fundamental computational modeling of beam–material interactions at the core of machine-protection methodologies; UCI adds machine learning and surrogate modeling for multiphysics thermo-fluid dynamics;

Argonne brings accelerator operations, controls, MPS, and high-performance computing workflows; and RadiaSoft brings accelerator software integration for beamline modeling and controls, including surrogate-model development and digital-twin orchestration. We will release *HED-Melt* to the HED community as a shared, documented framework collaborators can extend and apply at their own facilities. We anticipate committing approximately 1–2 person-months/year per PI/Co-PI, with dedicated graduate-student, postdoctoral, and staff effort at each institution.

Institutional Facilities and Capabilities. Our collaboration provides access to Argonne high-performance computing—the Laboratory Computing Resource Center (LCRC) and the Argonne Leadership Computing Facility (ALCF)—to develop software and to train and validate facility surrogates. We also provide APS-U operational data—beam-position, collimator-damage, and current measurements during beam aborts and other anomalies—essential for validating our tools and surrogates.

Workforce Development Opportunities. Workforce training is integral to this CART, with the explicit goal of producing the next generation of postdoctoral researchers by fostering Ph.D. students into independent accelerator scientists. UCSC (Lee) and UCI (Chandramowlishwaran) will jointly educate and mentor Ph.D. students in the numerical methods, physics, simulation, and AI/ML skills the research demands, spanning applied mathematics, accelerator physics, materials science, and machine learning. At UCSC we will engage the Santa Cruz Institute for Particle Physics (SCIPP) to broaden student exposure to experimental and detector physics and to deepen collaboration. Argonne and RadiaSoft will coordinate this training by hosting UCSC and UCI students through internships and/or visiting-researcher programs, giving hands-on experience at an operating DOE facility and in industry-grade accelerator software. Together these pathways span academia, national laboratory, and industry, preserving corporate knowledge across the field.

3. Desired Collaborative Partner Attributes

We seek to engage facilities designing or operating high-intensity accelerator systems for which dynamic machine protection is essential to automated operations. Institutions upgrading existing facilities or designing new ones make natural partners, and we welcome collaborators contributing complementary experimental testing facilities, controls integration, or additional workforce-training structures, such as a research team lead by Dr. Remi Lehe in Advanced Modeling Program (AMP) at LBNL. Between UCSC and AMP, there was already a tangible collaboration as part of sharing a summer internship student in Summer 2025, who is going to join the Applied Mathematics PhD program at UCSC under PI Lee's supervision in Fall 2026.

4. Management, Synergies, and AI/ML Integration

Preliminary CART Management Concept. UCSC will serve as the intellectual and administrative lead with guidance from each partner. Tasks will be evaluated against milestones with quantified metrics: algorithms must meet rigorous benchmarks, and surrogates and controls integrations must achieve target fidelity and reliability. Workforce and educational milestones will be tracked per institution for students and postdocs, and inter-institutional progress through regular meetings.

Programmatic Synergies. This work complements existing partner efforts, most significantly APS-U operation, where operations indicate a need to better understand beam-abort loss dynamics. We will leverage existing and planned APS-U machine studies to validate the developed models and control strategies.

AI/ML Integration. AI/ML is integral to the work plan, embodying the human–machine co-development the program seeks: we use automated tools for code development and validation, and AI/ML to design surrogate network architectures. The resulting software integrates into operational workflows, including automated MPS that detect and adapt to machine anomalies.

References: [1] A.J. Dick et. al, *Phys. Rev. Accel. Beams* **28**, 123001 (2025).

Letter of Intent (LOI): Machine Learning-Enabled Integrated Simulation Workflows for Accelerator Design

NOFO: DE-FOA-0003620 **Track/Topic:** Track 2 (CARTs), Topic 2.1

PI: Leon van Riesen-Haupt, Assistant Professor, Old Dominion University
Phone: 757-683-5801 **Email:** lvanries@odu.edu
Co-Investigators / Senior Personnel: J. R. Delayen, S. U. De Silva, Q. Su, M. Yadav, **Old Dominion University**, X.Lu, **Northern Illinois University**, S. Li, N. Bidault, **University of Hawaii**

Collaboration note: We are in active discussions with collaborators across universities and national laboratories; additional partners are welcome.

Overarching CART Research interests and 5-year vision.

Next-generation accelerator design demand simulation toolchains that span high-dimensional, deeply coupled design spaces. Currently, optimization remains human-in-the-loop and reliant on localized intuition, while subsystem integration is bottlenecked by informal constraint propagation. Our core question is how **machine learning (ML) and large language models (LLMs)** can enable **integrated end-to-end workflows** can enable integrated end-to-end workflows that preserve strict physics fidelity, ensure traceability, and deliver interpretable trade studies across these highly constrained frontiers. The outcomes of this research will be equally applicable to other accelerator challenges, including light sources and industry applications.

Over five years, we will develop a modular, community-facing framework that (a) transfers design insights from prior simulation campaigns, (b) enables constrained multi-objective co-optimization with robust uncertainty quantification, and (c) delivers control-aware design artifacts. Significantly, we plan to validate this framework by testing it directly at various accelerator test facilities, including the University of Hawai'i accelerator, by the end of the project to examine its efficacy for high intensity, low emittance applications. This CART will ultimately compress collider design cycles, chart undiscovered global optimums, and establish transferable workflows to transform future high-energy physics facilities.

NIU Core Technical Scope and the CART Big Picture.

NIU's technical contributions are strategically woven into the broader CART architecture. We propose a 5-year research program to fundamentally transform accelerator development by integrating Machine Learning (ML) directly into the RF and beamline design workflows. By transitioning from manual iteration to ML-driven co-design, and grounding these digital models in physical testing, we aim to deliver highly optimized, operationally robust RF architectures for frontier applications. To rigorously test this workflow, we will benchmark our tools against the most demanding components of next-generation accelerators and critical facility upgrades. Ultimately, these validated models will enable the rapid design of highly compact, efficient, and versatile accelerators.

Our outputs will integrate directly into the CART-wide interoperable framework. To execute this vision, NIU will drive this transformation through two tightly coupled technical pillars that map directly to the foundational pillars specified in the CART LOI:

1. **Subsystem Optimization: ML-Assisted Cavity Design (Mapping to CART Pillar 1):** Directly addressing the CART's goal of optimizing individual aspects, the foundation of our effort focuses on the electromagnetic and multiphysics optimization of individual RF cavity structures. To efficiently navigate complex, multi-parameter design spaces, NIU will deploy intelligent optimization frameworks—such as active learning and Bayesian optimization—that strategically sample high-fidelity simulation codes (e.g., ACE3P and CST). Rather than relying on exhaustive manual parameter sweeps, this ML-guided exploration will dynamically balance competing objectives, such as maximizing shunt impedance and controlling peak surface fields. Supported where appropriate by advanced techniques like surrogate modeling to reduce computational bottlenecks, this workflow accelerates the design cycle and charts optimal, high-gradient cavity geometries that broaden the search far beyond traditional local intuition.

2. **Integration: Interoperable, Multi-Domain RF Workflows (Mapping to CART Pillar 2):** Directly addressing the CART's central integration objective, we recognize that a single optimized cavity must seamlessly interoperate within the broader accelerator architecture. NIU will focus on the integration layer, establishing multi-domain workflows that allow RF systems to ”talk” directly to other subsystem workflows through well-defined interfaces. We will ensure complex RF parameters (e.g., wakefields, beam loading compensation, and RF power distribution) are dynamically exchanged as constraint ”contracts” with the optics and beam dynamics workflows of our CART partners. By orchestrating this interoperability, we enable true system-level co-design that incorporates control-aware operability margins early in the process. Application drivers for this integrated framework will be drawn from a diverse suite of candidate testbeds, including future collider subsystems and critical facility upgrades.

Operational Expertise and Physical Testbeds.
To ensure ML workflows produce facility-ready technologies, theoretical designs must be grounded in physical reality. NIU provides the operational expertise to embed practical constraints (e.g., RF conditioning, thermal management, and tuning) as foundational parameters in the ML training data. Leveraging our proximity to nearby Argonne National Laboratory and Fermilab, we plan to explore validating AI-generated RF designs on operational testbeds, aiming to close the loop between digital twin predictions and real-world hardware.

Workforce Development.
The bulk of the simulation orchestration, data generation, and potential physical testbed validation in this effort will be driven by NIU graduate students. To support this, we benefit from the **DOE Chicago Accelerator Science Traineeship (CAST)**, a collaborative program already in place co-run by NIU and the Illinois Institute of Technology (IIT). CAST serves as an established vehicle to attract talented students and offer them hands-on experience bridging accelerator physics and computational science. By drawing students from this existing pipeline, our CART research will provide them with practical, frontier ML-driven RF challenges, ultimately preparing them to build, operate, and innovate upon future U.S. accelerator facilities.

Management concept: We envision a highly integrated, collaborative management model. NIU will lead the RF and cavity design tasks, while coordinating seamlessly with partner institutions leading the complementary beam dynamics and core ML infrastructure tasks. A CART-wide steering committee will oversee the effort, utilizing routine technical syncs and milestone reviews.

Contact for collaboration discussions: CART PI: Leon van Riesen-Haupt (ODU), lvanries@odu.edu; NIU contact withint this CART team: Xueying Lu, xylu@niu.edu

Letter of Intent (LOI): Machine Learning-Enabled Integrated Simulation Workflows for Accelerator Design

NOFO: DE-FOA-0003620 **Track/Topic:** Track 2 (CARTs), Topic 2.1

PI: Leon van Riesen-Haupt, Assistant Professor, Old Dominion University
Phone: 757-683-5801 **Email:** lvanries@odu.edu
Co-Investigators / Senior Personnel: J. R. Delayen, S. U. De Silva, Q. Su, M. Yadav, **Old Dominion University**, X.Lu, **Northern Illinois University**, S. Li, N. Bidault **University of Hawaiʻi**

Collaboration note: We are in active discussions with collaborators across universities and national laboratories; additional partners are welcome.

Research interests and 5-year vision.

Modern accelerator facilities, including future colliders, accelerator-based light sources, and other applications requiring low-emittance and high-brightness beams, increasingly require integrated accelerator design workflows that can optimize strongly coupled subsystems while accounting for performance, tolerances, and operational constraints. The proposed CART will develop machine-learning-enabled, physics-informed simulation and optimization frameworks that connect subsystem models through uncertainty-aware, community-facing workflows for accelerator design.

Within this broader CART, the University of Hawaiʻi at Mānoa will contribute a focused effort on AI/ML-enabled injector design and optimization. The injector is a critical front-end subsystem for advanced accelerators because it defines the initial beam quality delivered to the downstream machine. Beam brightness, emittance, bunch length, energy spread, timing jitter, halo formation, and loss at the injector stage can strongly influence luminosity, backgrounds, stability, and commissioning complexity in colliders and accelerator-based light sources. As future machines move toward increasingly stringent performance requirements, injector design must move beyond nominal working-point optimization toward robust, control-aware design.

UH brings specialized expertise in high-intensity, low-emittance beam dynamics derived from its free-electron-laser infrastructure and ongoing accelerator recommissioning activities. UH's role in the CART will be to lead the development of intelligent optimization workflows for injectors, using its university-scale accelerator as a testbed for validating methods on a real machine. The emphasis will be on transferable methods for injector design.

The UH technical scope will include three connected components:

First, UH will develop AI-ready injector modeling workflows that connect accelerator design variables to beam parameters for downstream accelerator performance. These variables may include cathode and emission parameters, RF phase and amplitude, gun and capture-section settings, magnetic transport, aperture constraints, and alignment errors. The corresponding outputs will include emittance, bunch length, charge, energy spread, beam size, halo indicators, and sensitivity to jitter or hardware variations. The goal is to provide injector models that can interface cleanly with the larger CART framework for optics, RF, and system-level design.

Second, UH will develop ML-enabled optimization methods for robust injector design. Surrogate modeling, active learning, and Bayesian optimization, will be used to explore high-dimensional injector parameter spaces more efficiently than brute-force simulation alone. The optimization objec-

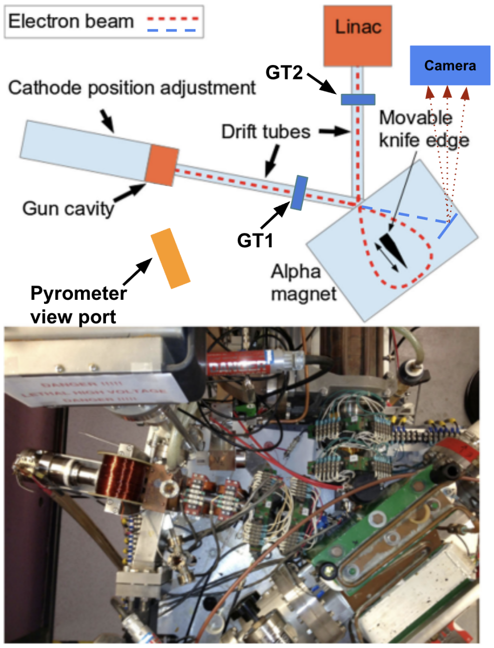

Figure 1: Schematic of the UH injector.

tive will not be limited to achieving the best nominal beam quality. Instead, the workflow will also identify operating regions that remain robust under realistic hardware limits and uncertainties, including RF jitter, cathode variation, alignment tolerances, space-charge effects, dark current, halo growth, and multipacting-prone regimes. This emphasis is important for injectors where performance must be robust to realistic hardware variations while meeting downstream luminosity, loss, and background constraints.

Third, UH will contribute to control-aware injector design. In practice, injector performance depends not only on the beamline design but also on whether the machine can be commissioned, diagnosed, and tuned reliably. UH will therefore incorporate operability considerations into the design workflow, including the identification of sensitive tuning knobs, the propagation of uncertainty from measured quantities to inferred beam states, and the definition of safe operating boundaries. This will allow injector design outputs to be expressed not only as optimized parameter values, but also as tolerable ranges that can be used by the larger CART integration layer.

Integration with the proposed framework and accelerator design: The UH accelerator laboratory provides a compact but realistic test environment for this work. The UH electron linac, previously used for infrared free-electron-laser and inverse-Compton-scattering x-ray source studies, is currently being recommissioned and modernized. Its injector and early beamline include cathode, RF, transport, charge, temperature, and camera-based beam imaging diagnostics. This infrastructure provides an accessible hardware platform for testing whether AI/ML-guided injector design recommendations remain meaningful under real accelerator conditions. It also provides an opportunity to compare simulation-based operating regions with measured beam behaviors and to evaluate whether uncertainty-aware optimization improves robustness in practice.

The UH effort will integrate directly with the ODU-led CART framework. Injector design outputs will be communicated to the rest of the accelerator workflow through beam distributions, tolerable parameter ranges, uncertainty estimates, and performance comparisons. These outputs can then be used in downstream lattice, RF, and accelerator design studies. Conversely, downstream requirements from beam optics, cavity design, beam-beam constraints, and background mitigation can be propagated back to the injector optimization problem. This two-way coupling is essential for moving from sequential subsystem optimization to integrated accelerator co-design.

The UH contribution complements the broader strengths of the CART by providing the source/injector pillar and an experimental testbed for validating AI/ML-enabled optimization workflows. The effort will also support workforce development and produce transferable AI/ML workflows for robust injector design, advancing integrated, physics-faithful, and control-aware accelerator design for future collider and accelerator-based user facilities and light sources.

Contact for collaboration discussions: Leon van Riesen-Haupt (ODU), lvanries@odu.edu; UH contact within this CART team: Siqi Li, siqili@hawaii.edu.

Letter of Intent (LOI): Machine Learning-Enabled Integrated Simulation Workflows for Accelerator Design

NOFO: DE-FOA-0003620 **Track/Topic:** Track 2 (CARTs), Topic 2.1

PI: Leon van Riesen-Haupt, Assistant Professor, Old Dominion University
Phone: 757-683-5801 **Email:** lvanries@odu.edu
Co-Investigators / Senior Personnel: J. R. Delayen, S. U. De Silva, Q. Su, M. Yadav, **Old Dominion University**, X.Lu, **Northern Illinois University**, S. Li, N. Bidault, **University of Hawai‘i**

Collaboration note: We are in active discussions with collaborators across universities and national laboratories; additional partners are welcome.

Research interests and 5-year vision.

Next-generation accelerator design demand simulation toolchains that span high-dimensional, deeply coupled design spaces. Currently, optimization remains human-in-the-loop and reliant on localized intuition, while subsystem integration is bottlenecked by informal constraint propagation. Our core question is how **machine learning (ML) and large language models (LLMs)** can enable **integrated end-to-end workflows** that preserve strict physics fidelity, ensure traceability, and deliver interpretable trade studies across these highly constrained frontiers. The outcomes of this research will be equally aplicable to other accelerator challenges, including light sources and industry applications.

Over five years, we will develop a modular, community-facing framework that (a) transfers design insights from prior simulation campaigns, (b) enables constrained multi-objective co-optimization with robust uncertainty quantification, and (c) delivers control-aware design artifacts. Significantly, we plan to validate this framework by testing it directly on the Unviersity of Hawai'i accelerator by the end of the project to examine its efficacy for high intensity, low emittance applications. This CART will ultimately compress collider design cycles, chart undiscovered global optimums, and establish transferable workflows to transform future high-energy physics facilities.

Work scope concept (open, multi-institution CART).

We propose two tightly connected pillars:

1) Design optimization of individual aspects (examples; open to more).

The goal is to establish systematic, reusable workflows for major accelerator design components, each grounded in validated simulation and augmented by ML to explore feasible regions efficiently and reduce reliance on ad hoc tuning.

1a. **Optics design:** combine physics-based optimizers with ML-guided exploration (e.g., active learning / Bayesian optimization or related constrained-search methods) to map feasible solution families and quantify trade-offs (chromatic performance, dynamic aperture, tolerances). A complementary thread is “experience transfer”: extracting reusable patterns from existing designs in the literature to warm-start optimization and broaden search beyond local intuition.

1b. **Cavity structure design:** rf cavity optimization by exploring complex multi-parameter design spaces and identifying optimal geometries with reduced computational cost. Using advanced approaches such as surrogate modeling and Bayesian optimization to improve cavity performance metrics including accelerating gradient, quality factor, and field stability. These intelligent optimization frameworks support the development of next-generation accelerator systems through faster design cycles, enhanced efficiency, and real-time adaptive control.

1c. **Sources/injectors:** Optimize high-brightness injector systems by integrating beam dynamics simulations with ML exploration to map robust operational configurations for cathodes, electron/ion guns, and capture sections. This workflow targets collider-critical constraints—including emittance preservation, halo control, and space-charge mitigation—under realistic hardware boundaries like RF jitter, alignment tolerances, and multipacting risks. By optimizing these complex injection frontiers, the framework ensures front-end performance scales seamlessly to support downstream luminosity and background goals.

1d. **Additional aspects (open):** e.g., magnet design and field-quality/tolerance workflows; collective effects and impedance/wakefields; diagnostics placement; alignment/tuning strategies; and other cross-cutting beam dynamics topics appropriate to the CART.

2) Integration: interoperable, control-aware, multi-domain workflows.
The central objective is an integration layer that lets subsystem workflows talk to each other through well-defined interfaces. We envision exchanging key quantities either as precise values *or as admissible ranges* ("contracts") so constraints can propagate robustly across domains. Technical elements include:

- **System-level optimization:** multi-objective, multi-fidelity strategies that co-optimize across various subsystems (e.g. optics and cavity design) under realistic constraints (apertures, gradients, power, tolerances, beam loss limits), with uncertainty-aware trade studies.
- **ML/LLM-enabled workflow orchestration:** Machine learning models such as neural networks will be used to build surrogate models that replace computationally expensive simulation codes with low-fidelity digital twins for rapid design iteration and parameter exploration. These surrogate models can also provide additional information to support optimization algorithms and design decision-making. The long-term goal is to develop an agentic workflow framework connected to accelerator design tools, documentation, and experimental feedback for more integrated and adaptive accelerator development.
- **Control-aware design:** incorporate operability margins early by treating tunability and instrumentation needs as first-class design constraints, reducing downstream rework in commissioning-style studies.

Institutional Capabilities and CART Expertise.
The proposed multi-institution CART unites highly targeted, complementary technical capabilities optimized for next-generation collider design challenges:

- **Old Dominion University (ODU):** Acts as the lead institution, leveraging its Center for Accelerator Science and a dedicated AI-for-Accelerators faculty cluster hire spanning Physics, Electrical and Computer Engineering, and the School of Data Science. Working closely with **Jefferson Lab**, faculty members at ODU bring proven expertise in collider optics design (FCC, LHC, LHeC), advanced SRF structure optimization, and ML/LLM workflow orchestration. ODU's long-running **VITA program** (recruiting 6–7 students annually) anchors the workforce plan to train four Ph.D. students in these integrated disciplines.
- **University of Hawai'i (UH):** Brings specialized expertise in high-intensity, low-emittance machine dynamics derived from their FEL infrastructure, leading the development of intelligent optimization workflows for advanced collider injectors.
- **Northern Illinois University (NIU):** Brings expertise in normal-conducting RF cavities and beam dynamics design to the co-design framework. This technical effort will directly synergize with the **CAST** Traineeship program on workforce development.

The collaborative framework remains open to additional institutional partners who can contribute distinctive modeling or technological capabilities to these core pillars. This is extends to national labs, especially for purposes of testing the method in real life applications.

Synergy and application drivers.
This effort directly targets the urgent design and tolerance timelines of future flagship facilities: including light sources and colliders such as the EIC, FCC-ee, and frontier muon colliders. By anchoring our ML/LLM co-design workflows to these highly coupled, extreme-parameter machines, the CART addresses the high-energy physics community's most pressing design bottlenecks while ensuring ultimate workflow transferability.

Contact for collaboration discussions: Leon van Riesen-Haupt (ODU), lvanries@odu.edu.

Letter of Intent

Title: THz Two-beam Structure Wakefield Acceleration for Compact Sub-GeV to GeV Accelerators

Topic number and name:	2.3 Emerging Accelerator and Radiation Concepts and Fundamental Physics
PI Name, Job Title, Institution:	Gwanghui Ha, Assistant Professor, Northern Illinois University
PI Phone Number, PI Email Address	+1 815-753-1461, gha@niu.edu
List of Co-investigator and Senior Personnel	John Power (ANL), Chunguang Jing (Euclid Techlabs)

Proposed CART Research Direction and Impact

This LOI proposes a research direction on THz two-beam structure wakefield acceleration. The concept uses a drive-bunch train to resonantly excite GW-level sub-THz/THz wakefields in a power-extraction structure. The extracted electromagnetic power is then coupled to a separate accelerating structure for main-beam acceleration. The objective is to develop a practical two-beam accelerator architecture in 0.1–1 THz range with high gradient, reduced footprint, and manageable beam dynamics.

The THz regime can reduce the total drive-beam charge required for high-gradient acceleration. Conventional GHz two-beam acceleration (TBA) generally requires hundreds of nC of total drive-beam charge, while a sub-THz/THz system can reach high gradients with tens of nC (see Fig. 1, simulations with 1 nC/bunch). This can relax driver requirements and reduce accelerator-system size and complexity. The two-beam architecture also avoids some limitations of collinear wakefield acceleration, where drive and main beams co-propagate in the same structure and acceleration efficiency depends strongly on single-bunch shaping, beam loading, and drive/witness separation.

Recent progress in THz and sub-THz wakefield acceleration has shown that compact structures can sustain extremely high fields and that relativistic electron beams can generate intense narrowband radiation in this frequency range. However, a practical accelerator architecture has not yet emerged because key system-level challenges remain unresolved, including multi-GW THz power generation, controlled power transfer, and resonant bunch-train stability. Our previous work on beam-driven THz power generation, bunch-train generation, and beam-based diagnostics at AWA provides a direct foundation for addressing these challenges.

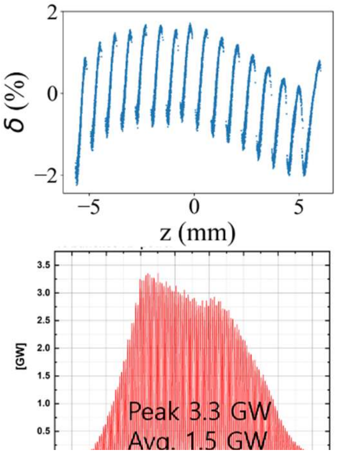

Figure 1: S2E simulated drive beam and CST simulated RF profile

Successful development of THz-TBA would provide multi-GW power and sustained gradients of several 100 MV/m for compact sub-GeV to GeV accelerators, with potential applications to compact FEL drivers, FLASH radiotherapy accelerators, and medical radioisotope production if adapted to ion or proton beams. The drive-side power-extraction system could also serve as an extreme-power THz source for high-field science. Physics understandings from structure investigation and beam breakup would help resolving current challenges wakefield accelerator research. Also, the developed technologies such as AI-based control and THz power transfer could be applied to other fields beyond particle accelerators.

Five-Year Thrusts

Thrust 1. THz Structure Concept, Fabrication, and Beam Validation. The first challenge is that the optimal structure type for the 0.1–1 THz regime is not yet established. At these frequencies, the structure must provide strong wakefield excitation, acceptable aperture, manufacturable geometry, tolerable surface fields, manageable transverse wakefields, and usable coupling to an external accelerating structure. This thrust would compare corrugated metallic, dielectric-loaded, hybrid, and possibly cryogenic structures for power extraction and acceleration. Candidate structures would be evaluated using accelerator-level metrics, including wakefield amplitude, aperture, mode purity, transverse wake strength, fabrication tolerance, surface-field limit, thermal behavior, and power-transfer compatibility. Fabrication methods would be developed, and fabricated structures will be benchmarked through wakefield measurements.

Thrust 2. BBU Dynamics and Transverse Stability. The second challenge is beam breakup (BBU). BBU in a THz-TBA is not simply a scaled version of conventional GHz-TBA or THz collinear wakefield acceleration. Unlike collinear acceleration, transverse wake builds up resonantly along the bunch. Unlike GHz regime, drive bunches are only a few ps apart, which does not allow slow mitigation methods. This thrust would develop predictive BBU models and suppression strategies, including a modified quadrupole-wiggler-based BNS damping, structure-by-structure cancellation through phase-space reversal, or dipole-mode control. The goal is to establish design rules for stable operation, including focusing strength, alignment tolerance, and structure requirements.

Thrust 3. THz Power Transfer. The third challenge is power transfer. The extracted power must be delivered to an accelerating structure with adequate efficiency, mode purity, and timing control. In the 0.1–1 THz range, RF waveguide transport becomes difficult because of ohmic loss and fabrication sensitivity, while quasi-optical transport introduces coupling, diffraction, and mode/phase-control challenges. This thrust would evaluate waveguide-based transport with mode conversion and quasi-optical transport with coupling through antenna. The comparison focuses on efficiency, mode purity, timing and phase control, alignment tolerance, fabrication complexity, and compact-layout compatibility.

Thrust 4. AI/ML-assisted operation. The fourth challenge is beam characterization and control. The scale of bunch train and strong quality degradation by BBU significantly limit the high-resolution characterization of the beam, while the system performance is sensitive to beam parameters. This thrust would develop or adopt AI/ML-assisted diagnostic and tuning technique to reconstruct drive-beam and wakefield from beam images, energy spectra, and radiation signals and control drive-bunch parameters. AI/ML surrogate models would also reduce the cost of time-domain RF/THz transport simulations.

NIU Role, Collaboration, and Workforce Development

The initial collaboration would involve NIU, the Argonne Wakefield Accelerator (AWA) team, and Euclid Techlabs. NIU would lead primarily overall beam dynamics, drive-bunch-train generation and transport, BBU modeling, beam diagnostics, and proof-of-principle experiments. The anticipated NIU effort would be one faculty PI, one postdoc, and two to three graduate students, subject to final CART scope and resource allocation. AWA would provide the beam-test facility, lead AI/ML-based control and prediction, and contribute to beam dynamics, RF/THz design, diagnostics, experimental execution. Euclid would lead RF/THz structure design, engineering, fabrication, and related technology development. The CART teaming process would expand this core framework by adding complementary expertise in high-power THz diagnostics, quasi-optical THz transport and coupling, high-gradient and cryogenic structures, laser-driven THz acceleration, and AI/ML-enabled modeling and control. These capabilities are needed to evaluate GW-level THz power generation, efficient power transfer, end-to-end beam–THz interaction, surface-field and breakdown limits, and real-time optimization.

The project would train students in beam dynamics, wakefield acceleration, RF/THz structure design and fabrication, electromagnetic simulation, beam diagnostics, data acquisition, AI/ML-assisted control and prediction, and multi-institution collaboration, directly building on ongoing NIU, AWA, and Euclid strengths in wakefield acceleration, beam diagnostics, phase-space control, structure development, and AI/ML-enabled accelerator operation. It will be synergistic with NIU's CAST program (graduate) and Argonne's SULI program or Lee Teng fellowship (undergraduate).

Harnessing Electron-Laser Interactions for Optimized Sources of X-rays (HELIOS-X)

Topic Number and Name: 2.3 Emerging Accelerator and Radiation Concepts and Fundamental Physics
PI Name, Job Title, Institution: Pietro Musumeci, University of California, Los Angeles
PI Phone Number: (310) 2069164 **PI Email Address:** musumeci@physics.ucla.edu
Co-investigators and senior personnel:; Sergio Carbajo, University of California, Los Angeles; Agostino Marinelli, Stanford University / SLAC; Siqi Li, University of Hawai‘i

Statement of Specific Research Interests: Over the past decade, significant advances in the precise control of relativistic electron beams, the generation of structured light and radiation fields, advanced undulator technologies, and predictive modeling of short-wavelength radiation emission have opened new opportunities in photon science. These developments make it now possible to consider coherent radiation sources in which not only the intensity, but also the temporal structure, polarization, bandwidth, coherence, and extraction efficiency of the emitted light are engineered at the source. These advances are enabling transformative techniques in quantum optics, providing unprecedented precision in manipulating quantum materials, and offering new insights into ultrafast processes in femtochemistry and structural dynamics of biological molecules. Building on these advances, the proposed CART will investigate the beam–radiation physics needed to realize compact, versatile, and high-efficiency coherent photon sources based on tailored electron beams, advanced undulator systems, structured electromagnetic fields, and controlled laser/electron interactions to enable new capabilities at next-generation light sources.

This effort addresses an important gap in the present accelerator ecosystem. Major X-ray user facilities are optimized to deliver high-quality photon beams for users and are necessarily limited in the time they can devote to disruptive source-physics research involving new beam formats, unconventional undulator configurations, nonstandard laser/electron interactions, or high-risk tuning. A CART structure can fill this gap by combining university-scale expertise and testbeds, advanced theory and modeling, structured-light and ultrafast laser capabilities, and targeted experiments at national laboratory facilities. The collaboration will develop and investigate novel interaction schemes and design principles for next-generation coherent radiation sources, while remaining open to advanced acceleration techniques when they provide genuinely new beam or radiation parameter space.

Proposed Approaches and Methods: The research will be organized into three independent but interconnected work packages (WPs), culminating in a fourth, integrative WP:

- WP1: Optimizing Electron–Laser Interactions: Investigate the physics of electron–laser coupling towards advanced interaction schemes for controlling X-ray properties such as bandwidth and pulse shape, cascaded electron–photon processes, and improving efficiency via advanced simulation models and non conventional coupling schemes. Laser based undulators and Inverse Compton Scattering will also be investigated.
- WP2: Controlling Electron Phase Space Distributions: Pursue both theoretical and experimental development, including scaled-down tests at available facilities, of innovative methods for generating shaped electron beams, in particular, addressing how imposed electron-beam structure maps into radiation power, spectrum, pulse duration, coherence, polarization, and shot-to-shot stability. . This includes microbunching, pulse-train formation, laser modulation, phase-space linearization, and preservation of beam structure through acceleration and transport.
- WP3: Advancing Laser Shaping and Control: Design and refine advanced laser-shaping and control strategies to achieve precise, dynamic manipulation of both laser and electron beams, which is critical for optimizing the performance of next-generation X-ray light sources. As an example, programmable spatio-temporal control of the photoinjector laser has recently been shown to imprint on demand temporal structure on relativistic electron bunches that persists

through acceleration, magnetic compression, and undulator transport, and similar techniques can be applied to seed lasers as well.

- WP4: Integrated Experimental Demonstration: Conduct integrated experiments to demonstrate the generation of shaped radiation pulses. These proof-of-principle experiments will validate the proposed concepts and showcase the potential for agile, high-performance X-ray pulse generation in future light source facilities.

Transformative and Cross-Agency Impact: By harnessing these capabilities, we are poised to unlock new regimes of experimental science, where the tailored properties of X-ray pulses can be leveraged to probe, control, and ultimately design matter at the quantum level. This research direction promises to deepen our fundamental understanding of nature and drive technological innovation across a broad spectrum of disciplines. Moreover, the work would produce transferable tools and capabilities such as benchmarked FEL and beam-dynamics codes, AI/ML-assisted optimization workflows, compact magnetic-device designs, structured laser/electron interaction techniques, and experimentally validated scaling laws for advanced radiation sources, which are likely to have a lasting impact on other areas of accelerator science and related fields, fostering cross-disciplinary advances and new applications

Capabilities Offered to Potential Collaborators: The initial team would bring complementary expertise in FEL physics, advanced beam dynamics, structured electromagnetic-field generation, tapered undulators for high-efficiency energy extraction, permanent-magnet technology, high-brightness beam diagnostics, and start-to-end modeling. University-based testbeds can provide rapid iteration on beam–radiation concepts, microbunching techniques, diagnostics, and laser/electron synchronization, while national-laboratory partners such as SLAC and ANL can provide access to high-energy beamlines and frontier FEL/X-ray source environments. Collaborators from Stanford, UCLA, the University of Hawaiʻi, and potentially other institutions would provide complementary strengths in XFEL physics, structured light, ultrafast optics, computational modeling, and experimental implementation.

Engagement, Collaboration, and Workforce Development: Our team offers deep expertise in advanced electron beam dynamics, laser shaping and control, and the integration of accelerator-based light source technologies. We are prepared to contribute significant effort in experimental design, beamline operation, and theoretical modeling, leveraging our experience with both large-scale user facilities and university-based testbeds. Our capabilities include access to state-of-the-art laser laboratories, high-brightness electron sources and linear accelerators, and advanced diagnostics for both electron and laser beams. We are also committed to workforce development, offering experiential opportunities for undergraduate students and hands-on training for graduate students and postdoctoral researchers in accelerator science, laser technology, and data-driven experimental methods. Through established educational programs, including collaborations with universities hosting DOE traineeship programs, and close ties with national laboratories, we provide a robust pipeline for developing the next generation of scientists and engineers in this field.

In seeking collaborators, we are particularly interested in partners with complementary expertise in high-power laser systems, ultrafast optics, advanced materials, and AI/ML for accelerator control and diagnostics. We also welcome industrial partners who can support the development and scaling of novel components. We are also open to joint training programs, internships, and workforce exchanges to broaden the impact of the proposed research. Project management will be structured collaboratively, with regular meetings, transparent decision-making, and shared milestones to ensure efficient allocation of resources and rigorous evaluation of progress. The proposed CART research is highly synergistic with our ongoing accelerator R&D and workforce development activities, and we anticipate that the integration of AI/ML tools aligned with Genesis-Mission initiatives such as the multi-office accelerator team (MOAT) will further enhance experimental agility, data analysis, and optimization tasks throughout the project.

Physics of Materials for High Gradient Acceleration

Letter of Intent for the DOE DE-FOA-0003620
Collaborative Accelerator R&D Team (CART) Program
Topic 2.3: Emerging Accelerator and Radiation Concepts and Fundamental Physics
PI: James Rosenzweig
Institution: UCLA Department of Physics and Astronomy
Phone: (310) 806-1186
Email: jrosenzw@ucla.edu
Co-Investigators / Senior Personnel: Sami Tantawi (ASU), John Power (ANL), Evgenya Simakov (LANL), Gerard Andonian (UCLA)

The search for very high field acceleration techniques in structure-based accelerators has moved forward in a non-systematic way for over three decades now, driven by the need for more new accelerators with a more compact footprint. These applications notably range from high-impact light sources such as X-ray free-electron laser (XFELs) and inverse Compton scattering (ICS) sources, to future particle physics colliders (*e+e-*, muons) for discovery and precision physics.

Much of the recent reported progress has been experimentally driven, as the space of possibilities in choice of materials, design philosophies, operational frequency and experimental conditions is vast. The nucleus of the proposed CART collaboration has been at the forefront of this effort in a wide array of initiatives, which have yielded surprising and promising results. These diverse discovery areas range from very high field cryogenic copper RF accelerators, to mm-wave-to-THz acceleration and radiation production in dielectric wakefields. Indeed, these efforts have already launched impactful new research and development efforts, with cryo-RF leading to new pathways to an ultra-compact XFEL (now being commercialized for advanced chip metrology), a collider initiative termed C^3, new medical accelerators for flash cancer therapy, and high-capability ultra-fast electron diffraction facilities. Likewise, in high frequency dielectric-wake based accelerators, new paths to GeV/m acceleration (as well as attendant materials physics limitations) and uniquely capable narrow-band, high power mm-wave/THz sources.

It has been recognized for some time in the high gradient community for some time that in order make consistent progress towards very high gradient acceleration in structure-based accelerators, a more systematic approach is needed, with a heavy emphasis on materials science. This was the topic of a dedicated workshop on Materials for Accelerators hosted by the NSF STC Center for Bright Beams at Cornell in summer 2025. The topics discussed there included dielectric, cryo-RF and beyond, to high field photocathodes. The start-of-the-art in the field identified at the workshop aids in setting the rich physics goals of this CART, which aims to embrace advanced fabrication methods, unique experimental facilities, and deep strength in computational modeling to give an emergent picture of the frontier in high gradient-supporting materials.

As noted, peak fields supported by structure-based accelerators are now in the 0.5-2 GV/m, with new horizons clearly in sight. For cryo-RF, alloys and engineered materials with custom grain boundaries must be considered, as well as surface finishing techniques. In dielectrics, new materials such as CVD diamond show great promise, with an extremely low loss tangent at high frequency, representing the tip of the iceberg of candidate materials. Finally, we note that the use of dielectrics at cryogenic temperatures remains a very promising nearly unexplored path, with envisioned loss tangents below 1E-8 foreseen. This gives a compelling bridge between cryo-RF and high field dielectric research at high fields.

Plans for a five-year research program exploring the limits of high gradient performance of solid-state materials. are as follows:

Computational and theoretical model development: Basic physics models of the complex solid state systems, as well as their surface physics under that are adaptable to massively parallel computational evaluation. This is intended to be hierarchical, starting from first principles and proceeding to emergent models such as molecular dynamics models of breakdown dynamics. These theoretical/computational models will be initially benchmarked on data with known anomalies in need of explanation, such as cryo-copper surface breakdown and high-field induced conductivity in few GV/m wakefields. They will be later be trained on data to establish a ML-enabled digital twin. The models after training will be expanded to permit predictions concerning use of new materials/alloys/crystalline structures

Materials development and testing: The nucleus of the identified collaboration has expertise in fabricating both custom dielectric and metallic samples, as well as their testing. ASU has a new CVD apparatus coming online, and attendant sample testing capabilities in vacuum and at high fields in a large quasi-optical cavity. Loss tangents and surface resistivities will be recovered. UCLA has wide expertise in alloy and crystal structure engineering through the UCLA Nanolab.

Online testing of next-generation high gradient structures: Synergistically developed new cryo-RF structures will be tested at both LANL, with its new capabilities in cryogenic high-power RF environments. Breakdown and dark current emission provide rich physics signatures. At UCLA, we have a dedicated cryo-RF infrastructure to test novel photocathodes up to 200 MV/m surface electric fields, and study beam production; UCLA also has capabilities for dielectric wake studies at cryogenic temperatures, including copious diagnostics of the coherent Cerenkov radiation, which paints a picture of the interior state to the dielectric under high field conditions. At ASU, X-band RF power is available for high field testing. Finally, higher wakefield amplitudes will be obtainable at the AWA facility, based on unique pulse compression schemes.

This CART, if successful, lay the foundations for obtaining extremely high field acceleration in structures, though advanced understanding of materials in high field environments. It will in turn enable the development of new paths to compact accelerators with advanced compelling applications in the multitude of arenas named above. It is clear that in the absence of this broad, comprehensive, multi-year effort which involves the relevant physics, engineering, materials science and ML-oriented computational methods, that this goal would not be obtained.

For potential collaborators, this project offers a strong, energetic nucleus of existing collaborators with expertise in high field accelerator structures, their fabrication and testing, and associated attendant computational methods. This nucleus is already strongly engaged in the experiments at ASU, UCLA and ANL. This wide laboratory infrastructure infrastructure would be made available to CART team members.

We are actively seeking help from new collaborators in materials science and fabrication techniques, and in particular on theoretical/computational modeling. Expertise in ML-aide material design would be highly desired. We also would appreciate help in areas related to implementation high field structure design and testing methods. Collaborators are also sought with strengths in cryogenic methods.

It should be noted that the research programs at UCLA and ASU have very strong workforce development components, particularly in the experimental programs described. Graduate student research is emphasized in all the programs, and a long, successful track-record the production of the next generation of accelerator and beam scientists. It is expected that new opportunities will be offered using the Tigner Fellowship and the SC-GSR programs.

This CART will be managed in a mode developed over time in UCLA-centered collaborations, with weekly Zoom meetings to coordinate research priorities and execution, and diffusion of results at conferences and through publication. In this way, resource allocation and real-time management of the project and progress evaluation may occur.

Letter of Intent: Integrated Design of Cost-Effective Advanced Compact Accelerators and Radiation Sources

NOFO: DE-FOA-0003620 **Track/Topic:** Track 2 (CARTs), Topic 2.3

PI: Qianqian Su, Assistant Professor, Old Dominion University **Contact:** qsu@odu.edu; (424) 535-7271

CoPI/Senior Personnel at Old Dominion University: M. Yadav, L. Van Riesen-Haupt, S. U. De Silva, J. R. Delayen

CoPI/Senior Personnel at University of California, Los Angeles: C. Joshi, W. Mori, C. Zhang

Collaboration note: We welcome discussions with potential collaborators interested in participating in and develop the CART research vision.

Specific Research Interests and 5-Year Vision

Accelerator-driven light sources provide unique capabilities for scientific discovery through bright, coherent, and ultrafast radiation. Radiation-generation concepts such as synchrotron sources, free-electron laser (FEL), inverse Compton sources, and plasma-based light sources all rely on high-brightness charged particle beams undergoing controlled motion in structured electromagnetic fields. Developing integrated frameworks for beam generation, acceleration, optimization, and radiation production is therefore critical for next-generation accelerator and radiation-source technologies.

The proposed research aims to develop integrated computational, artificial intelligence (AI) and machine learning (ML), and experimentally informed frameworks for the design and optimization of advanced compact accelerators and radiation sources. The effort will focus on next-generation accelerator and radiation concepts with emphasis on the generation and optimization of ultra-high-brightness charged particle beams and their associated radiation production. Research activities will combine start-to-end modeling of beam generation and acceleration, beam transport, beam–field interaction, and radiation generation with ML-assisted optimization and reduced-order modeling. Building upon recent experimental advances, the program will investigate advanced accelerator concepts, including hybrid radio-frequency (RF) and plasma-based accelerator architectures, as potential pathways toward compact, cost-effective accelerator systems. Physics simulations, proof-of-concept experimental results, and machine learning will be integrated to guide the development of future accelerator and radiation-source technologies. Initial proposed research thrusts include:

- **Novel Advanced Accelerator Concepts for High-Brightness Beam Generation and Transport:** The team will investigate hybrid accelerator concepts for generating, accelerating, and transporting ultra-high-brightness beams for compact accelerator and radiation-source applications. One potential research direction is investigating accelerator architectures that combine mature RF accelerator technology with the high-gradient capabilities of plasma-based acceleration to achieve compact, cost-effective systems while preserving beam quality. Building on recent experimental demonstrations of high-efficiency advanced acceleration with multi-GeV energy gain, high transformer ratio, sub-percent energy spread, and micron-level emittance preservation, research activities will focus on high-energy beam generation, beam quality preservation, advanced beam manipulation, and integrated start-to-end modeling of beam transport and beam–field interactions.
- **Optimization of High-Brightness Beams and Cost-Effective Accelerator Systems:** The project will investigate how AI/ML-assisted optimization, surrogate modeling, and integrated computational design can improve accelerator performance while reducing facility size, operational complexity, and overall cost. Particular emphasis will be placed on physics-informed neural networks, operator learning, and other reduced-order modeling techniques for rapid design-space exploration and optimization of beam brightness, beam stability, transport efficiency, tunability, and generation efficiency of coherent radiation in advanced accelerator systems.
- **Integrated Modeling of Beam Dynamics and Radiation Generation:** The proposed effort will de-

velop an integrated computational framework for start-to-end modeling of beam generation, transport, beam–field interaction, and radiation generation in self-consistent electromagnetic environments. This framework will serve as the foundation for AI/ML-assisted accelerator and radiation-source design by enabling the generation of high-fidelity training data and training of reduced-order representations. The framework will combine beam dynamics, computational electromagnetics, plasma modeling, and radiation calculations to study beam–radiation coupling across multiple accelerator and radiation-generation regimes. Scalable simulation workflows and reduced-order models will support predictive design, optimization, and evaluation of next-generation accelerator and radiation-source concepts.

If successful, the CART would establish integrated computational, AI/ML, and experimentally informed frameworks for the generation, transport, optimization, and radiation production of ultra-high-brightness beams, enabling the evaluation and design of next-generation compact accelerator and radiation-source technologies.

Collaboration Opportunities and Institutional Capabilities

Old Dominion University (ODU): Expertise in superconducting and advanced accelerator technologies, beam dynamics design and simulation, AI/ML-assisted accelerator optimization, and high-performance scientific computing. ODU works closely with Jefferson Lab, a world leader in superconducting radio-frequency (SRF) technologies and electron sources. Computational capabilities include the ODU high-performance computing platform and Google Cloud agentic-AI resources, supporting scalable simulation, data-driven modeling, and AI-assisted accelerator design. ODU's long-running VITA program creates strong synergy with the proposed CART by providing an established framework for workforce development and training in accelerator science.

University of California, Los Angeles (UCLA): Expertise in plasma accelerator theory and simulation, beam–plasma interaction modeling, machine learning for accelerator applications, and ultrafast laser, beam, and plasma interaction experiments. Capabilities include advanced particle-in-cell simulations for plasma modeling, experimental experience in laser, beam and plasma physics, and access to national leadership-class computing facilities for large-scale scientific computing.

The proposed CART will provide graduate and undergraduate training opportunities in computational and experimental accelerator physics and machine learning. The team is also interested in enhancing existing DOE facilities and translating advanced accelerator and radiation concepts toward practical and cost-effective accelerator technologies and radiation-source systems with potential industrial and user-facility applications. We welcome additional collaborators and look forward to refining and strengthening the CART research vision through continued discussions and partnerships.

Initial CART Organization and AI/ML Integration

We envision a CART organized around coordinated research thrusts in accelerator physics, beam-radiation interaction, computational modeling, AI-assisted accelerator optimization, and the integration of simulation, machine learning, and proof-of-concept experiments. The collaboration will emphasize integrated start-to-end modeling and AI/ML-assisted design of high-brightness beam generation and accelerator-driven radiation systems. AI/ML methods, including physics-informed models, operator learning, virtual diagnostics, and optimization-ready workflows, will be integral to the research program. Shared computational infrastructure, collaborative software development, benchmarking and validation activities, and regular meetings will support progress toward scientific milestones, while cross-institutional student training, co-mentoring, and workforce development involving universities, national laboratories, and industry partners will be strongly encouraged.

Title of LOI: Next-Generation Photoemission Electron Sources for Accelerator Science
Topic number and name: 2.4 Advanced Particle Sources
PI Name, Job Title, Institution: Prof. Siddharth Karkare, Associate Professor, Arizona State University
PI Phone Number: 607-351-9631 **PI Email Address:** karkare@asu.edu
List of co-investigators and senior personnel (if appropriate): Prof. Jared Maxson (Cornell), Prof. Rehan Kapadia (USC), Prof. Pietro Musumeci (UCLA)

Dear Program Manager,

We are pleased to submit this Letter of Intent for a CART focused on next-generation photoemission electron sources. By bringing together researchers in photonics, materials science, condensed matter physics, and accelerator science, and leveraging recent advances in integrated photonics, plasmonics, nanofabrication, advanced manufacturing, and artificial intelligence, the proposed CART aims to develop transformative electron source technologies for scientific, medical, industrial, and national security applications. These include cutting-edge research facilities such as X-ray free-electron lasers, ultrafast electron scattering instruments, and advanced accelerator concepts for future colliders, as well as radiotherapy systems, industrial irradiation sources, security screening technologies, and next-generation manufacturing tools. Across these applications, there is a growing demand for electron sources with higher brightness, improved spatio-temporal control, greater stability, and enhanced operational robustness than can be achieved with existing technologies.

As a part of this CART proposal, over the next 5 years we expect to address the following areas:

1. Development of robust and brighter photoemission and electron amplification technologies
2. Integration of nanoscale photonics and plasmonics to enable spatio-temporal control of emitted electrons at the nanometer-femtoscond scale
3. Investigation of the dynamics of nanostructured, spatio-temporally correlated electron beams near the cathode and their impact on various applications.
4. Demonstration of the impact of advanced electron sources in electron guns

The proposed CART seeks to transform electron sources by leveraging advances in materials science, photonics, and nanotechnology to control not only when electrons are emitted, but also where they are emitted, how they are correlated, and how they evolve immediately after emission. Such capabilities could fundamentally expand the range of beam formats available for accelerator applications and create opportunities for new modes of operation that are inaccessible using conventional source technologies.

The CART would provide substantial opportunities for workforce development through interdisciplinary training of undergraduate students, graduate students, and postdoctoral researchers. Trainees would gain experience at the intersection of accelerator science, photonics, materials science, nanotechnology, computation, and advanced instrumentation. Cross-institutional mentoring, student exchanges, collaborative research experiences, and engagement with national laboratories and industry partners would further enhance workforce development outcomes and help prepare the next generation of researchers and engineers in advanced particle source and accelerator technologies. CART would provide also opportunities of participants to take accelerator physic courses at participating institutions and through USPAS and avail of professional development opportunities at the various participating institutes.

The participating investigators offer complementary expertise spanning photocathode physics, accelerator science, condensed matter physics, nanophotonics, plasmonics, advanced materials synthesis, nanofabrication, ultrafast optics, and electron beam diagnostics. Together, the team brings experience in the development of advanced photoemissive materials, integrated photonic devices, high-brightness electron sources, and accelerator-based applications. Participating institutions provide access to a broad range of facilities including photocathode growth and characterization systems, nanofabrication facilities, ultrafast laser infrastructure, photoemission spectroscopy and microscopy tools, beam diagnostics, electron guns, and accelerator test facilities. We also plan to access accelerator test facilities at various national labs through synergistic collaborations and the BeamNetUS program.

The CART proposal will fund primarily university-based partners, however, funded and unfunded collaborations with national labs and industries would be established through various other synergistic awards. We seek collaborators with expertise in various areas including advanced materials synthesis, condensed matter theory, nanophotonic and plasmonic device design, accelerator beam dynamics, ultrafast spectroscopy, artificial intelligence and advanced manufacturing.

We envision a CART organized around interconnected thrusts focused on advanced photoemissive materials, nanoscale photonic and plasmonic architectures, beam generation physics, and accelerator integration. Research priorities would be established collaboratively among participating investigators and adjusted as research findings evolve and new opportunities emerge. Shared facilities, coordinated experimental plans and runs, regular reviews, bi-weekly meetings and cross-institutional mentoring would provide mechanisms for fostering collaboration and maximizing impact.

Artificial intelligence and machine learning are expected to play important roles throughout the proposed effort. Potential applications include inverse design of photonic and plasmonic structures, optimization of photocathode synthesis and processing, automated analysis of experimental data, accelerated materials discovery and synthesis, and adaptive optimization of source operating conditions. The CART therefore offers opportunities not only to leverage AI as a research tool, but also to develop new AI-enabled approaches to scientific discovery and engineering design.

We believe that a CART focused on next-generation photoemission electron sources would provide a unique opportunity to unite multiple scientific communities around one of the major challenges in accelerator science and technology. By combining advances in materials science, photonics, nanotechnology, and artificial intelligence, the proposed effort seeks to create transformative electron source technologies that will benefit scientific, medical, industrial, and national-security applications for decades to come.

Sincerely,
Siddharth Karkare
Arizona State University
On behalf of the proposed CART team

Letter of Intent — Collaborative Accelerator Research Team (CART)

Title: *Next-Generation Digital Twin Methodologies for High-Temperature Superconducting Systems*
Topic: 2.5: Superconducting Magnets

Principal Investigator: Lance Cooley, Florida State University
Phone: 630-336-7806 **Email:** ldcooley@asc.magnet.fsu.edu
Co-Investigators and Senior Personnel: Isobel Ojalvo (Princeton University); Holger Witte (Massachusetts Institute of Technology); Nicholas Pohlman (Northern Illinois University)
National Laboratory Connections: Stoyan Stoynev, Vittorio Marinozzi, Maria Baldini, Nhan Tran, Abhijith Gadrankota, Maira Khan (Fermi National Accelerator Laboratory); Giorgio Vallone (Lawrence Berkeley National Lab) *(Lead and partner roles are being finalized.)*

Statement of Research Interests: High-temperature superconducting (HTS) technologies are enabling a new generation of high-field magnets, superconducting machinery, energy-storage systems, and power-delivery technologies. Yet their development remains limited by coupled electromagnetic, thermal, mechanical, and cryogenic behavior that is difficult to predict across conductor, device, and system scales.

This CART will establish the scientific foundations for AI-enabled digital twins of HTS systems. Building on collaborations initiated through Genesis and the DOE-HEP Magnet Development Program, the team will combine expertise in HTS materials, conductors, magnets, cryogenic systems, multiphysics simulation, experimental diagnostics, and scientific machine learning to develop predictive digital representations spanning conductor and cable physics through full magnet operation. These digital twins will integrate simulation, experimental data, and AI/ML to accelerate design, testing, commissioning, diagnostics, and operation while reducing technical risk.

Although motivated by high-field accelerator and detector magnets, the methodologies developed through this CART are broadly applicable across HTS technologies. The CART will provide interdisciplinary training in superconductivity, scientific computing, and AI/ML, helping build the workforce needed to accelerate HTS technologies from discovery to deployment.

Five-year questions we aim to investigate:

- Can first-principles multiphysics models and AI/ML surrogates be fused into digital twins?
- Can the existing wealth of conductor, cable, and magnet characterization data be collected to make the digital twins trustworthy?
- Can experimental diagnostic signals be assimilated to reliably predict instabilities, degradation, and quench/thermal-runaway?
- Can digital twins be deployed in real time for in-the-loop protection and control?
- Can a digital twin resolve the hierarchy of contributions from conductor, cable, and magnet in overall performance?
- Can surrogate and assimilation methods generalize across conductor types and architectures?

Approach and Methods: AI/ML is integral to every layer of the program. We will combine: (1) fundamental wire and cable material characterization data linking microstructure to in-field current-carrying and stability behavior; (2) improvement in high-fidelity multiphysics simulation (coupled electromagnetic and thermal, field-dependent $Ic(B,T,\theta)$, AC losses); (3) real-time data assimilation and weakly/self-supervised anomaly detection on magnet diagnostic stream, and (4) experimental validation on conductor-, cable-, and coil-scale platforms, closing the loop from synthetic to measured data. Sequence-aware architectures will capture ramp transients and history-dependent effects, and surrogates will be benchmarked for accuracy, latency, and generalization.

Transformative Impact: If successful, the CART would deliver foundational concepts and open tools for digital-twin-enabled HTS systems: shorter design-iteration cycles, predictive rather than reactive protection, deeper understanding of degradation and failure precursors, and a path to intelligent, self-monitoring operation. Because the framework spans conductor to magnet and is relevant across HTS applications, its benefits extend well beyond accelerator magnets to the wider community developing HTS for energy and science.

What We Offer: This collaboration brings together complementary expertise spanning the full conductor-to-system hierarchy of HTS technologies. MIT and NHMFL contribute decades of leadership in HTS magnets supported by NSF, NIH, and other sources external to HENP office. The collaboration will tap new and stockpiled data related to conductor, cable, and magnet development, together with experimental datasets generated through major high-field magnet development programs. These activities provide access to a strong foundation in HTS materials science, conductor characterization, and magnet performance.

Princeton contributes expertise in scientific machine learning and real time anomaly detection while Fermilab contributes expertise in AI/ML for superconducting systems, physics-informed surrogate modeling, magnet diagnostics, and experimental validation. LBNL contributes expertise in HTS conductors, high-field magnet science, and multiphysics simulation. NIU contributes a growing workforce of students able to collect, analyze, and iterate on data collected at FNAL.

Collectively, the team brings demonstrated capabilities in HTS materials characterization, magnet diagnostics, AI-enabled anomaly detection, physics-informed surrogate modeling, and coupled electromagnetic-thermal simulation. This collaboration also benefits from access to unique laboratory infrastructure, including conductor-characterization facilities, HTS test platforms, magnet-test facilities, and large experimental datasets that can be leveraged to develop and validate trustworthy digital twins. Together, these capabilities provide a unique foundation for developing predictive digital twins that connect HTS materials, conductors, cables, magnets, and cryogenic systems within a unified scientific framework.

This collaboration is positioned to deliver a high return on investment by virtue of its strong synergies with Genesis, magnet technology programs in FES and HENP, milestone initiatives in ARPA-E, and larger consortia in fusion energy, data centers, and high power-density machines. If successful, the CART will provide leveraging for significant initiatives in the areas above.

Level of effort and capabilities: The CART's intention is to build an academic complement to Genesis, LDRD, and other activities in the DOE labs. FSU would commit PI effort for overall coordination plus conductor, cable, and test coil characterization workflows; Princeton would commit PI and student/postdoc effort on AI/ML methods, surrogate development, and data assimilation; NIU would commit students available to work on-site at Fermilab and as interns at CART partners collecting and analyzing data. Fermilab and LBNL would contribute senior magnet-science, diagnostics, and HTS-conductor expertise with access to magnet-test, conductor-characterization, and instrumentation facilities. The team intends to release open surrogate models, datasets, and analysis pipelines consistent with the FOA's open-science expectations.

Workforce development: Undergraduate, graduate students and early-career researchers would train across materials, experiment, simulation, AI/ML, and accelerator science, co-advised by university faculty and national-lab scientists, with rotations between campus and laboratory test facilities.

What We Seek from Collaborators: We seek additional academic and national-laboratory partners with expertise in HTS materials and conductors, high-field magnet systems, cryogenics, multiphysics simulation, and scientific machine learning. We also welcome collaborators contributing complementary diagnostics, HTS applications beyond magnets, and workforce-development opportunities that strengthen a coordinated, multi-institution research effort.

Management and Synergy: The university lead will coordinate a shared research agenda through a steering group of institutional leads and annual milestone reviews. The proposed work builds on ongoing collaborations in HTS conductors, magnet development, AI/ML, and real-time data magnet diagnostics efforts across participating institutions.

Development of integrated HTS conductor-to-magnet technologies supported by robust AI/ML

Topic 2.5 Superconducting Magnets

Daniel Davis, Research Faculty, ASC-NHMFL-Florida State University (PI)
(850)644-1104, ddavis@asc.magnet.fsu.edu
Chiara Tarantini tarantini@asc.magnet.fsu.edu (Co-PI), Jeseok Bang (Senior)

The new R&D mission in superconducting magnet development for HENP is developing HTS (High Temperature Superconductors) magnet technologies that can outperform Nb-Ti and Nb_3Sn (LTS), in operating temperature and/or magnetic field generation. HTS has been available for >20 years, but no accelerator-relevant demonstrator exceeding LTS capabilities has yet been realized, highlighting the significant technical challenges and inefficiencies from the fragmented, sub-critical funding of recent multi-institutional development. There are two key problems that require integrated understanding: The first is to understand the conductor at a level similar to what we have of LTS and second to understand how to put the two available HTS conductors Bi-2212 and REBCO into the high stress and high quench risk magnets that HENP wants to build from them. Especially for REBCO coated conductors, maintaining consistent quality across multiple production sources is critical, requiring high-throughput, precision evaluation supporting a reliable, accessible, and developer-oriented database. This CART will build a tightly integrated multi-university effort to address the key barriers limiting HTS magnets for HENP and other applications. This proposed effort aligns very well with the core mission of the Applied Superconductivity Center (ASC) at the National High Magnetic Field Laboratory (NHMFL), which ranges from fundamental studies of LTS and HTS materials at the atomic and microstructural levels to the development and demonstration of practical conductors, cables, prototype magnets, and record-setting high-field magnets towards applications including the 32 T & 40 T user programs. ASC holds the world DC field records for R&D insert solenoids in the following classes: Bi-2212 (34.1 T) and REBCO pancake No-Insulation (>49 T) magnets inside a 31 T/40 mm bore magnet, as well as REBCO magnets made of CORC cable carrying >4 kA with current densities >250 A/mm^2 inside our 12 T/161 mm bore magnet. Furthermore, ASC's three-decades superconducting materials database provides a uniquely valuable foundation for the next-generation data-driven large-scale magnet development. All these R&D activities are underpinned by PhD, MS and BS students and postdocs, providing substantial workforce development for future generations of scientists and engineers. ASC also maintains many strong collaborations within the US Magnet Development Program, and with companies like Cryomagnetics LLC and Quantum Design-Oxford (previously OI-NS) to build commercial, compact, high-field magnet systems. We understand in our bones that **no magnet is ever better than its conductor,** so the cable/magnet design must be tailored to the conductor's properties. Accordingly, ASC focuses on understanding the conductor and building test articles with the goal to identify the strength and limitations of HTS conductors.

Key scientific questions that our recent work has raised for REBCO and Bi-2212 are: **1)** What features (microstructural, physical, or chemical) fundamentally limit current density, mechanical stability (e.g. pre-existing or stress-induced defects), and quench resilience? **2)** How can conductor architectures, insulation, strengthening strategies, and processing routes be optimized to deliver predictable, scalable, and high-performance behavior in high-field (>20–50 T) magnet environments? **3)** What conductor degradation mechanisms emerge during cable/magnet fabrication and operation (e.g., strain, thermal cycling, electromagnetic loading, quench), and how can they be mitigated through materials, conductor, cable and magnet design strategies?

Potential for use and/or development of AI/ML: We seek partner(s) who can propose an AI/ML platform with two complementary layers: (1) AI-enabled analysis of experimental data, including image analysis and metadata-driven sample tracking to enhance efficiency; and (2) a sandbox-style database in which AI operates strictly on curated internal data to minimize hallucination and protect sensitive information. This approach enables reliable data extraction and integration, bridging the gap between conductor and magnet. From the materials and conductor's perspective, our approach builds on ASC's extensive experimental database, integrating AI/ML to link microstructure, processing, and magnet performance:

- REBCO coated conductors: AI/ML will identify, classify, and quantify various defect types (processing- or stress-induced) through automated image analysis, and correlate these defects to local I_c drops along the conductor revealed by our special in-line lengthwise I_c measurements.
- Bi-2212 conductors: We will convert cross-sectional microscopic images into structured metadata, to identify phases, quantify filament bridging, and correlate such features to wire design, thermal processing, superconducting connectivity, and the critical current density (J_c), all of which are highly convoluted and could benefit from ML pattern recognition.

ASC's experimental datasets will be used to train and validate AI/ML models. By identifying the key limiting factors, this platform will enable targeted strategies to optimize conductor design, processing, and ultimately magnet system performance. From the cable and magnet design perspective, challenging factors remain for HTS: mechanical stress degradation, high AC losses and error fields, and quench management. Robust designs are necessary to prevent damaging cables, solenoids, or dipole magnets during operation. Several cables (e.g. Rutherford, CICC, CORC/STAR, untwisted stack) will be tested under realistic conditions. High-field and higher-temperature tests of multiple relevant cables wound into solenoids equipped with extensive diagnostics (aligned with the Magnet Development Program) will be performed and meta-data tagged so that AI/ML can assist in:

- Correlating local strain fields, critical current degradation, and microscopically identified cracks or conductor/wire distortions and then quantifying these defects in cable/magnet design limits;
- Predicting degradation and performance loss due to stress from cabling, thermal processing, winding, cool-down and operation; designing reinforcement strategies for cables and magnets to increase strain tolerance;
- Simulating and predicting hysteresis losses to optimize filament size and twist pitch;
- Developing early quench detection through ML training on experimental data
- Simulating, predicting, and validating quench strategy designs.

We believe that this CART will have a transformative impact by enabling reliable HTS conductors and ultra-high-field magnet technologies by developing an AI compatible handbook of how to design and construct robust R&D magnet systems. Such a database would greatly expand opportunities for next-generation magnet technologies in areas such as particle accelerators, fusion energy, medical imaging, quantum materials, and many other high-field scientific and technological instruments.

Synergy with Existing Research & Workforce Development - To potential collaborators we offer ASC integrated engineering, materials science and physics expertise, as well as advanced electromagnetic and microscopic characterizations. Our strong workforce training and mentorship means that our BS, MS, PhD and PD are ready to start CART activities from day one. (ASC-site)

We seek potential collaborators with expertise and capability in AI/ML and multi-physics modelling who can deepen understanding of HTS materials processing, complex 3D cable, and magnet construction and then test relevant to HENP applications. We expect our collaborators to host our students just as we wish to host theirs to make the collaboration efficient and fruitful.

CART management - Research tasks will be determined by expertise, capability, and research interests (e.g. materials and conductors, cable, magnets…) that align with the CART goals and resources allocated according to the level of efforts and relevance. Management will be organized in a collaborative and milestone-driven structure.

Letter of Intent: CART: Accelerating Magnet Technology and Implementation through Student Engagement and Innovation

Topic: 2.5 Superconducting Magnets

Principal Investigator: Nicholas Pohlman, Professor, Department of Mechanical Engineering, Northern Illinois University; Contact: 815-753-9913, npohlman@niu.edu

Senior Personnel at NIU:

Mechanical Engineering		Electrical Engineering		Industrial & Systems Eng.
Iman Salehinia Associate Professor isalehinia@niu.edu		Benedito Fonseca Associate Professor bfonseca@niu.edu		Christine Nguyen Associate Professor cnguyen@niu.edu

National Laboratory Connections at Fermilab:

Stoyan Stoynev stoyan@fnal.gov		Steve Krave skrave@fnal.gov		Stephen Gourlay sgourlay@fnal.gov

Funding Opportunity FOA Number: DE-FOA-0003620

The most recent roadmap of the Magnet Development Program indicates the multi-pronged approach to deliver higher field devices for a variety of future use cases in scientific discovery and fusion energy systems. In the next five years, NIU will lead and support multi-institutional teams to focus on questions around the mechanical integrity and electromagnetic performance of high temperature superconducting (HTS) magnets. Integrating multiple scales will enable investigation of mechanical degradation and delamination of REBCO and related conductors during both winding and operation, including realistic strain and fatigue limits. Additionally, localized dependence of critical current, screening current–induced fields, and quench behavior will determine field quality, protection strategies, and reliable long-term operation. The system-wide teams can increase the variety of applications that support HEP science studies and FES development for energy production.

NIU's existing partnership with Fermilab on REBCO conductor fabrication, magnet diagnostics, and operation provides a template: mixed teams of undergraduates, graduate students working alongside faculty and MDP-connected experts. The next generation of students is transitioning from digital-native to AI-native, so we will use AI and ML tools in an integrated way—for experiment design, data evaluation, and proposing revisions in magnet layouts and operating modes—rather than leaving AI as a separate research theme. A diverse bullpen of collaborators is necessary to meet the research needs while also providing broad perspective for new learners that will make up the future workforce. The combination of historical and institutional perspective from existing experts with the integrated AI toolset of the next generation users will increase innovation for application of magnets to unexpected outcomes.

The College of Engineering and Engineering Technology at NIU is the right size to readily mix faculty within the disciplines of Mechanical, Electrical, Industrial, and Mechatronics Engineering; Furthermore, existing connections with Physics and Computer Science departments can be incorporated when additional subject matter expertise is needed. The format has previously been successful under a prior DOE-RENEW grant with numerous faculty joining the initiative that followed the interest of engaged students. Contributions from multiple levels at multiple universities can be beneficial:

- Undergraduates will have option to commit some weekly effort during academic term with expansion to 100% effort during dedicated summer internships. Their fundamental questions can help avoid the stasis of "it's always been done that way…"
- Graduate students at both master's and PhD levels will be supported at 100% of available effort year-round with focused, long-term research and development projects.
- Faculty will be supported commensurate with the number of undergraduate and graduate students being mentored through CART-supported research.

The balance of number of graduate and undergraduates will depend on the rapidly changing needs of partners at Fermilab or other partner institutions to advance any of the areas of the MDP roadmap. Workforce development is similarly level-specific. Students connected to Fermilab already receive multiple elements of training:

1. Onboarding practice for employment at an academic institution, site access for national lab(s), and professional development to integrate within existing teams
2. Effective communication with technical personnel through formal and informal presentations; preparation of manuscripts for public reports or conference/journal submissions
3. Project planning and cross-pollination of technical ideas for synergistic outcomes that remix based on broad connections rather than narrowly focused results
4. Safe operation in experimental design for cryogenics, Oxygen Deprivation Hazards, and high voltage along with data collection methods for a variety of DAQ tools.

NIU partners will continue to use best practices in early-stage entrepreneurial management to invest time and energy into high-yield outcomes rather than focus solely on incremental knowledge growth. Thus, partnership with other institutions would increase the network sharing plans and outcomes that offer opportunities with greatest potential. Pitching ideas regularly to a diverse audience helps focus on the long-term benefit and also communicates where gaps can be filled with partnership. The larger collaboration can help avoid redundant work while also increasing opportunities of innovations through unexpected mixing. It has been beneficial to use a technical advisory board to review proposals bi-annually from any combination of students, faculty, and national lab personnel for entrepreneurial recombination. Those opportunities with greatest promise receive the subsequent investment allowing the financial and personnel resources to be redistributed quickly and strategically.

The next generation of workforce will need a variety of integrated tools for long-term success. Soft skills in communication and collaboration will need to be integrated with the increasing use of AI tools that fully connect to the foundational knowledge of STEM disciplines. NIU's breadth of disciplines and partnerships with national laboratories is poised to satisfy CART objectives for simultaneous workforce training and innovative research outcomes in producing superconducting magnets for the 21st century.

Advanced conductors for superconducting magnets of future particle accelerators

Topic: 2.5 Superconducting Magnets

Venkat Selvamanickam, Professor, University of Houston

Ph: (713) 743 4044; e-mail: selva@uh.edu

Our Research Interests

RE-Ba-Cu-O (REBCO, RE = rare earth) superconducting tapes were originally developed for electric power applications at liquid nitrogen temperatures in low magnetic fields. Over the past 15 years, these superconductors have been adapted for use in high magnetic fields at lower temperatures. However, critical gaps must still be bridged before REBCO superconductors become viable for the superconducting magnets used in future particle accelerators.

The focus of our planned Collaborative Accelerator Research Team (CART) is to develop, test, and validate advanced REBCO conductors that address these challenges. Our approach pairs innovative conductor designs with computational modeling, optimizes REBCO tape fabrication to realize these designs, and includes constructing and testing cables and magnets under operating conditions relevant to particle accelerators. Existing AI/ML techniques used for quality control in REBCO tape fabrication will be augmented and expanded to meet all research objectives.

We plan to investigate the following core questions:

- **Quench Stability:** How can we enhance the quench stability of REBCO superconducting magnets, and what conductor design changes will achieve this?
- **Delamination Strength:** How can we improve the delamination strength of REBCO conductors? What design changes are required, and how can we non-destructively test the delamination strength of long tapes?
- **Cable Design & Screening Currents:** Which REBCO cable designs are suitable for high currents (> 10 kA) to achieve optimal magnetic field homogeneity? What are the best conductor designs to minimize screening currents?
- **Cryogenic Insulation:** What cryogenic insulation materials and methods are most suitable for REBCO magnets?
- **High-Throughput Testing:** What is the best method to test the homogeneity of the critical current of long REBCO tapes in high magnetic fields, at low temperatures, and across multiple field orientations at a high throughput?
- **Quality Evaluation:** How can we non-destructively evaluate the quality of electrical contacts, joints, and terminations?

Transformative Impact: The CART will deliver and validate a REBCO conductor that meets the rigorous requirements of future accelerators, establishing a clear pathway for the construction of large-scale magnets.

What We Offer

The University of Houston has a proven track record of developing advanced REBCO superconductors featuring high critical currents in high magnetic fields, superior mechanical strength, quench resilience, and low AC losses.

We possess comprehensive facilities and deep expertise in reel-to-reel tape fabrication and the testing of REBCO tapes, wires, and cables. Our infrastructure includes:

- **Film Deposition:** Five reel-to-reel REBCO film deposition tools using metal-organic chemical vapor deposition (MOCVD) and pulsed laser deposition (PLD).
- **Buffer Growth & Processing:** Five physical vapor deposition tools for epitaxial buffer stack growth (four reel-to-reel and one stationary platform); reel-to-reel substrate electropolishing
- **Post-Processing:** Reel-to-reel tools for copper electroplating, silver magnetron sputter deposition, and laser slitting.
- **Measurement:** Reel-to-reel critical current measurement tools operating at 77 K (0 T) and at 65 K (up to 5 T).

Our expertise spans HTS tape fabrication, advanced characterization, electromechanical and electromagnetic testing, and coil/cable fabrication—all of which will be fully accessible to the CART. Furthermore, our workforce development offers researchers rigorous training in HTS fabrication and advanced testing, refines problem-solving skills to meet time-sensitive milestones, and provides creative opportunities to innovate solutions for complex engineering challenges.

What We Seek

We are seeking partners with expertise in:

- **Simulation & Modeling:** To drive material selection, fabrication/test tool design, and conductor/cable/magnet design.
- **Magnet Engineering:** To construct and test magnets utilizing our advanced conductors.
- **High-Field Testing:** To conduct high-current, high-magnetic-field testing on our conductors.
- **Metrology:** Experience adapting cross-industry metrology tools.
- **Cryogenics:** Specialized cryogenic engineering expertise.

The HTS-SENSE CART: Distributed Fiber Optic Sensing and Machine Learning for Next-Generation Accelerator Magnets

Track 2: Collaborative Accelerator Research Teams (CARTs) for Long-Term Generic Accelerator Research

Kenichi Soga, Professor, University of California at Berkeley
(510) 664-7534, soga@berkeley.edu
Senior personnel: Linqing Luo, Gang Huang, Lawrence Berkeley National Laboratory

1. Statement of Research Interest

High-temperature superconducting magnets, particularly those using RE-Ba-Cu-O coated conductors, represent a paradigm shift for future high-energy physics accelerators, high-field fusion devices, and advanced medical gantries. Despite their potential to operate at unprecedented magnetic fields and elevated cryogenic temperatures, these magnets face severe operational risks. The slow quench propagation velocity makes conventional voltage-tap detection methods inadequate, risking localized thermal runaway and catastrophic, irreversible magnet damage. Consequently, there is an urgent need for advanced, non-invasive diagnostic tools capable of monitoring temperature, mechanical strain, and quench initiation in real time across the entire volume of the magnet structure.

The acronym HTS-SENSE represents our focus on High-Temperature Superconducting magnets using a System for Embedded Non-destructive Sensing and Evaluation. The mission of our CART is to develop the fundamental distributed diagnostics technology, operational safety methods and associated workforce that will be required for the high-field HTS magnets to enable future accelerator facilities.

Over the next five years, our CART foresees investigating several critical scientific and engineering questions. We will examine how distributed fiber optic sensors behave under extreme mechanical strain and intense ionizing radiation over extended operational lifetimes, and how to decouple temperature and strain signatures in cryogenic environments. We will also investigate the optimal physical integration methods to embed optical fibers directly within REBCO-based winding packs without introducing mechanical defects or compromising electrical insulation. Our proposed approach uses high-speed optical frequency domain reflectometry and Rayleigh backscattering to achieve millimeter spatial resolution of thermal and mechanical variations along the conductor. If successful, the transformative impact of this CART will be the realization of a self-monitoring, fail-safe HTS magnet technology, effectively eliminating the risk of catastrophic thermal runaway and paving the way for magnets operating routinely beyond 20 T.

2. What we can offer for the collaboration and what we seek from the collaboration

To achieve our long-term research goals, my team at UC Berkeley and collaborators at Lawrence Berkeley National Laboratory offer substantial expertise and state-of-the-art capabilities to potential collaborators. We will make available our expertise in cryogenic fiber-optic sensor calibration, high-resolution optical interrogation, and specialized HTS coil fabrication technologies. We commit to a level of effort equivalent to two full-time senior scientific staff members, two postdoc scholars, and two PhD graduate students dedicated to this initiative. We offer robust workforce development opportunities, including structured research internships for undergraduate students, co-advising arrangements for graduate students, and hands-on research focused on advanced diagnostics for HTS magnets.

To complement our capabilities, we seek collaborators who can offer complementary expertise, facilities, and educational frameworks. Specifically, we are looking for collaborators with access to high-energy protons or neutron irradiation facilities to perform in-situ testing of fiber survivability. We also seek partners with deep expertise in advanced finite element modeling of coupled electromagnetic-thermal-structural phenomena in HTS coils to help validate our experimental sensor data. Collaborators who can offer expertise in HTS cable manufacturing, such as CORC®, STAR® round wires and stacked-tape cables, are also highly desired to effectively develop and apply our diagnostic capabilities.

3. Workforce development

Workforce training is an integral part of our CART, with UC Berkeley serving as the primary hub for cultivating the next generation of accelerator scientists and engineers. We will leverage our unique position as a world-class research university to offer robust educational and research opportunities. This includes recruiting undergraduate and graduate students from the UC Berkeley Departments of Physics, Nuclear Engineering, Mechanical Engineering, and Electrical Engineering and Computer Sciences to participate directly in hands-on research. Graduate students will benefit from a joint-mentorship model, co-advised by UC Berkeley faculty and senior scientists at Lawrence Berkeley National Laboratory, bridging the gap between academic learning and large-scale national laboratory research environment. Furthermore, we will actively recruit diverse talent by partnering with established UC Berkeley diversity initiatives, such as the Summer Research Opportunity Program and the Compass Project, to provide research pathways for underrepresented minorities in STEM. Postdoctoral scholars in this program will receive comprehensive mentoring in project management, grant writing, and interdisciplinary collaboration, preparing them for leadership roles in academia, national laboratories, and private industry.

4. Potential management of CART collaboration and resource allocation

To ensure the success of this multi-institutional effort, the CART will be managed through a structured and collaborative governance model. We propose establishing an executive steering committee comprised of principal investigators from each participating institution, which will meet quarterly to choose research tasks, allocate resources based on project milestones, and evaluate technical progress. Resource allocation will be tied directly to a peer-evaluated gating process, ensuring that funding is dynamically directed to the most promising and impactful research pathways. This research is highly synergistic with the U.S. Magnet Development Program, sponsored by DOE Office High Energy and Nuclear Physics, allowing us to leverage shared laboratory infrastructure, and existing university-national laboratory collaboration to maximize the impact of the CART collaboration.

5. Application of the AI/ML for the proposed research

The integration of artificial intelligence and machine learning (AI/ML) tools is a fundamental part of our research strategy. The massive volume of high-frequency spectral data generated by distributed fiber optic sensors requires automated, real-time processing that exceeds the capabilities of traditional deterministic algorithms. We will utilize machine learning models to perform rapid data filtering, feature extraction, and pattern recognition to distinguish benign mechanical shifting from early-stage quench initiation. Beyond using existing tools, our CART will actively pursue the development of novel AI/ML methods designed specifically for transient cryogenic sensor data, enabling predictive health monitoring and automated fault-recovery protocols for HTS magnets in radiation environment.

Project Title: AI-Assisted Design and Low-Temperature Manufacturing of Strain-Compatible A15 Nb_3Sn Films on Copper for Next-Generation SRF Cavities

Track/Topic: Track 2: FY2027 CART/Topic 2.6 Superconducting RF

Lead Institution: Virginia Tech
Principal Investigator (PI): Wenjun (Rebecca) Cai, Associate Professor, Materials Science and Engineering, Virginia Tech, Office Phone: (540)-231-5697, email: caiw@vt.edu
Co-PI: Mitsu Murayama, Professor, Materials Science and Engineering, Virginia Tech
Co-PI: Qi An, Associate Professor, Materials Science and Engineering, Iowa State University
Co-PI: Lin Li, Associate Professor, School for Engineering of Matter, Transport and Energy, Arizona State University
Collaborators: Drs. Hui Tian, Michael J Kelley, Rongli Geng, Thomas Jefferson National Accelerator Facility

This LOI outlines the formation of a FY2027 CART focused on developing a transformative **low-temperature manufacturing pathway** for A15 phase Nb_3Sn superconducting coatings on copper substrates for next-generation superconducting radio-frequency (SRF) accelerator technologies. The proposed effort directly supports DOE Accelerator Stewardship priorities in superconducting RF materials and manufacturing. It also integrates artificial intelligence and machine learning (AI/ML) into process optimization, workforce development, and interdisciplinary education.

Nb_3Sn is a highly promising superconducting material for future SRF accelerators because of its higher critical temperature and potentially lower cryogenic operating costs compared with Nb cavities. However, current Nb_3Sn coating technologies typically rely on vapor diffusion or other high-temperature processing routes at approximately 1100–1200 °C. Such high manufacturing temperatures are not only close to the melting point of copper substrates (1084.62 ºC), but also generate residual stress/strain in Nb_3Sn coating when cooled down from the manufacturing temperature to the cryogenic operating temperatures. The large thermal expansion mismatch between the brittle A15 Nb_3Sn and ductile Cu phases leads to high residual stress, interfacial debonding, cracking, and degradation of superconducting performance. Recent study shows that, for a 2 μm thick Nb_3Sn film to remain crack-free, the residual strain must stay within a limited range: no more than 2.3% compressive strain and no more than 0.9% tensile strain [1].

The **central hypothesis** of this CART is that low-temperature electrochemical synthesis of Nb-Sn coatings, combined with physics-informed AI-guided manufacturing and interface engineering, can dramatically reduce residual thermal stress accumulation while enabling strain-compatible, crack-free Nb_3Sn/Cu architectures with improved superconducting performance. Compared with high temperature vapor diffusion or physical/chemical vapor deposition methods, low-temperature electrochemical deposition [2, 3] offer several potential advantages, including (1) **low residual strain** (due to manufacturing temperature ~ 25 ºC), (2) **uniform coating thickness** on complex substrate geometries (due to electrode potential/current control), and (3) **scalable manufacturing**. However, the formation of a pure A15 Nb_3Sn phase through this approach has not yet been demonstrated, highlighting the need for systematic studies to precisely control stoichiometry through electrochemical potential and current regulation. Previously, the PI's group developed three patents (WO Patent 2013/066454, US Patent 14/935,398, US Patent 15/749,165) related to the room-temperature electrodeposition of Al–Mn alloys/multilayers and Al–Ni alloys using ionic liquids. These studies demonstrated that alloy composition can be precisely controlled by tuning the electrolyte chemistry (such as pH) and using pulsed-potential deposition (e.g. by tuning the duty cycles at Al and Ni reduction potentials). This prior work provides a strong practical foundation for the proposed study.

A statement of specific research interests – Over the next five years, the proposed CART will investigate several fundamental scientific questions related to the low-temperature manufacturing of superconducting Nb_3Sn coatings for SRF accelerator applications. A central question is how electrochemical processing can enable the direct formation of strain-compatible A15 Nb_3Sn coatings on Cu substrates. This includes understanding Nb and Sn co-reduction mechanisms and electrochemical phase formation pathways. The project will further investigate how electrochemical potential and current, electrolyte chemistry, and non-equilibrium growth conditions influence stoichiometry, phase stability, and suppression of competing Nb–Sn phases. A second major research direction focuses on the mechanisms governing residual stress generation, strain compatibility, interfacial stability, and crack formation in Nb_3Sn/Cu systems. The CART will study how nanoscale defects, grain boundary, and microstructural heterogeneity contribute to stress accumulation. A third major thrust involves the development of physics-informed AI/ML frameworks for accelerated coating manufacturing and optimization. The project will establish multimodal datasets linking electrochemical processing conditions, phase evolution, microstructure, interface chemistry, residual stress states, and superconducting performance metrics. These datasets will be integrated with computational thermodynamics, atomic simulations, and ML approaches to establish predictive processing–structure–property relationships to rapidly optimize manufacturing windows. If successful, the CART could have transformative impact by establishing a fundamentally new low-temperature manufacturing pathway for superconducting Nb_3Sn coatings compatible with scalable and complex SRF cavity fabrication.

Collaborations and team management – The CART offers potential collaborators complementary expertise spanning electrochemical synthesis, electron microscopy, computational materials science, mechanics, and AI/ML-assisted materials discovery. Prof. Cai (Virginia Tech) will lead the overall effort and contribute expertise in electrochemical synthesis, ionic liquid processing, and AI-assisted materials design. Prof. Murayama (Virginia Tech) will provide advanced transmission electron microscopy capabilities for nanoscale structural and defect characterization. Prof. An (Iowa State Univ) will contribute computational thermodynamics, density functional theory, and AI-guided phase stability modeling. Prof. Li (Arizona State Univ) will contribute residual stress analysis and interfacial mechanics modeling. Scientists at Jefferson Lab will provide SRF application guidance and unique superconducting characterization infrastructure for evaluating Nb_3Sn coatings under accelerator-relevant conditions.

The CART will also provide substantial workforce development opportunities through interdisciplinary training. Graduate/undergrad students and postdocs will receive hands-on training in electrochemical processing, superconducting characterization, electron microscopy, computational materials science, and AI-assisted materials discovery. Through this CART, the team seeks additional collaborators with expertise in superconducting accelerator technologies, electrochemical manufacturing, in situ and operando characterization, quantum materials, and scalable manufacturing. The team also seeks access to complementary national laboratory infrastructure, and advanced superconducting testing capabilities.

The CART will be managed through monthly cross-institutional virtual meetings, annually in-person workshops, shared milestones, and coordinated experimental–computational research tasks designed to promote rapid feedback between synthesis, characterization, modeling, and SRF performance evaluation.

References: [1] Wang, Z. et al., *Improvement of Surface Roughness and Cracking Study of Nb_3Sn SRF Films.* Materials Science *Applied Sciences* **2025**, *15*, 1991. [2] Sun, Z. et al., *Smooth, Homogeneous, High-Purity Nb_3Sn Superconducting RF Resonant Cavity by Seed-Free Electrochemical Synthesis. Superconductor Science and Technology* **2023**, *36* (11), 115003. [3] Franz, S. et al., *Electrochemical Synthesis of Nb_3Sn Coatings on Cu Substrates. Materials Letters* **2015**, *161*, 613–615.

SRF-CART:
From Fundamental Research in RF Superconductivity and Material Growth to Designer Nanostructured Surfaces with Enhanced SRF Performance

Topic number and name: 2.6 Superconducting RF
Principal investigator: Matthias Liepe, Prof. of Physics, Cornell University
PI contact information: 607 255 4951, MUL2@cornell.edu

List of Co-Investigators and Senior Personnel	
Institution Name	**Co-Investigators and Senior Personnel**
Cornell University	Matthias Liepe, David Muller
Old Dominion University	Jean Delayen, Alex Gurevich
University of Maryland	Steven Anlage
University of Florida	Richard Hennig

Specific research interests: Superconducting Radio-Frequency (SRF) resonators are a cornerstone technology of modern particle accelerators with a wide range of applications. These include fundamental sciences, industrial, medical, and defense applications, as well as quantum information technology. Developing new ways of optimizing next-generation superconducting surfaces can result in transformative gains in SRF cavity performance - higher quality factors, reduced cryogenic costs, and higher gradients. This SRF-CART will be a transdisciplinary research program in fundamental SRF science and materials.
Mission: To develop theoretical and experimental tools needed for the design of superconducting materials and thin films with enhanced and tailored SRF performance. To develop and realize next-generation superconducting surfaces needed for science and industry accelerators. To educate a cadre of scientists with competence in SRF science and technology and allied disciplines.
5-year research vision: This SRF-CART will collaborate to achieve new scientific breakthroughs in understanding the fundamental issues that govern SRF performance. Specifically, our vision for the 5 years includes the following high-impact research topics: (1) Mechanisms determining the fundamental limits of RF dissipation and the accelerating gradient in SRF cavities. This includes both the conventional Nb cavities operating at 2 K and higher-T_c materials such as Nb_3Sn, Nb-Zn alloys, Nb_3Al and others to provide extremely high quality factors at higher temperatures. (2) Detrimental effects of current-blocking structural defects such as grain boundaries and non-superconducting nanoprecipitates. (3) Nonlinear losses of trapped vortices driven by strong RF currents. (4) Theory of nonlinear electromagnetic response under strong RF filed including realistic strong electron-phonon coupling and nonequilibrium kinetics of quasiparticles augmented by DFT and machine learning to optimize the RF losses. (5) Understanding the fundamental mechanisms of losses in superconductors by measuring the surface resistance in wide ranges of RF fields and temperatures, including mK temperatures. (6) New ways of boosting SRF performance by nanostructuring the surface of a superconductor. This includes engineering an optimum density of quasiparticle states by forming a controlled distribution of appropriate atomic impurities at the surface and deposition of nm thick metallic or superconducting overlayers or multilayer structures. (7) High-performance thin-film superconductors on copper substrate.
Impact: This SRF-CART will deepen fundamental understanding of SRF materials and superconductivity in the presence of strong high frequency fields, providing greater predictive power. It will improve materials formation to further advance the performance of next-generation SRF surfaces tailored to specific applications. If successful, this CART will result in transformative SRF surfaces that will be the foundation for SRF cavities for new generations of scientific accelerators (including future accelerator projects involving DOE offices of NP, HEP and BES). It will benefit quantum information technology and medical applications and will make SRF cavities widely available, so that this powerful technology is no longer restricted to a few user facilities. This SRF-CART will train students and young researchers in SRF research and technology, who will fill a critical need for the U.S. DOE National Laboratories and the U.S. workforce. Results obtained during this project will be disseminated through scientific publications and conference presentations and transferred to the U.S. national labs, industrial partners, and academia.

Investigator and institutional capabilities: This Collaborative Accelerator Research Team brings together expertise and state-of-the-art techniques and tools in superconductivity theory, AI-driven and ab-initio materials science, materials growth, atomistic to mesoscale characterization, microwave microscopy, and experimental SRF science and technology. Both experimental and theoretical parts of this project will be integrated to provide the necessary inputs for further developments. For instance, the three-dimensional electron microscopy and scanning RF probe experiments of RF vortex entry and pinning properties will give inputs for DFT calculations of structural defects and for the theory to develop predictive models of surface optimization. The measurements of surface resistance in a broad range of temperatures will give key information about nonequilibrium kinetics and relaxation times. In turn, theoretical advances will guide the experiments on SRF cavities and surface nanostructuring. The synergy of the experimental, theoretical and computational work amplified by the expertise of the team members in their respective areas will provide a unique opportunity to address outstanding issues of SRF technology which cannot be addressed by individual investigators.

Workforce development in SRF science and technology will be one of the foundations of this program. Through closely integrated and interdisciplinary team science, and by leveraging of the existing DOE Accelerator Traineeship programs at ODU and Cornell, this CART will provide unique opportunities to students and early-career scientists.

Potential collaborators: We are interested in considering additional potential collaborator(s), particularly in the area of advanced thin-film growth.

Management plan: Cornell University will serve as lead institution and accept overall management responsibility. A Strategic Plan will provide direction for the SRF-CART's research and will be updated annually to respond to discovery and the evolving priorities in the world of accelerators. The revision process will be guided by an External Advisory Board (EAB) and will be finalized at an annual in-person SRF-CART meeting. The EAB will provide high-level guidance and evaluates progress. Senior investigators and students will submit annual internal progress reports. Semi-monthly meetings will ensure research coordination and tight collaborations among SRF-CART members.

Synergies: This SRF-CART will be a synergistic complement to ongoing activities at the partner institutions. Specific examples are the development of frameworks linking predictive AI and first-principles simulations at the University of Florida, developing quantitative electron microscopy methods for measuring and predicting materials properties at Cornell, Nb_3Sn-based SRF technology development at Cornell, development of SRF technology for a future HEP collider and industrial applications at Cornell, and DOE Accelerator Traineeships at Cornell and ODU.

AI/ML: The Hennig group has developed the UF3 framework for ultra-fast machine-learned interatomic potentials that can reach DFT accuracy while enabling molecular dynamics of up to $\sim 10^9$ atoms. Building on this capability, the SRF-CART will extend UF3 to the Nb–Sn chemistry (and related Nb–Zr and Nb_3Al systems) and use it to model the nucleation, Sn diffusion, and growth processes that set Nb_3Sn film structure. Coupling these atomistic simulations to AI-accelerated mesoscale microstructure-evolution models will let us predict the defects that limit SRF performance, e.g., tin-depleted regions, antisite disorder, and grain boundaries, and link them quantitatively to the superconducting properties computed by the theory groups. This closed loop from first principles to microstructure to RF response anchors our "SRF designer materials" goal, and the AI/ML methods advanced here, such as the active learning for training-set generation, uncertainty quantification, and inverse design of surface impurity and overlayer structures, will be delivered as transferable tools for the accelerator-materials community. The Muller group's electron ptychography enables 3D imaging with sub-Ångstrom lateral and nanometer-scale depth resolution. Currently, ptychography data acquisition takes a few seconds, but the reconstructions take several hours. They have recently developed AI-enabled algorithms to reduce this thousand-fold time mismatch and automate the data acquisition. The resulting three-dimensional data sets contain information about millions of atoms and are well suited for AI-based data segmentation, classification and quantification.

Title of LOI: Modeling sheet-to-cavity fabrication to enable tuning-free SRF structures
Track # 2 CARTS / Topic # 2.6: Superconducting RF – Advanced techniques for cavity fabrication
PI: Boyd Panton, Assistant Professor, The Ohio State University (OSU)
PI Contact Information: 614-687-8870, panton.7@osu.edu
Co-PI: Dr. Taejoon Park, Research Associate Professor, OSU
Co-PI: Dr. Farhang Pourboghrat, Professor, OSU
Co-PI: Dr. Paul Carriere, SRF Fabrication Engineer, Thomas Jefferson National Lab (JLab)

Specific Research Interests

The team proposes to develop a comprehensive modeling framework that enables manufacturing niobium (Nb) superconducting radiofrequency (SRF) cavities that do not require frequency tuning. This framework will require advancing the fundamental understanding of forming, machining, and welding processes which are critical to the SRF structure. Manufacturing the SRF cavities to precise dimensions is critical to achieving target frequencies; however, a standard final operation for the cavities is frequency tuning via high skilled artisanal deformation of the cavity structure. Compounding this bespoke finishing process is the heavy reliance on trial-and-error methods and specialized expertise as the current standard for SRF cavity manufacturing. These trial-and-error methods are costly and increasingly unsustainable given Nb's expense and a declining availability of skilled workforce. While prior research including DOE funded work has advanced knowledge of Nb metallurgy and deformation behavior, significant gaps remain in understanding the complex multi-axial forming, machining, and electron beam welding (EBW) processes specific to SRF applications. Building on existing work, this research aims to develop predictive, science-based tools to enable efficient, optimized design and manufacturing of SRF cavities and cryomodules. Physics informed AI/ML will be integrated into this effort to reduce experiments and multiphysics models.

Research Interests:

1) Integrated system of multiphysics and AI/ML models (i.e. forming, machining, EBW, and metrology) to fabricate from initial sheet material to final cavity
2) Investigating the applicability of surrogate alloys and processes for Nb cavity manufacturing
3) Engineering and scientist workforce upskilling with integrated model framework

Research Questions Investigated in the Next 5 Years

1) Can an integrated system of multiphysics and AI/ML models be developed that can enable the evolution of SRF fabrication from an art to a science, eliminatoing the need for frequency tuning?
2) Can surrogate materials (i.e. aluminum, copper) be used to build this integrated system of models, and can these models then be translated to Nb SRF cavities?
3) Can this integrated modeling framework be used to reduce the time for training or amount and level of talent needed for the SRF cavity workforce?

Proposed Approaches and Methods

Integrated System of Models: The proposed research will use a hybrid experimental-multiphysics model-AI/ML model framework. These seamlessly connected models will include forming, machining, EBW, and metrology. Metrology is a critical area of research due to the dependence of cavity frequency on geometry. While coordinated measuring machines (CMM) are the gold standard for metrology full measurement of all parts between manufacturing processes would be prohibitively costly and time consuming. Research in this area will include identification of critical features and translation of CMM to methods that can capture these features with a lower cost, less time, and less skill. These measurements will inform the model of any modifications required before and between each manufacturing process to avoid the cumulative effect of dimensional errors. This will also develop model – process – structure (geometry) – frequency relationships.

Physics Based AI/ML: Experiments will be used for verification and validation of multiphysics models. The multiphysics models will be used to increase the dataset available for development of the AI/ML models. These multiphysics models have heavy computational needs. The AI/ML model will be able to guide the next iterations of the multiphysics models and experiments. The end goal will be inverse predictions with input required geometries resulting in and output of the necessary manufacturing process variables. The models will also enable investigation of conditions not possible in the experimental setup.

Surrogate Materials: Nb has a very high cost and is also difficult to obtain. This work proposes to use aluminum and/or copper as surrogate materials. The model framework will be built using these surrogate materials, and then they will be translated to Nb. Particular interest will be paid towards what material and manufacturability properties are of highest importance in this translation process. This will have an added benefit of reducing the amount of Nb data required to verify and validate the models.

Surrogate Process: Access to EBW is very restricted due to the high use of the equipment at Jefferson Lab for the Electron Ion Collider project. Other DOE lab partners also have very high use of their equipment. These labs are high use and do not have excess personnel to be assigned to these research projects. The team proposes to use laser beam welding of the surrogate materials to avoid dependency on EBW systems. This will enable rapid advancement of research, which will then be translated to EBW. This will have an added benefit of reducing the amount of EBW data required to verify and validate the models.

Workforce development: The team has a history of workforce development including scientists, engineers, and trades people. Our workforce development has spanned high school interns, undergraduate researchers, graduate researcher associates, and postdoctoral fellows. We are integrated with state and local workforce organizations. The multi-university, national lab, and industry team will enable the study of training with the various models and research topics across the different levels of personnel involved.

Transformative Impact of Proposed CART Research

1) Evolve the SRF cavity fabrication from an art to a science by developing a comprehensive sheet-to-cavity multiphysics AI/ML model framework (i.e. forming, machining, welding, metrology).
2) Eliminate the need for Nb SRF cavity frequency tuning.
3) Enable prototype development with surrogate materials and processes.
4) The framework will reduce the cost of SRF cavity manufacturing, reduce the learning curve for the workforce, and be broadly applicable to other advanced manufacturing of national interest.

Collaboration

Our Strengths: Our current team includes leading scientists in modeling and experimental forming, laser and EBW, and advanced SRF cavity fabrication. We have experience with a range of materials including aluminum, copper, and Nb. Our capabilities include advanced characterization systems, forming equipment, laser welding equipment, and limited access to EBW equipment at Jefferson Lab. The team has a history of workforce development discussed in detail above.

Our Needs: We are seeking collaborators with expertise in machining, metrology, physics/materials informed AI, and industrial partners who design or manufacture SRF cavities or components. They will need to have access to advanced manufacturing research facilities that can support the required work.

Proposed CART Management

The management structure for the CART will include a governing board led by OSU. This board will consist of PIs from all academic institutes and subs. The board will meet monthly to report on progress. A partial staff member at OSU will support coordination, reporting, and evaluation. Research tasks and resource allocation will be determined prior to submission, and the project will run accordingly.

Synergy with Other Research and Workforce Development Efforts

The proposed CART research team has been selected as the leading scientists in their respective fields. The proposed research builds on pillars of their careers. Science and engineering workforce training will occur through CART funded work, and complimentary funding on synergistic projects. Forming, machining, EBW, and metrology are enabling technologies that are widely required across nationally important sectors. Synergic research will continue across the DOE, the DOW, and private industry.

Predictive Understanding of the Electrodynamic Consequences of Inhomogeneity in Superconductors for Accelerator Applications

Topic: 2.6 Superconducting RF

PI: Mumtaz Qazilbash, Professor, Department of Physics, William & Mary
PI Phone number: (757)221-3542, PI E-mail address: mmqazilbash@wm.edu
Co-investigators: Rongli Geng, SRF S&T Department Head, Jefferson Lab; **Enrico Rossi**, Professor, Department of Physics, William & Mary; **Jigang Wang**, John and Mary Weaver Professor, Department of Physics and Astronomy, Iowa State University, and Group Leader, Light-Matter Quantum Control, Ames National Lab

Motivation and Opportunity - Superconductors such as Nb_3Sn, NbN, and NbTiN are among the most promising materials for next-generation accelerator technologies due to their high critical temperatures, large superheating fields, and favorable electrodynamic properties. These materials are also representative of a broader class of technologically important superconductors whose performance is governed by structural and electronic disorder spanning multiple length scales. A persistent challenge in superconducting materials science is understanding how defects, grain boundaries, strain fields, vacancies, and off-stoichiometric regions influence superconducting electrodynamics. While significant advances have been made in materials synthesis and characterization, no predictive framework currently exists that connects microscopic disorder landscapes to macroscopic electromagnetic response. As a result, optimization of superconducting materials remains largely empirical. This challenge is particularly important for superconducting radio frequency (SRF) accelerator technologies, where RF surface resistance, vortex penetration, dissipation mechanisms, and ultimately cavity performance are determined by low-energy electrodynamic processes occurring at nanometer to micrometer length scales. Understanding how inhomogeneities including disorder affect superconducting electrodynamics is therefore essential for realizing the full potential of Nb_3Sn and related materials for future accelerator facilities. Similar challenges arise in superconducting detectors, quantum devices, and high-field superconducting technologies. Establishing predictive structure-property relationships for disordered superconductors thus represents a cross-cutting scientific opportunity with broad relevance across the DOE mission space.

Scientific Vision - We propose a Collaborative Accelerator Research Team (CART) focused on developing a predictive understanding of superconducting electrodynamics in the presence of inhomogeneities. This objective will be achieved over a 5-year period through the integration of broadband optical measurements, nanoscale imaging, pump-probe spectroscopy, materials synthesis, microscopic theory, and physics-informed machine learning. The central hypothesis of this CART is that spatial variations in heterogeneous superconductors strongly affect the physics and performance of SRF cavities while at the same time generating measurable electrodynamic signatures that can be used to establish predictive relationships between microstructure and electromagnetic response. We will investigate how grain boundaries, compositional heterogeneity, strain, and defects influence the electrodynamics of accelerator-relevant superconducting thin films, including Nb_3Sn, NbN, and NbTiN. The project will combine, in a tight experiment-theory feedback loop, complementary experimental and theoretical capabilities unavailable within any single institution. Altogether, these efforts will establish a quantitative framework linking disorder landscapes to superconducting RF electrodynamics and accelerator-relevant superconducting performance metrics.

Research Thrusts

Thrust 1: Broadband Infrared and THz Spectroscopy – William & Mary will perform broadband infrared and THz spectroscopy of Nb_3Sn, NbN, and NbTiN thin films under cryogenic temperatures and magnetic fields. These measurements will determine electronic behavior including optical conductivity, superconducting gap characteristics, quasiparticle scattering rates, superfluid density, and collective excitations as functions of composition, processing history, and disorder. Particular emphasis will be placed on identifying spectroscopic signatures associated with disorder-induced pair breaking and superfluid suppression, vortex penetration, and emergent electrodynamic behavior relevant to SRF performance.

Standard experiments for chemical and structural characterization of films will continue within the present cooperative arrangement between Jefferson Lab and the Applied Research Center at William & Mary.

Thrust 2: Cryogenic Near-Field THz Imaging and Ultrafast Dynamics – Iowa State University/Ames National Laboratory will employ cryogenic infrared and THz near-field nanoscopy, operating at 1.8 K and under a magnetic field up to 5 T, to directly image nanoscale variations in superconducting response. These unique measurements will reveal how local structural, grain-boundary, and compositional inhomogeneities modify superconducting properties at length scales relevant to electronic heterogeneity and coherence length thereby providing unprecedented insight into local electrodynamic behavior. In addition, ultrafast pump-probe optical measurements under magnetic fields will reveal nonequilibrium quasiparticle dynamics and vortex-related dissipation in inhomogeneous superconductors.

Thrust 3: Accelerator-Relevant Materials Synthesis and Characterization – Jefferson Lab will provide expertise in SRF materials science, superconducting film synthesis, and accelerator applications. The laboratory will synthesize and characterize accelerator-relevant superconducting films and materials platforms, including Nb_3Sn-based systems directly relevant to future SRF technologies. These materials will provide the foundation for experimental investigations and ensure that the scientific advances generated by the CART remain closely connected to critical challenges in accelerator science and technology.

Thrust 4: Theory and Physics-Informed Machine Learning for Inhomogeneous Superconductivity – Theory efforts at William & Mary will focus on developing a general theoretical framework to quantify the role of different types of inhomogeneities in the electrodynamics of accelerator-relevant superconducting thin films. Such a framework will be developed and refined by directly comparing its predictions to spectroscopy and nano-imaging measurements. The framework will then be used to design a machine-learning (ML) approach capable of inferring the makeup of the inhomogeneities present from the measured electrodynamics of an SRF cavity. The problem is ideally suited for an AI approach given that (i) it can be viewed as a “tomographic reconstruction” problem, a problem that AI networks excel at solving, and (ii) a very large number of training sets can be created by theoretically simulating the cavity electrodynamic response for different disorder configurations. The theoretical-computational-AI approach will provide a powerful, flexible tool to characterize and optimize superconducting thin films and SRF cavities in realistic conditions, where the effect of inhomogeneities cannot be neglected.

Workforce Development and Training - Workforce development will be an integral component of the CART. Graduate students and postdoctoral researchers will receive interdisciplinary training spanning superconducting materials science, accelerator physics, optical spectroscopy, nanoscale imaging, theory, and AI/ML-enabled scientific discovery. The collaboration will provide opportunities for cross-institution mentoring, collaborative research projects, and participation in accelerator-science activities at Jefferson Lab. Through exposure to complementary experimental, theoretical, and computational approaches, trainees will develop the broad skill set needed to contribute to future accelerator facilities and the broader superconducting technologies workforce.

Expected Outcomes and Relevance to DOE Accelerator Stewardship - This CART will establish a rigorous scientific foundation for understanding disorder-modified superconductivity in accelerator-relevant materials. The resulting framework will be broadly applicable to complex superconductors and other quantum materials in which emergent properties arise from spatially heterogeneous electronic states.

The proposed research addresses a fundamental and generic challenge in accelerator science: understanding how microscopic inhomogeneities control the electromagnetic properties of superconducting materials used in advanced accelerator technologies. The collaboration leverages complementary expertise at William & Mary (lead institution), Jefferson Lab, Iowa State University/Ames National Lab to create a strong, multidisciplinary team with the breadth of expertise needed to execute the proposed research program. The project directly supports the goals of the CART program by advancing cross-cutting accelerator science, developing predictive scientific frameworks, integrating AI/ML into accelerator research, and training the next generation of researchers at the intersection of accelerator technology, superconducting materials, and spectroscopy- and data-driven discovery.

SRF Cavity Performance Improvement through Optimization of Microstructure

Topic: 2027 Track 2 CART topic 2.6 Superconducting RF

PI: Eric M. Taleff, Professor, The University of Texas at Austin
Phone: 512-471-5378; Email: taleff@utexas.edu

Co-investigators:
1. Shreyas Balachandran, Associate Professor, College of Engineering, FAMU-FSU, Florida State University.
2. Philip Eisenlohr, Associate Professor, Michigan State University
3. Pashupati Dhakal, Senior Staff Scientist (SRF), Thomas Jefferson National Accelerator Facility

Summary of proposed research:

Research to date has unambiguously established the important role of microstructure, particularly grain structure and dislocation substructure, in limiting the highest performance of Nb superconducting radio frequency (SRF) cavities. For example, dislocation substructures in unrecrystallized regions of the microstructure can trap magnetic flux, leading to lower quality factors and restricting accelerating gradients, especially in the dirty superconducting limit. Controlling microstructure during the fabrication and processing of traditional Nb SRF cavities is essential to reducing the non-BCS components of surface resistance and consistently achieving a high quality factor ($Q_0 > 5\times10^{10}$ at 2 K and 25 MV/m) and high accelerating gradient ($E_{acc} > 40$ MV/m). Translating the scientific understanding of these effects into practical material standards, fabrication guidelines, and heat-treatment and surface-processing methods remains a non-trivial challenge for consistently producing high-performance SRF Nb cavities at reduced cost. The importance of these issues extends beyond traditional Nb SRF cavities into SRF applications that will use Nb_3Sn coatings on Nb and bimetallic concepts using Cu and Nb (Cu+Nb) to enable novel cooling strategies. Because Nb still serves as the base material in these applications, controlling Nb microstructure to achieve consistently high performance remains a key issue in these new SRF structures. Moreover, it is not only the initial microstructure in an SRF cavity that determines its lifetime performance, but also largely unexplored changes during service due to irradiation, high-cycle fatigue and small-scale plasticity within the first 1 to 2 µm of the surface (electromagnetic pressure can easily create stresses of 50 to 100 MPa at 2 K) that produces damage at the grain scale and smaller, which may be important to observed degradations in cavity performance during service. Both the change in near-surface microstructure and associated changes in microscopic surface morphology, such as intrusions and extrusions from cyclic dislocation slip events, may affect performance. We hypothesize that these effects will be particularly important to cavities that use Nb_3Sn coatings, which generally have low ductility.

We propose a program of research that addresses three critical areas relevant to Nb-based SRF cavities.
1. We will use the principles of physical and mechanical metallurgy to translate current scientific understanding for the effects of microstructure on SRF performance into practical standards and guidelines for consistently producing high-performing SRF cavities. We will work with a domestic supplier of ASTM Type 5 Nb sheet, ATI Specialty Alloys & Components (Albany, OR) and its research metallurgist, Dr. Matthew Carl, to develop new strategic material processing and fabrication routes that enable the consistent production of high-performing Nb SRF cavities at reduced cost.
2. We will extend our understanding of the processing of Nb SRF cavities into the processing of large-scale Cu+Nb bimetallic materials for low-frequency SRF structures as an alternative to Nb thin film on Cu strategies. This will require new strategies for controlling the microstructure in bimetallic structures to achieve superconducting performance comparable to that of traditional Nb SRF cavities.
3. We hypothesize that dislocation substructure developed from small-scale plastic deformation at the grain level and smaller during service may be a mechanism important to the degradation of SRF cavity performance. We suggest that this mechanism may be particularly important to Nb_3Sn coated

Nb cavities. We propose to investigate the role of small-scale plasticity, which can occur during cavity installation, tuning, maintenance, or actual service (the latter raising the possibility of fatigue), in performance over the life of SRF cavity operation.

Our approach to this research is to integrate the diverse set of expertise, experience, and technical capabilities available within our team. Eric M. Taleff, project lead, brings experience in physical and mechanical metallurgy, metals processing, mechanical testing, and microstructure characterization. His facilities at The University of Texas at Austin bring unique capabilities for processing and testing materials at high temperatures under vacuum. Shreyas Balachandran brings expertise in microchemical and microstructure characterization, cryogenic mechanical testing, and physical property measurements. His facilities at Florida State University include unique capabilities for low-temperature testing and measurements as well as microstructural characterization. Philip Eisenlohr brings expertise in computational micromechanics and crystal plasticity. His facilities at Michigan State University include capabilities to simulate complex crystal plasticity problems. Pashupati Dhakal brings deep expertise in Nb SRF cavity fabrication and performance. His facilities at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) include capabilities for fabricating and testing full cavities.

The proposed research has the potential to produce several transformative impacts important to DOE and its facilities. These include the following.

1. Improve capabilities to consistently fabricate traditional Nb SRF cavities with high performance.
2. Lower the cost of traditional Nb SRF cavities while developing a reliable domestic Nb vendor.
3. Enable the production of Cu+Nb bimetallic structures with Nb microstructures that consistently produce SRF performance equivalent to that of traditional Nb SRF cavities.
4. Produce strategies to reduce performance degradation in Nb_3Sn coated Nb cavities through an improved understanding of mechanisms that cause performance degradation during service.

These impacts are likely to extend beyond SRF applications into areas such as quantum information systems.

Openings for potential collaborators:

Our team welcomes collaborators with expertise in Nb-based SRF cavity fabrication, service, performance measurement, and performance degradation during service. We see a strong potential for collaboration with the DOE Facility for Rare Isotope Beams (FRIB) on the MSU campus, which has a long history in the design and use of Nb accelerator cavities. Controlling microstructural features to improve SRF cavity performance is a challenging, multi-length-scale problem, and collaborations with computational physicists and theorists in this area would be highly beneficial.

Other:

Research activities will be guided by input from stakeholders at DOE facilities (e.g., Jefferson Lab and other potential DOE partners) and from industry (ATI). The PI team will meet regularly through video conference to assess progress, update tasks and goals, and refine research directions.

Synergies important to this team include activities at the National High Magnetic Field Laboratory, the Applied Superconductivity Center at Florida State University, and the wealth of activities at Jefferson Labs.

AI/ML tools will be an integral component in these research activities. Machine learning algorithms offer unique capabilities for interpreting the complex microstructures produced during the processing of Nb-based materials and structures for SRF applications. These algorithms also offer methods for sifting out important correlations from the extremely complex relationships among material processing, microstructures, and the properties they produce. We further envision that the proposed research will produce datasets essential for training AI/ML tools for future DOE activities.