Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

Strategic Plan, 2021-2026

Vision and Mission

Vision

Gain the fundamental understanding needed to transform the brightness of electron beams available to science, medicine, and industry.

Mission

Transform the reach of electron beams by advancing fundamental knowledge and applying it to increase beam brightness x100 and reduce the cost and size of key enabling technologies. Ensure that these new approaches are realized in operating accelerators by transferring the best of them to national labs and industry. Educate and inspire a diverse generation of students to prepare them for a broad set of career paths including leadership in interdisciplinary team science.

CBB's scientific advances are extending the capabilities of the approximately 15,000 U.S. researchers who rely on large particle accelerators to advance the frontiers of physics, chemistry, materials science, biology, and medicine [1]. CBB's research will reduce the cost and improve the performance of small laboratory instruments and industrial tools, as well as large colliders and X-ray sources. CBB will help realize university-scale X-ray FELs capable of femtosecond imaging; ultrafast electron diffraction set-ups that can image not only nanoscale, but also molecular assemblies; and electron microscopes equipped with bright sources that directly investigate phonon-coupling dynamics, opening new pathways for quantum materials [2]. Brighter beams in future electron-ion colliders will unlock the secrets of the "glue" that binds the building blocks of visible matter in the universe; and simpler, cheaper designs may enable an electron-positron collider that glimpses closer to the big bang. CBB will also extend the capabilities of beams available to medicine and industry, which currently operate 30,000 accelerators and add 10 new ones each day [3]. Areas of growth include semiconductor fabrication, metrology, and new green technologies. These advances are CBB's *outcome legacy* and realizing them depends on effective Knowledge Transfer to national labs and industry.

Large-scale colliders, intense X-ray sources, and electron microscopes are essential tools for science and industry, yet the U.S. educates few students to understand the bright electron beams

on which they depend for success. Approximately a dozen U.S. universities offer doctoral degrees in accelerator science [4], together producing 15–20 doctoral accelerator scientists per year; but the estimated need at labs and in industry is four times that number [4]. CBB graduate students are helping to bridge this gap, and its undergraduates are considering accelerator science as a potential career path. Importantly, approximately half of CBB's students are in areas that the Department of Energy has identified as areas of critical need (*physics of large accelerators and systems engineering* and *superconducting radiofrequency accelerator physics and engineering*) [5]. Other CBB students are opening new areas of research in condensed matter and surface physics. This is CBB's *convergence legacy*. In addition to their subject area training, CBB students integrate professional development with their research and become experienced in the practice of team science. CBB partners with University of Puerto Rico at Mayagüez, Clark Atlanta University and Florida International University in its research and educational programs. As a result, CBB is bringing welcome diversity to accelerator science and other related disciplines.

Table I. CBB institutions, senior investigators, and their indispensable expertise.

Partner	Project Leaders	Indispensable Expertise
ASU	Karkare, Padmore	Photoemission and electron transport
BYU	Transtrum	Theoretical condensed matter physics
UCLA	Musumeci, Rosenzweig	Photoinjectors, xFELs
U Chicago	Kim, Sibener	Particle physics, surface chemistry
Cornell	Arias, Bazarov, Hines, Liepe, Maxson, Muller, Sethna, Shen	Electronic structure calculation, photoemission sources & electron transport, surface characterization, SRF acceleration, ultrafast electron microscopy, electron microscopy, condensed matter theory, ARPES
U Florida	Hennig	Materials design
FNAL	Posen	SRF cavities
U New Mexico	Biedron	Free-electron lasers; artificial intelligence/machine learning
NIU	Chubenko	Photoemission and electron sources

Guiding Principles

CBB is a close knit, interdisciplinary team whose success depends on both individual discovery and close collaboration between researchers leading to a constantly expanding web of knowledge – advances that would normally be out of reach for single research group. CBB actively builds collaboration and counts on the participation of each individual in an environment that allows them

to reach their full potential. Through intensive dialogue, CBB research is informed by and shared with the wider community so that its advances are put to use in accelerators at national labs, universities, and industry.

With these aspirations in mind, CBB is guided by the following principles.

1. Research alignment - projects will address Center Outcomes and will be aimed at gaining a fundamental understanding of the phenomena that limit accelerator performance, and at using that understanding to overcome those barriers.
2. Team science - Every project will be uniquely suited to a Center in that it will depend for success on the diverse expertise of at least two team members, typically from distinct disciplines.
3. Program evolution - The research program will be dynamic, responding to new opportunities, reacting to new insights into the needs of beam users from industry and national laboratories, and moving on when projects come to completion or no longer bear fruit.
4. Civic engagement - Participants will participate fully in activities within their Theme and across the Center in order to build a coherent, collaborative community and capitalize on opportunities at the intersections of the themes.
5. Diversity - Participants will commit to diversity, and to gaining the awareness and knowledge needed to create an environment in which students, postdocs and faculty of all races, ethnicities, religious beliefs, and genders can thrive.

Optimal Outcomes

1. **Beam Production (PHC)**: The understanding, materials, and technology necessary to produce the brightest possible electron beams across the wide span of beam currents, pulse durations, and operating environments demanded by forefront scientific research and emerging technological applications.

2. **Beam Acceleration (SRF):** The advanced methods and surfaces for next-generation SRF cavities that will enable game-changing reduction of cooling power needs (10× lower than traditional bulk Nb cavities), will enable higher temperature operation (well above the 2.17K Lambda point of liquid helium), and will provide higher accelerating fields (2× higher than traditional bulk Nb cavities) for lower cryogenic system costs, energy sustainability, and simpler refrigeration.

Generation of brighter beams will have a long-standing impact on the NSF Big Ideas of "Understanding the Rules of Life" and the "Quantum Leap."

3. **Beam Dynamics and Control (BDC):** Methods for beam transport that preserve beam quality of x100 brighter beams in linear accelerators and electron microscopes and x10 brighter beams in storage rings: Brightness conservation of beams from extreme-low mean-transverse-energy (MTE) linac sources subject to intense Coulomb interactions (*Conserve*), increased brightness of beams in storage rings (*Cool*), and advanced techniques for the optimization of many-parameter accelerators (*Control*). By ensuring that CBB advances in beam production and beam acceleration are realized in brightness at the target, this theme unifies the center's research.

CBB's team science approach is motivated by the **Growing Convergence Research** NSF Big Idea, which informs our research and education objectives and activities and is stimulating new areas of research in disciplines such as condensed matter physics and surface science.

4. **Workforce Development (WD):** Effective CBB collaborations across disciplines and institutions based on the successful application of team science and training that cultivates and intellectually diverse workforce.

5. **Diversity (D):** Measurable impact on the participation of underrepresented groups in sciences and technology, particularly in accelerator science, with the goal of exceeding national metrics in the field of physics.

6. **Knowledge Transfer (KT):** The transfer of CBB-developed knowledge, methods, and workforce to other research groups, national labs, and industry. This transfer is based on joint research, strong community involvement, and the publication of results in diverse journals, international workshops, and conferences.

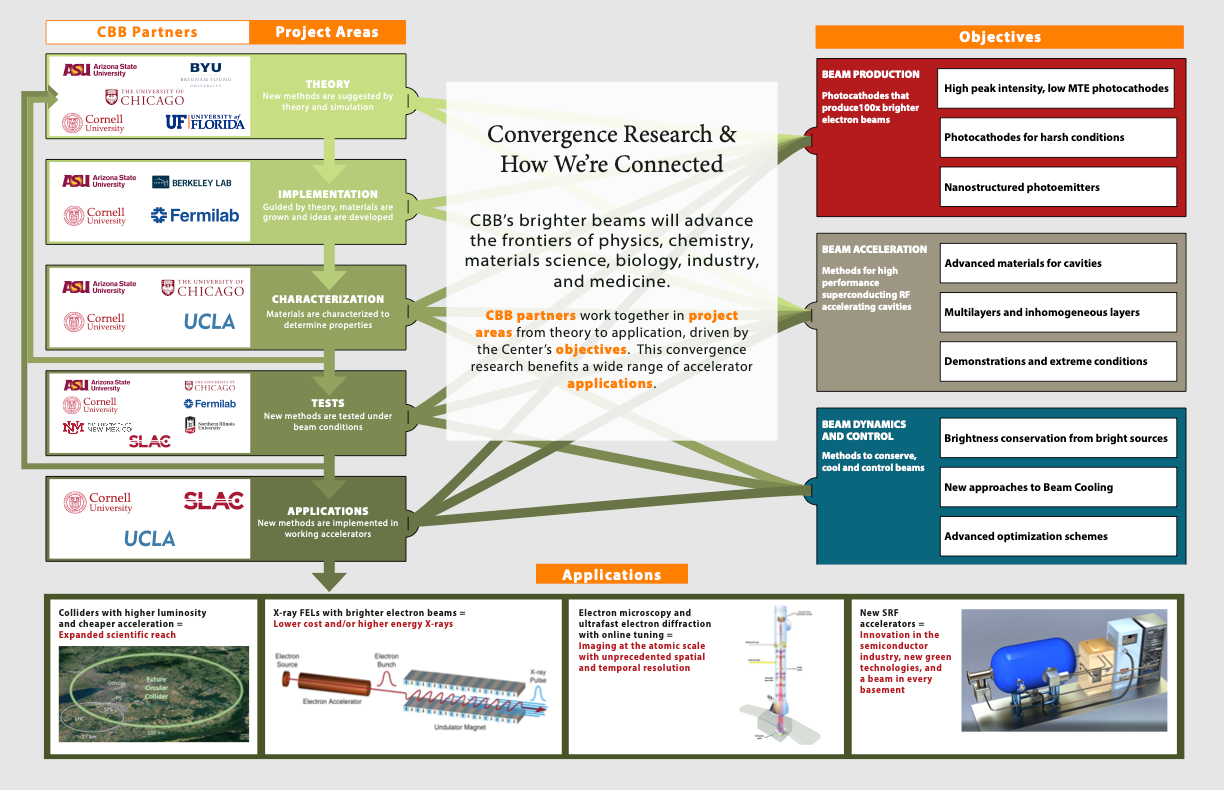

Figure 1. CBB research roadmap. CBB activities in the project areas (left) advance CBB towards it objectives (right). The objectives have been selected to benefit a wide range of beam applications (bottom).

RESEARCH:
Performance Objectives and Deliverables

CBB's research is guided by its objectives and deliverables. Each deliverable requires the combined expertise of multiple CBB PIs, who contribute by developing theory, growing or characterizing samples or prototypes, assessing performance, and ultimately putting CBB methods into place in working systems. The CBB research roadmap, shown in Figure 1, illustrates these activities and their interconnections.

BEAM PRODUCTION

Optimal Outcome: The understanding, materials, and technology necessary to produce the brightest possible electron beams across the wide span of beam currents, pulse durations, and operating environments demanded by forefront scientific research and emerging technological applications.

Objective 1: Develop photocathodes for high peak-intensity beam generation with low Mean Transverse Energy (MTE) and good quantum efficiency (QE).

Deliverable 1.1: A photocathode with MTE < 35 meV and QE $> 10^{-3}$ at low or moderate laser fluence and at room temperature (**Fall 2025**)

> **Plan:** CBB has demonstrated MTE of 47 meV and QE > 10^{-3} in a Cs_3Sb photocathode grown on an STO substrate. A CBB atomically ordered Cs_3Sb photocathode with near-zero physical and chemical roughness [6] will be tested in a TEmeter and if ordering is sufficient, theory shows that CBB will meet this deliverable. We will also test K_2CsSb and Na_2KSb, as well as other novel materials, for low MTE and high QE close to threshold.

Deliverable 1.2 (Priority): A photocathode with MTE < 35 meV and QE $> 10^{-3}$ at laser fluences in excess of 50 μJ/cm^2 by developing cryo-cooled single-crystal, epitaxial alkali antimonides or other materials **(Fall 2026**)

> **Plan:** Such a photocathode is likely to be an epitaxial, high quantum efficiency, semiconducting photocathode, and for ease of use, it will ideally have significant response with visible or near-IR light. Target materials include epitaxial alkali antimonides, including Cs_3Sb, which has been experimentally demonstrated.
>
> **End User:** This photocathode is envisioned for applications such as the LCLS-II-HE SRF photoinjector. IDES/JEOL has also expressed interest in implementing such a photocathode in one of its electron microscopes. This photocathode would also be required

for a potential CBB demonstration of high current and low emittance (see *BDC Deliverable 1.2*). Finally, this cathode will be implemented in the MEDUSA beamline at Cornell, where success may inspire other scientists to adapt their ultrafast electron diffraction (UED) and ultrafast electron microscopy (UEM) beamlines to accommodate the photocathode and a suitable laser. The transfer of this technology is *KT Deliverable 2.1*.

Risk: The primary risk is that at the photoemission threshold, the multiphoton response of the epitaxial photocathode may be larger than predicted, which will spoil the MTE. Examples of other phenomena that might increase the MTE to above-predicted values are non-idealities in the experimental band structure, defects in the lattice, or surface contaminants producing surface non-uniformities.

Mitigation: If Cs_3Sb (for example) suffers from higher than predicted multiphoton photoemission, CBB will direct effort to characterize the source of the unexplained excess. In the case of surface contamination, CBB will theoretically survey and grow epitaxial compounds that are less reactive, such as sodium-based alkali antimonides, or CsSb. In the case of nonidealities in the experimental band structure, CBB will also explore alternative epitaxial compounds. In addition, CBB will explore methods by which to engineer away the nonidealities or their effects, such as by inducing strain or changing the emission crystal face, among other techniques. Finally, in all cases, CBB can additionally engineer hetero-structured photocathodes with low electron affinity to increase QE and thereby reduce the need for high laser fluence. This will delay the completion of this Deliverable until 2025 or 2026, depending on the obstacle. The additional effort or hardware will be redirected from Deliverable 1.3, 3.2 or 3.3, depending on whether the obstacles relate to photoemission theory, growth, or test facilities.

Deliverable 1.3: First principles predictions of MTE and QE spectral response for relevant photocathode materials **(Fall 2026)**

Plan: Develop theoretical techniques to explain the process of photoemission as it is relevant to photocathodes and test them experimentally.

Objective 2: Design materials for long-lived cathodes in extreme electric field and high average current

Deliverable 2.1 (Priority): Photocathode that can operate for >1 week with MTE <35 meV at 50 $\mu J/cm^2$ laser fluence and high field (>50 MV/m) for high peak current applications such as compact XFELs (**Summer 2025**)

Plan: This photocathode is a more advanced version of the photocathode in *PHC Deliverable 1.2*. CBB will pursue multiple approaches including developing 2-D material coatings such as single-layer graphene or hexagonal boron nitride on high QE alkali-

antimonide materials, exploring new alkali antimonides like CsSb and Na_2KSb or III-Nitride based semiconductors, or developing new robust work function reducing layers for GaAs or other III-V materials. Testing at high fields is *BDC Deliverable 1.3* and has been done in the high-field PEGASUS beamline at UCLA, where they have enabled larger charge generation and a series of new free electron laser experiments. A new cryogenic RF photocathode gun test system is being commissioned at UCLA (CYBORG). In addition, photocathode tests at ANL's AWA are planned for January 2025.

End User: This photocathode will be critical for the realization of advanced accelerators such as compact X-ray FELs and would benefit large low rep-rate X-ray FELs such as FLASH if they were modified to accept such photocathodes. The transfer of this technology is *KT Deliverable 2.2*.

Risk: There is a risk of QE reduction and MTE increase due to surface effects/reconstructions/impurities and scattering during emission from coated cathodes. Imperfect coverage by the capping layer could result in penetration of contaminants causing QE degradation. Delamination of 2-D coverage layers can occur in high-field environments.

Mitigation: Mitigation is achieved by using multiple approaches and testing various systems/protection mechanisms simultaneously as stated in the plan. Additionally, as CBB observes failures of the approaches being tried out, CBB will investigate the reasons for the failures, both theoretically and experimentally and try to mitigate them. CBB can also employ QE enhancement techniques via optical or plasmonic effects and try to design/modify electron guns or the operating conditions to mitigate the QE/MTE degrading effects. Because compact X-ray FELs photocathode are still under development, and therefore the need for this photocathode less urgent than the photocathode for Deliverable 1.2, CBB will reevaluate our level of effort and the specific target in 2024. Resources could be shifted from Deliverables 1.3, 3.2 and 3.3 to achieve this deliverable if necessary.

Deliverable 2.2 (Priority): Photocathode that can operate for >1 week with MTE <100 meV and QE>1% under high average current (>10 mA) conditions (**Summer 2026**)

Plan: CBB is pursuing multiple approaches. One approach is to apply 2-D material coatings like single layer graphene or hexagonal boron nitride to high QE alkali-antimonide materials. CBB has demonstrated single layer graphene protection of arbitrary air-sensitive metallic photocathodes via a new technique for graphene transfer (patent applied for) and is now applying the procedure to alkali antimonide photocathodes. It is also developing theoretical methods for predicting transmission through these layers.

CBB is also exploring new alkali antimonides such as CsSb and Na_2KSb or III-Nitride based semiconductors, and is developing new robust work function reducing layers for

GaAs or other III-V materials. Successful high-current testing of GaAs photocathodes activated with Sb-O-Cs exhibit lifetimes up to 50% better compared to Cs alone [7].

Testing is being done in the HERACLES facility at Cornell, which delivers high power electron beams from a DC gun. This work is *BDC Deliverable 1.3*.

End User: BNL electron cooler for the Electron Ion Collider at BNL. The transfer of this technology is *KT Deliverable 2.3.*

Risk: There is a risk of QE reduction and MTE increase due to surface effects/reconstructions/impurities and scattering during emission from coated surfaces. Imperfect coverage by the capping layer could result in penetration of contaminants causing QE degradation. Ion back bombardment in high current can cause any nm-scale heterostructures to break and surfaces to deform.

Mitigation: Mitigation is achieved by using multiple approaches and testing various systems/protection mechanisms simultaneously as stated in the plan. Additionally, as CBB observes failures of the approaches being tried out, CBB will investigate the reasons for the failures, both theoretically and experimentally and try to mitigate them. CBB can also employ QE enhancement techniques via optical or plasmonic effects and try to design/modify electron guns or the operating conditions to mitigate the QE/MTE degrading effects. Resources could be shifted from Deliverables 1.3, 1.4, 3.2 and 3.3 to achieve this deliverable if needed.

Objective 3: Approach fundamental brightness limits with nanostructured photoemitters

Deliverable 3.1 (Priority): A photoemission electron source with sub-100 nm spot size (**Summer 2025**)

Plan: DONE. CBB used a spiral photocathode with plasmonic focusing to obtain a 100 nm spot size. The 4D brightness reached 120 electrons/nm^2 with emittance less than 60 pm-rad [8]. CBB is also exploring an alternative approach using nano-scale work-function patterning using an impurity-free nanofabrication process.

End User: This source targets ultrafast electron microscopes and electron energy loss spectroscopy (EELS) systems, including ultrafast electron microscopes operating in stroboscopic regime and ultrafast EELS systems. A stretch goal is continuous beam electron microscopy. The transfer of this technology is *KT Deliverable 2.4.*

Deliverable 3.2: An electron source with normalized transverse emittances approaching the thermal limit of 25 meV or less, depending on system temperature, for single electron per bunch beams (**Fall 2026**)

> **Plan:** Use tip-based photocathodes to produce emittances at this scale of 10 picometers. This goal is achievable with current methods and measurement tools. This objective requires activities and investment in source fabrication (ie, nanolithography), theoretical computation of photoemission performance, surface characterization, and ultimately beam generation with low emittance diagnostics, such as photoemission electron microscopy. This technology would benefit ultrafast electron microscopes operating in stroboscopic regime and ultrafast EELS systems. Continuous beam electron microscopy is a stretch goal.

The Beam Production deliverables and their timelines are shown in Figure 2.

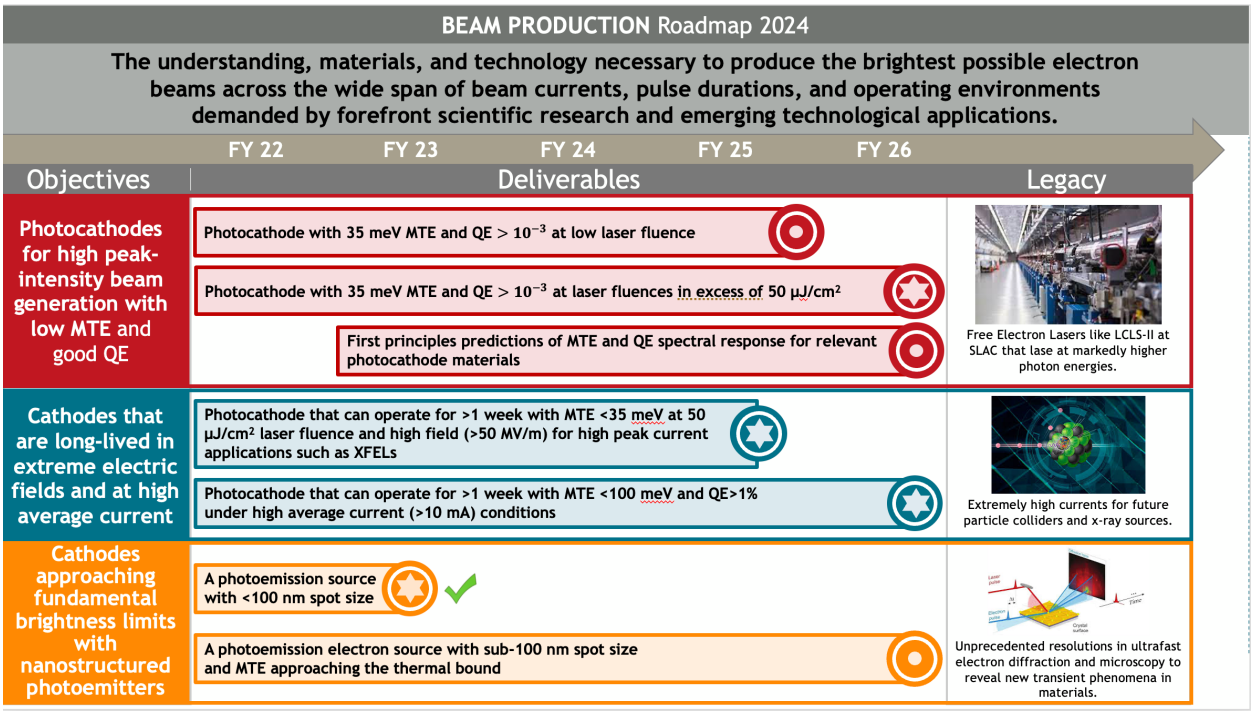

Figure 2. The Beam Production roadmap.

BEAM ACCELERATION

Optimal Outcome: The advanced methods and surfaces needed for next-generation SRF cavities that enable game-changing reduction of cooling power, higher temperature operation, and higher

accelerating fields for lower cryogenic system costs, energy sustainability, and simpler refrigeration.

Objective 1: Advanced SRF materials growth: Developing improved growth methods and understanding the impact of realistic (non-ideal) surfaces on performance.

Deliverable 1.1 (Priority): Methods of growth and their refinement leading to annually significantly enhanced performance for Nb_3Sn on Nb and Cu substrates (**Annual**)

> **Plan:** In a tight feedback loop, CBB will identify sources of performance limitation of current Nb_3Sn films and develop mitigation methods, i.e., improved growth methods and protocols for this material.
>
> **End User:** Industry and national labs supplying and processing SRF cavities. The transfer of this technology is *KT Deliverable 2.5*.
>
> **Risk:** Achieving high-quality Nb_3Sn coatings that support RF performance approaching the predicted ultimate limit of this material will require growth control well beyond what is currently achievable. Within the timeframe of CBB, further advancements in Nb_3Sn growth should be expected, but the rate of progress and the size of the resulting RF performance gains are punctuated in time and are difficult to predict.
>
> **Mitigation:** CBB is exploring a range of Nb_3Sn growth methods to maximize the likelihood of achieving improved Nb_3Sn films with enhanced RF performance. CBB has the required broad range of expertise in theory, material growth, and surface characterization to systematically advance this material, and efforts could be further focused on Nb_3Sn as the priority material in later years if necessary to deliver Nb_3Sn ready for adoption by labs and industry.

Deliverable 1.2: Methods of growth and their refinement leading to annually significantly enhanced performance for Nb-Zr alloys (**Annual**)

> **Plan:** CBB predictions show that Nb-Zr alloys may hold great promise but are currently in the early phase of their development as an SRF material, and performance impacting mechanisms and defects are currently being uncovered. In a tight feedback loop, CBB will predict the performance potential of Nb-Zr alloys, develop and improve growth methods and protocols for this novel material, and determine RF performance. The end users of this activity are industry and national labs supplying and processing SRF cavities.

Deliverable 1.3: Determination whether other materials have potential for higher efficiency and/or higher fields above Nb_3Sn and Nb-Zr limits (**Fall 2025**)

Plan: CBB will predict the performance potential of novel SRF materials (beyond Nb, Nb_3Sn, and Nb-Zr). Theory will calculate thermodynamics and superconducting properties from first principles. These calculations will be paired with multi-scale, continuum models to extrapolate these properties to relevant performance metrics. Theory and experiment will work together to study surface/interfacial electron-hole pair coupling effects. The tight feedback loop between theory and experiment will help to restrict the search space. This deliverable is an intermediate step that will guide the choice of materials selected for the pursuit of Objective 3.

Objective 2: Multi-layers and inhomogeneous layers: Increasing RF performance via surfaces by design.

Deliverable 2.1: Determination whether inhomogeneous surface layers can offer significantly increased RF performance over homogeneous materials (**Fall 2024)**

Plan: CBB will use a combination of theory and experiment to understand the role of layered effects on RF performance. On the theory side, CBB uses mesoscopic models to conduct numerical experiments of performance for various layer configurations. CBB uses ab initio calculations to understand and leverage the inverse-Q phenomenon. On the experimental side, CBB will study surface oxides and conduct RF performance tests on layered systems. This deliverable is an intermediate step that will guide the choice of materials selected for the pursuit of Objective 3.

Objective 3: Higher efficiency and higher fields: Demonstrate higher RF performance in proof-of-principle SRF cavities and study RF superconductivity under extreme conditions.

Deliverable 3.1 (Priority): Surfaces from non-Nb with cooling power <4W/(active meter)/$(MV/m)^2$, corresponding to a 10x reduction in cooling power (**Fall 2026**)

Plan: CBB will synthesize compact proof-of-principle SRF cavities using the optimal protocols and materials developed under Objective 1. CBB will then use these to demonstrate reduction in cooling power. These activities will be accompanied by development of relevant theories of superconductivity to predict RF dissipation and by advanced surface characterization to identify structures and inhomogeneities that limit cavity performance.

End Users: Industry and national labs supplying and processing SRF cavities. Future SRF driven accelerators running in CW mode, including compact SRF accelerators for industrial applications, e.g., for wastewater treatment. The transfer of this technology is *KT Deliverable 2.5*.

Risk: The primary risk is related to transferring CBB's high-efficiency surfaces from small samples to the larger size and complex shape of an SRF cavity. Growth method(s) might have to be adjusted and re-optimized to achieve uniform high-quality films. Residual loss mechanism will have to be controlled to fully utilize the low BCS surface resistance of the compound higher-T_c superconductors.

Mitigation: Risk is reduced by developing multiple Nb_3Sn growth methods that offer different advantages in scaling up to full cavity size. If needed, effort could be focused on achieving highly efficient cavity operation at the cost of reducing effort on pushing maximum $_{fields}$ above 50 MV/m (Objective 3.3).

Deliverable 3.2 (Priority): Non-Nb, high efficiency surfaces capable of sustaining an accelerating field of 25 MV/m (**Fall 2023**)

Plan: CBB will synthesize compact proof-of-principle SRF cavities using the optimal protocols and materials developed under Objective 1. CBB will then use these to demonstrate and study operation of non-Nb surfaces at medium accelerating fields. These activities will be accompanied by development of relevant theories of superconductivity and by advanced surface characterization to identify structures and inhomogeneities that limit maximum fields of non-Nb surfaces.

End User: Industry and national labs supplying and processing SRF cavities. Future SRF driven accelerators running in CW mode, e.g., a future circular collider (FCC). The transfer of this technology is *KT Deliverable 2.5*.

Risk: Recent improvements in Nb_3Sn growth have brought this deliverable within close reach. Another iteration in improving Nb_3Sn growth for reduced surface roughness and/or optimized film thickness is needed, and the rate of progress is difficult to predict.

Mitigation: Risk is reduced by exploring multiple directions in improving Nb_3Sn growth for higher maximum fields. If additional time is needed to complete this objective, effort on achieving maximum fields above 50 MV/m could be temporarily reduced.

Deliverable 3.3: Non-Nb surfaces supporting accelerating fields exceeding 50 MV/m (**Fall 2026**)

Plan: CBB will synthesize samples and proof-of-principle SRF cavities using the optimal protocols, laminates, and materials developed under Objectives 1 and 2. CBB will then use these to probe superconductivity under extreme conditions and to demonstrate surface fields exceeding those required for 50 MV/m accelerating fields. CBB will measure maximum flux-free fields and compare results with theoretical predictions. These surfaces would benefit pulsed linacs requiring high field gradients, such as a linear collider and compact, pulsed X-ray FELs.

The Beam Acceleration deliverables and their timelines are shown in Figure 3.

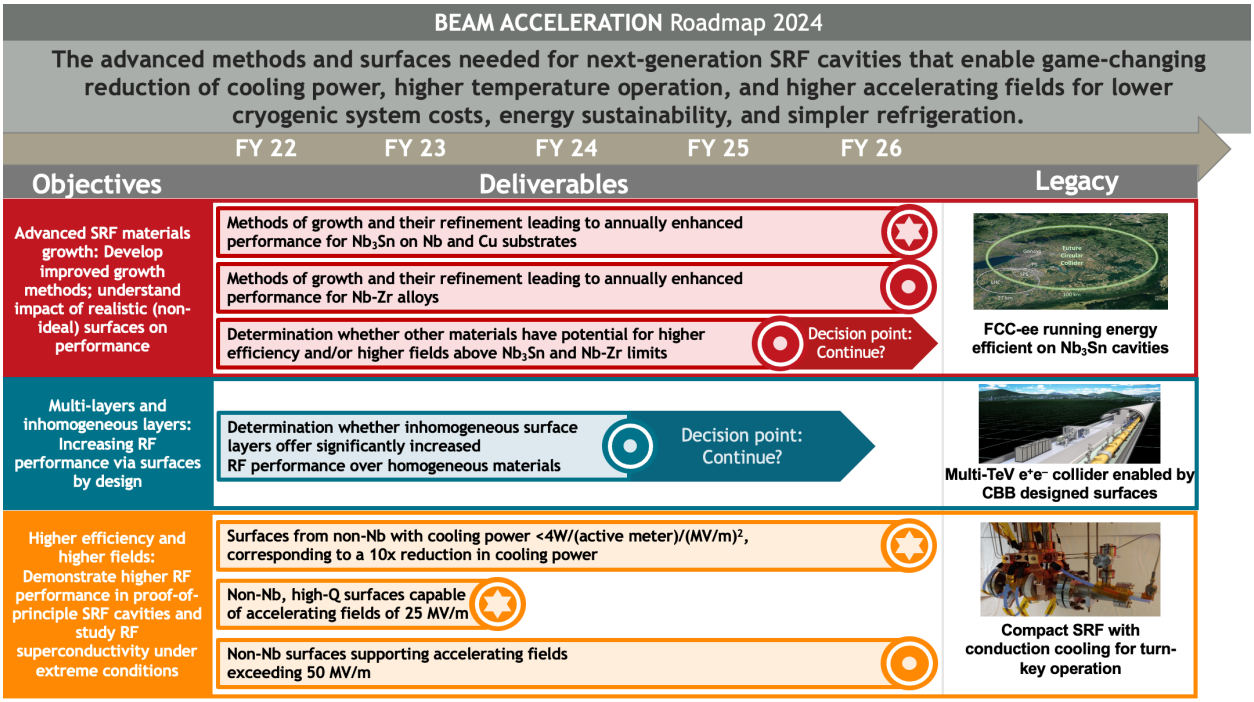

Figure 3. The Beam Acceleration roadmap.

BEAM DYNAMICS AND CONTROL

Optimal Outcome: Brightness conservation of beams from extreme-low MTE linac sources subject to intense Coulomb interactions (*Conserve*), increased brightness of beams in storage rings (*Cool*), and advanced techniques for the optimization of many-parameter accelerators (*Control*). By ensuring that CBB advances in beam production and beam acceleration are realized in brightness at the target, this theme unifies the center's research.

Objective 1 (Conserve): Probe the ultimate limits of brightness conservation in the presence of collective effects in low MTE photoinjector beamlines.

Deliverable 1.1: Simulation of two beamlines showing reduced emittance due to low MTE photocathodes **(2022)**

> **Plan: DONE.** CBB simulations of an injector for LCLS-II-HE demonstrated that the emittance of the produced beam was reduced when using a very low MTE photocathode. MTE as low as 10 meV affected the resulting emittance. Simulations of a low bunch charge UED beamline also showed sensitivity of the emittance to the photocathode MTE [9].

Deliverable 1.2: Experimental demonstration of sub-nanometer emittance in at least one beamline with low bunch current with improvements thereafter (**Fall 2026**)

> **Plan: DONE.** CBB demonstrated the generation of sub-nanometer emittances at the MEDUSA beamline at Cornell at low bunch charge (Q ~ 500 e) [10]. Experiments are underway at other CBB beamlines with the goal of systematically improving the beam brightness ($B \propto Q/\varepsilon^2$), leveraging the continuous development of photocathodes under *PHC Deliverables 1.1* and *1.2* and special capabilities such as the cryogenic operation of photocathodes that are available at some of CBB's facilities.

Deliverable 1.3 (preliminary): Identification of beamlines for a potential experimental demonstration of the simultaneous generation of low emittance and high bunch charge (~100 pC), using CBB low-MTE photocathodes and diagnostics, that when coupled with a bunch-compression beamline would produce beams with 5D normalized brightness $\hat{I}/\epsilon_\perp^2$>10^{15} Am^{-2} (**Spring 2023**)

> **Plan: DONE**. CBB simulated beamlines to which CBB has access including PEGASUS, the FAST-IOTA injector, ANL's AWA, and the UCLA C-band cryogun (CYBORG) and determined that CBB could conduct or participate in a convincing demonstration of the scientific reach of CBB low MTE photocathodes (*PHC Deliverable 1.2*). This built on earlier CBB demonstrations in simulation of the impact of low MTE photocathodes for an SRF gun for LCLS-II-HE and a beamline for ultrafast electron diffraction (UED) [9].

Deliverable 1.3 (Priority): Experimental demonstration of the simultaneous generation of low emittance and high bunch charge (~100 pC) at Fermilab's FAST, ANL's AWA or UCLA's PEGASUS using CBB technology (**Spring 2026**).

> **Plan:** Demonstrations at AWA and PEGASUS have proved feasible in simulation and we are now designing the experiments. CBB scientists are also exploring a possible demonstration at FAST and will pursue it if approved by Fermilab.

Deliverable 1.4: Characterization and specification of the performance of photocathodes in either high field or high current conditions as needed to complete *PHC Deliverables 2.1* and *2.2* (**Annual, starting 2023**)

> **Plan:** Robust photocathodes developed under *PHC Deliverables 2.1* and *2.2* will be tested at high current (>10 mA) using facilities such as the HERACLES beamline (Cornell) and at high gradient using the PEGASUS beamline (UCLA) and CYBORG (UCLA). Low-MTE cathodes grown at Cornell have been transported to UCLA and tested in the PEGASUS high gradient gun, but show some degradation in performance. The AWA facility may be available for high gradient testing and has the advantage of being nearer

Cornell. We will also test the performance and ruggedness of graphene-coated cathodes in a poor vacuum environment and/or high-gradient gun.

Objective 2 (Cool): Develop methods for cooling beams using optical stochastic cooling to increase beam luminosity in next-generation colliders.

Deliverable 2.1: Proof-of-principle demonstrations of key elements of optical stochastic cooling at IOTA and CESR (**Spring 2022**)

> **Plan: DONE**. Deliverable was achieved with the experimental demonstration of optical stochastic cooling at IOTA [11] and the implementation of an OSC model in the popular codes BMAD [12] and ELEGANT [13].

CBB's longer term deliverables related to optical stochastic cooling have been removed due to lack of person-power and opportunity for collaboration within CBB.

Objective 3 (Control): Investigate advanced optimization schemes, including machine learning (ML) and parameter reduction techniques, for precision phase-space control of particle accelerator systems.

Deliverable 3.1: Electron Microscope tuned using ML techniques whose performance is comparable to that of traditional operator tuning **(Summer 2022)**

> **Plan: DONE**. CBB achieved performance comparable to that of traditional operator tuning using its ML techniques on aberration correctors for three microscopes: Nion UltraSTEM, ThermoFisher Spectra 300 S/TEM, and a ThermoFisher Titan 300 Cryo-S/TEM. In each case, CBB trained a convolutional neural network to determine the beam emittance from a single ronchigram and applied gaussian processes to optimize corrector parameters [14], [15]. Some work to optimize the procedure continues.

Deliverable 3.2 (Priority, under review): Electron Microscope whose higher-order aberrations are tuned using ML techniques, replacing the regular maintenance interventions by microscope company specialists that are required to keep the conventional alignment software operational. **(Summer 2025)**

> **Plan**: In Spring 2024, CBB expects to share its tuning results with Thermo Fisher Scientific (TFS), which manufactures electron microscopes, and Corrected Electron Optical Systems (CEOS), which manufactures most aberration correctors. Further plans will depend on their feedback and may include extending the CBB tuning procedures to higher-order aberrations.

End User: Microscope and aberration corrector companies such as TFS and CEOS. The transfer of the microscope tuning technology is *KT Deliverable 2.6*.

Risk: Tuning higher order corrections will require considerable effort, so CBB plans to undertake it only if there is a likelihood that it will be put to use in commercial microscopes.

Mitigation: Mitigation will be a topic of discussion with TFS and/or CEOS.

Deliverable 3.3: Methods for efficient characterization and tuning of accelerators **(Summer 2025)**

Plan: CBB participants have applied ML to optimize and control accelerators [16], [17], but so far these optimizations have mainly focused on controlling scalar parameters (e.g. beam size, emittance, position). Our plan is to apply ML to problems with increasing dimensionality: by controlling multiple scalar parameters (experimentally exploring the Pareto front between multiple parameters), or by directly controlling the beam phase-space *distribution*, i.e., beyond its averaged values.

Deliverable 3.4: Summary of the boundaries of applicability of ML in accelerators (**Fall 2026**).

Plan: A recent report led by a CBB alumnus [18] broadly addresses the use of machine learning for particle accelerators. CBB participants continue to successfully apply ML techniques to a wide array of accelerators ranging from university-scale test facilities (with limited diagnostics) to large facilities available at the National Laboratories. Likewise, CBB has applied ML to control both pulsed and CW accelerators. We expect the results of this work to inform future similar reviews.

The Beam Dynamics and Control deliverables and their timelines are shown in Figure 4.

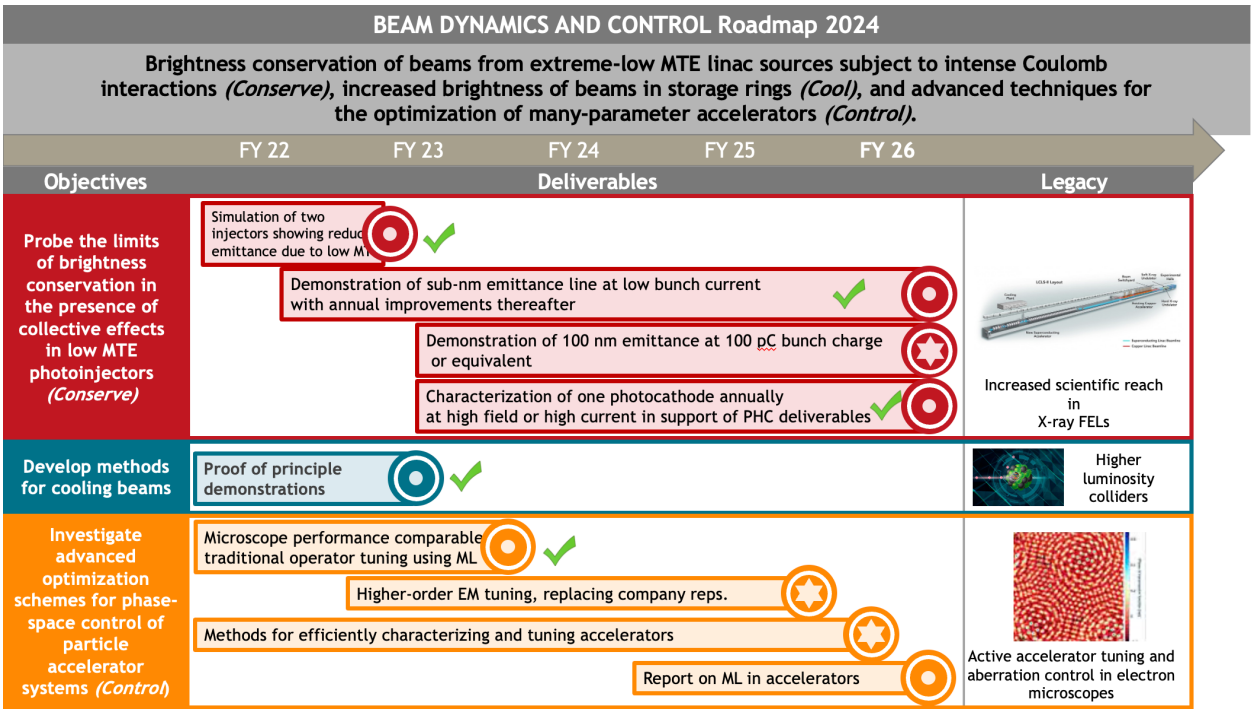

Figure 4. The Beam Dynamics and Control roadmap.

WORKFORCE DEVELOPMENT: Performance Objectives and Deliverables

Optimal Outcome: Effective CBB collaborations across disciplines and institutions.

Objective 1: Use team science to enable all participants—faculty, postdocs, and students—to be successful in convergence research.

Deliverable 1.1: Effective communication practices across all aspects of research and administration (**Annual**)

> **Plan:** CBB communication practices include the *CBB Weekly News,* biweekly theme and grad-to-grad meetings, a monthly seminar series, an annual research planning day, an annual collaboration meeting, an annual symposium, and three international workshops. Our asynchronous communications include Indico (our slide archive), the CBB Handbook, our external and internal website, the CBB ontology, a YouTube channel, and occasional Newsletters. Finally, all new CBB members undergo a formal onboarding process.

Deliverable 1.2: Shared goals and shared recognition **(Annual)**

> **Plan:** The Strategic Plan documents our goals, and all faculty, postdocs and students must identify the deliverable that they address with their work. CBB will communicate community needs and the broader impacts of our research to members through frequent seminars from industry and national labs, pedagogy talks at the Annual Meeting, industry participation at the Annual Symposium, and international workshops. To make CBB a truly multi-institutional center, CBB will use rotating venues for its seminars, meetings, and symposia and will sponsor student/postdoc research visits.

Deliverable 1.3: Strong leadership and transparent decision-making **(Annual)**

> **Plan:** CBB will use transparent processes for decision making based on annual reports and reviews as well as an annual proposal system. CBB will define and communicate expectations, roles, and responsibilities through our onboarding process, the *CBB Handbook,* and reminders in *CBB Weekly News.*

Deliverable 1.4 (Priority): More annual collaborative papers or proceedings than PIs (**Annual**)

> **Plan:** CBB will evaluate annually.

Objective 2: Provide training that cultivates an intellectually diverse workforce of scientists who are well prepared to lead in their chosen fields and foster an appreciation for accelerator science.

Deliverable 2.1: Faculty, postdocs, and students with the skills necessary to accomplish CBB goals, become leaders in their fields, and appreciate research challenges in accelerator sciences **(Annual).**

> **Plan:** All CBB students will update their individual development plan annually. CBB will annually offer career development workshops; diversity, equity and inclusion training; mentoring training, pedagogy talks. CBB will offer hands-on accelerator training and/or training at the US Particle Accelerator School to interested students.

Objective 3: Monitor and evaluate the efficacy of the workforce development and diversity plans

Deliverable 3.1: Center programming that evolves to meet the needs of Center members based on an external evaluation designed to provide formative information (**Annual**).

> **Plan:** An independent team will annually evaluate CBB activities and climate. Their reports will be used to evolve and refine Center activities.

Deliverable 3.2: Middle school educational outreach modules that change student attitudes toward science, improve teacher satisfaction and confidence, and have a positive impact on the graduate student network formation **(Annual).**

> **Plan:** Teachers and students will complete post-activity surveys to assess impact. These surveys will be used to evolve and refine CBB modules and activities.

Deliverable 3.3: Research Experiences for Undergraduates (REU) programs that support undergraduate students and provides them with a valued research experience **(Annual).**

> **Plan:** An independent evaluator will annually evaluate the REU program. This evaluation will be used to evolve and refine the REU program.

The Workforce Development deliverables and their timelines are shown in Figure 5.

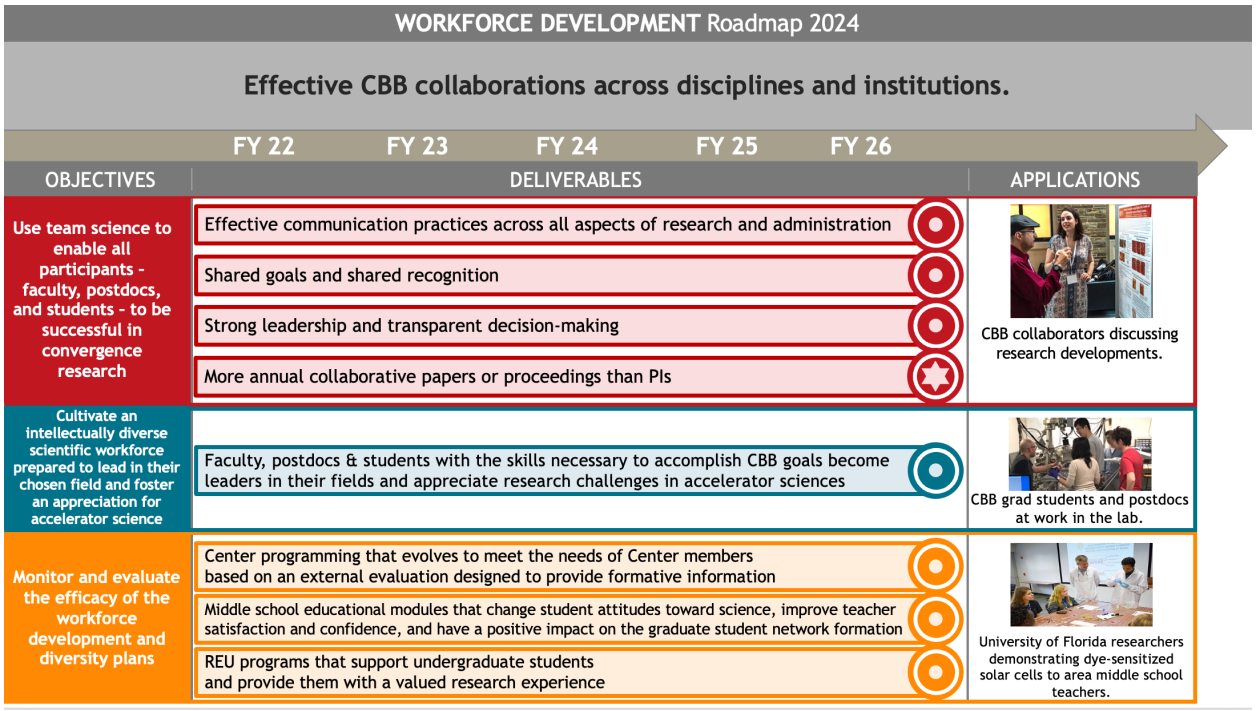

Figure 5. The Workforce Development roadmap.

DIVERSITY:
Performance Objectives and Deliverables

Optimal Outcome: Measurable impact on the participation of underrepresented groups in sciences and technology, particularly in accelerator science.

Objective 1: Train graduate students from underrepresented groups.

Deliverable 1.1 (Priority): Participation in CBB by women or non-binary researchers exceeds national physics levels at all levels annually **(Annual)**

> **Plan:** CBB will promote a diverse and inclusive workplace and culture through Center programming and will strive to implement diverse partnerships. CBB diversity will be measured annually.

Deliverable 1.2 (Priority): Participation in CBB research by members of underrepresented racial and ethnic groups exceeds national physics levels at all levels annually **(Annual)**

> **Plan:** CBB will promote a diverse and inclusive workplace and culture through Center programming and will strive to implement diverse partnerships. CBB diversity will be measured annually.

Objective 2: Provide opportunities for a diverse group of undergraduates to conduct research in accelerator science.

Deliverable 2.1 (Priority): Research Experiences for Undergraduates (REU) programs that engage four diverse undergraduates annually and provide them with a valued research experience **(Annual)**

> **Plan:** CBB diversity will be measured annually.

Objective 3: Stimulate a broad pipeline of middle-school students interested in STEM fields.

Deliverable 3.1: Middle school educational outreach modules that engage a diverse student cohort and change student attitudes toward science, improve teacher satisfaction and confidence, and have a positive impact on the graduate student network formation **(Fall 2026)**.

> **Plan:** CBB impact and diversity will be measured annually.

The Diversity deliverables and their timelines are shown in Figure 6.

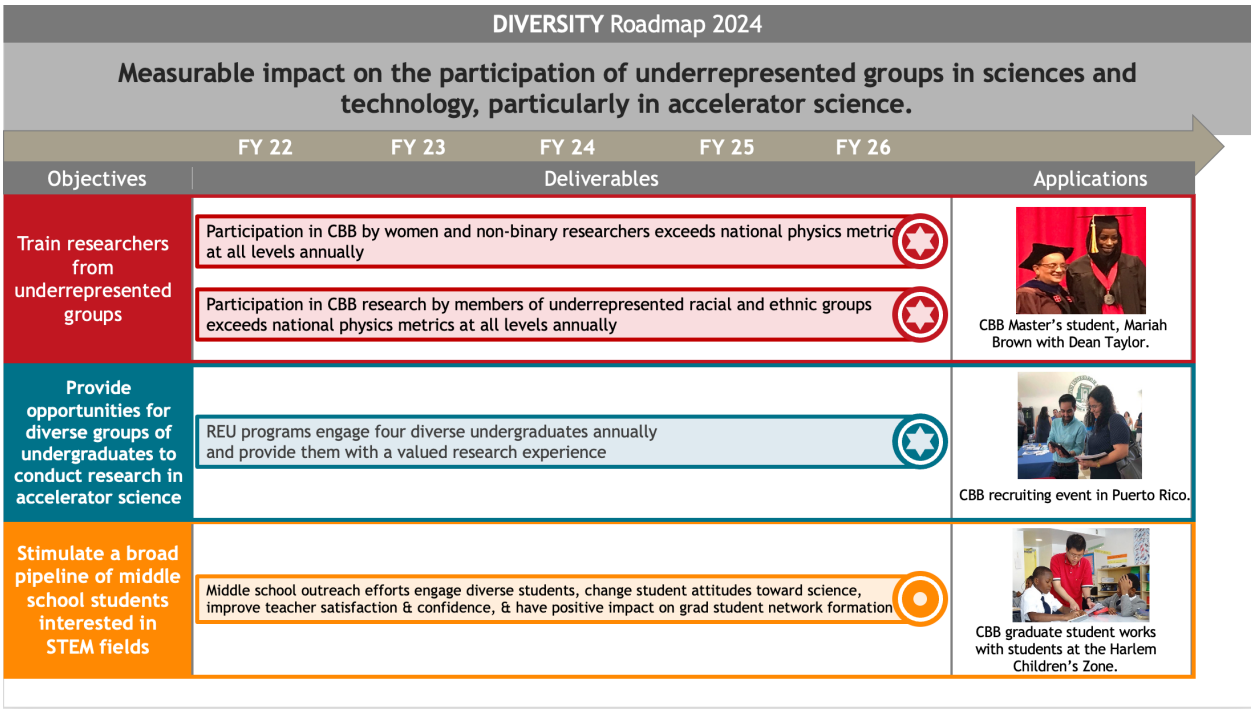

Figure 6. The Diversity roadmap.

KNOWLEDGE TRANSFER
Performance Objectives and Deliverables

Optimal Outcome: The transfer of knowledge and technology developed within the Center to other research groups, to national laboratories, and to industry, and to communicate frequently with industry and national lab partners to ensure CBB understands their requirements.

Objective 1: CBB shares its knowledge with accelerator scientists and scientists in related disciplines.

Deliverable 1.1: CBB knowledge shared through journal articles, conference proceeding articles, presentations, data sets, technical drawings and other media.

> **Plan:** CBB will publish its results in conference proceedings, journal articles, and invited and oral contributed talks. These will be targeted at a range of conferences and journals in order to reach scientists from both accelerator science and related fields.

Deliverable 1.2: Strong engagement with the accelerator community and the end use communities by hosting, co-hosting or participating in conferences and workshops, service on community panels and committees (including conference organizing committees), and initiating research collaboration with laboratory and industry scientists.

> **Plan**: CBB will host or co-host workshops or conferences annually, encourage faculty participation in professional committees, and continue to build connections with industry and laboratory scientists. CBB will maintain intellectual property agreements with all participating institutions and will adhere to its Data Management Plan.

Objective 2: CBB discoveries and designs are incorporated into a new generation of accelerators and commercialized as products.

Deliverable 2.1: The transfer of CBB methods for preparing a photocathode with MTE < 35 meV and QE $> 10^{-3}$ at laser fluences in excess of 50 μJ/cm^2 (*transfer of PHC Deliverable 1.2*).

> **End user:** This photocathode is aimed at the needs of the LCLS-II-HE SRF gun and electron microscopes. The LCLS-II-HE gun is required to deliver <100 μA beam current based on the project's requirements and, as an SRF gun, is expected to have good vacuum conditions. IDES/JEOL has also expressed interest in implementing such a photocathode in one of its electron microscopes.
>
> **Plan and Progress:** A NaKSb photocathode has demonstrated good lifetime in a working photoinjector [19] and in 2023, CBB showed high oxygen tolerance by CsTe

photocathodes [20]. Both indicate that MTE of 35 meV would be preserved in the LCLS-II-HE gun for the timescale of a day or more. DOE Basic Energy Sciences has funded a joint project in 2023 of CBB (Karkare, Maxson, Musumeci), SLAC (Vecchione) and LBNL (Filipetto, then at LBNL), and one outcome of that work is that SLAC is now able to grow alkali-antimonide cathodes in their growth chamber based on CBB recipes. These cathodes will also be tested in the Pegasus at UCLA and potentially in the HiRES gun at LBNL in preparation for use in LCLS-II-HE.

External support: A 2023 grant from the Department of Energy, Basic Energy Sciences.

KT status: 80% complete. Growth methods have been transferred to SLAC National Accelerator Laboratory. KT to SLAC will continue as further progress is made toward the technical deliverable.

Figure 7. Status of KT Deliverable 2.1. Light shading indicates partner identification and research collaboration, and dark shading indicates method transfer.

Deliverable 2.2. The transfer of CBB methods for a photocathode that can operate for >1 week with MTE <35 meV at 50 μJ/cm^2 laser fluence and high field (>100 MV/m) for high peak current applications such as compact XFELs (*transfer of PHC Deliverable 2.1*).

End user: This photocathode is directed at the needs of advanced accelerators such as compact X-ray FELs. This photocathode would also benefit large low rep-rate X-ray FELs such as FLASH if they were modified to accept such photocathodes.

Plan and Progress: CBB is connected with the compact X-ray FEL community, and the leader of one design (UCXFEL at UCLA) is a CBB participant. We expect that demonstration of a 100pC/100nm beam (*BDC Deliverable 1.3*) will assist in this transfer.

External support: CBB members are engaged with several venture capitalists (names/affiliations bound by NDAs) and companies for potential transfer.

KT status: 60% complete. Photocathode capabilities have been shared with the UCXFEL team for UCXFEL collaboration proposals and projects.

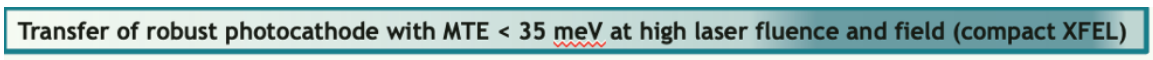

Figure 8. Status of KT Deliverable 2.2. Light shading indicates partner identification and research collaboration, and dark shading indicates method transfer.

Deliverable 2.3. The transfer of CBB methods for a photocathode that can operate for >1 week with MTE <100 meV and QE>1% under high average current (>50 mA) conditions for hadron coolers and colliders (*transfer of PHC Deliverable 2.2*).

End user: This photocathode would benefit an electron cooler for the Electron-Ion Collider at BNL, or other future proton colliders.

Plan and Progress: BNL is exploring the use of GaN-based cathodes or applying a robust coating to GaAs cathodes and CBB is collaborating with BNL scientist and CBB affiliate Luca Cultrera on this work. Another approach being pursued by CBB, Euclid Lab and LANL is to coat Cs_3Sb with graphene; here, CBB brings unique expertise in graphene coating techniques and has applied for a patent for its methods (M. Hines, W. DeBenedetti, "Method for Protecting Reactive Materials with Atomically Thin Film", application 63/185,407, 2021.) If protection is successful, CBB's close ties with Cultrera will facilitate adoption by BNL. CBB expects to deliver methods to BNL between 2025 and 2026.

External support: Related work to develop photocathodes for polarized electron beams is supported by grants from DOE Offices of Nuclear Physics and High Energy Physics.

KT status: 50% complete. Former CBB graduate student Jai Kwan Bae (PhD, 2022) transferred Sb-O-Cs GaAs activation know-how to JLAB during extended visit (funded by separate DOE Stewardship Track 3 award).

Figure 9. Status of KT Deliverable 2.3. Light shading indicates partner identification and research collaboration, and dark shading indicates method transfer.

Deliverable 2.4: The transfer of CBB technology for a photoemission source with sub-100 nm spot size and MTE approaching 25 meV (*transfer of PHC Deliverables 3.1 and 3.2*).

End user: This source targets ultrafast electron microscopes and electron energy loss spectroscopy (EELS) systems, including ultrafast electron microscopes operating in stroboscopic regime and ultrafast EELS systems. A stretch goal is continuous beam electron microscopy.

Plan and Progress: IDES/JEOL and CBB are in discussions about the transfer of such a source for use in an electron microscope, spurred by CBB's recent successful demonstration of sub-100 nm spot size [8].

CBB scientists (Karkare, Maxson) and Bryan Reed of JEOL are exploring funding opportunities to build and test a photocathode gun for a JEOL microscope. If successful, CBB would seek industry funding for further development.

KT status: 50% complete.

Figure 10. Status of KT Deliverable 2.4. Light shading indicates partner identification and research collaboration, and dark shading indicates method

Deliverable 2.5: The transfer of CBB methods for producing non-Nb, high efficiency surfaces with cooling power <1.5 kW/(active meter) or capable of sustaining accelerating fields > 25 MV/m (*transfer of SRF Deliverables 3.1 and 3.2*).

End Users: Industry and national labs supplying and processing SRF cavities. Future SRF driven accelerators running in CW mode, including compact SRF accelerators for industrial applications, e.g., for wastewater treatment.

Plan and progress: CBB scientists meet regularly with JLAB, FNAL, SLAC, and industry partners to ensure that its advances meet the needs of end-users and are subject to suitable performance tests. Discussions with accelerator companies, raw goods suppliers, and laboratories have been underway since 2022. Research continues.

In 2023, CBB filed a patent application for the use of ZrNb alloys for superconducting applications (Z. Sun, T. Oseroff, M. Liepe, "ZrNb Alloyed Surface as Superconducting Material," U.S. Patent Application 18/507843, November 13, 2023.)

External support: CBB scientists (Bazarov, Hoffstaetter de Torquat, Liepe and Maxson) submitted a joint proposal with scientists at Ion Linac Systems, a NM-based, US-owned and operated corporation, for beam testing a conduction cooled cavity and initiating knowledge transfer. This proposal was not funded but we are exploring other options.

KT status: 85% complete. CBB is keeping the DOE SC laboratories apprised of its steadily improving methods.

Figure 11. Status of KT Deliverable 2.5. Light shading indicates partner identification and collaboration, and dark shading indicates method transfer.

Deliverable 2.6: The transfer of CBB ML techniques for tuning aberrations in electron microscopes, replacing the regular maintenance interventions by microscope company specialists that are required to keep the conventional alignment software operational (*BDC Deliverable 3.2*).

End user: Companies such as Thermo Fisher Scientific (TFS), which makes microscopes, or Corrected Electron Optical Systems (CEOS), which makes microscope aberration correctors.

Plan and Progress: CBB scientist David Muller (Cornell) is collaborating closely with teams led by Heiko Muller at Corrected Electron Optical Systems (CEOS) and Dmitri Klenov of Thermo Fisher Scientific (TFS). CEOS has shared its proprietary tuning software API with CBB, so that CBB can control the corrector hardware, and TFS has provided a python interface to their microscope's hardware and detectors.

An early version of the CBB tuning software has been shared with TFS, and in April 2024, Muller demonstrated the ML-based version to TFS at their facility in Aacht. A report on the performance on the Cornell Titan and Spectra aberration correctors, now in preparation, will be provided to TFS and CEOS before the summer of 2024. Further plans, including extension to higher order aberrations and compensation, will depend on the TFS and CEOS need for this technology in their product.

KT status: 90% complete. A rapid tuning method has been demonstrated and the complete report for the companies (and journal article) is in preparation.

Figure 12. Status of KT Deliverable 2.6. Light shading indicates partner identification and collaboration, and dark shading indicates method transfer.

Deliverable 2.7: Incorporation of other CBB discoveries into new generations of accelerators or commercialization as products.

Plan and Progress: CBB collaboration with industry and lab scientists has already resulted in the incorporation of CBB technology and methods in operating accelerators. These include:

- **Modeling tools for photocathodes** (Tech-X, Boulder CO, SBIR-II): CBB Monte-Carlo codes developed for modeling photoemission from high QE semiconductor cathodes were incorporated into PIC software VSIM sold by Tech-X (2021).
- **High Brightness Source Optimization** (Thermo-Fisher Scientific, Waltham MA): CBB provided advice and consulting for technology incorporated into the new high-brightness TFS Spectra Cold-Field-Emission microscopes. The details are under NDA, but we can say that in addition to everything else, we did get a personal letter of thanks from CEO Marc Casper. When the product was released, some of the data we collected with them in the development was also used as part of the promotion (2019).
- **Loadlock for photocathode sharing** (Radiabeam, Santa Monica, CA): Successfully transferred two UHV photocathode suitcase delivery systems based on CBB PI in-house prototypes (2019-2020).
- CBB contributed the delay system that enabled the demonstration of **optical stochastic cooling** (OSC) at Fermilab's IOTA (2022) [11]. FNAL scientists now use CBB's

Elegant-based simulation of optical stochastic cooling in the development of future stages of OSC (2023) [21].

- **CBB stochastic space charge algorithm** capable of accounting for binary collisions during the emission process. The algorithm is now added as a module in the widely used General Particle Tracer (GPT) program (2021) [22].
- **CBB ML-based tuning of an electron beam** applied to hadron cooling at LEReC at RHIC (2022) [23].
- **ML on exascale HPCs for simulating atomic processes.** Ultra-Fast Force Field (UF3) codes provides accurate and efficient models and is now incorporated through CPU and GPU implementation for the LAMMPS code (Sandia) (2023).
- **High gradients in cold copper cavities** were first demonstrated in a SLAC/CBB collaboration (2018) [24]. This technology is now being developed by SLAC and others for applications such as a high energy linear collider and an injector to CESR.
- **High-performance niobium SRF cavity.** A niobium SRF cavity incorporating CBB advances is in operation at NSLS-II at BNL.
- **Cryocooled SRF systems.** JLAB, Fermilab and Cornell are building cryocooled SRF systems based on Nb_3Sn for applications such as waste treatment. All use CBB methods for Nb_3Sn growth (2023).
- **Chip inspection methods.** DARPA is funding the application of bright CBB electron beams at UCLA to microelectronics testing. Additional funding for this work is being sought from an NSF STTR with Radiabeam, DOE, and venture capitalists.

KT status: 80% complete. CBB is delivering a steady stream of KT, and this will continue in years 9 and 10.

Figure 13. Status of KT Deliverable 2.7. Light shading indicates partner identification and research collaboration, and dark shading indicates method transfer.

Objective 3. Trained graduate students are capable of recognizing and transferring these skills to industry and national lab partners.

Deliverable 3.1: Fifty-five trained graduate students who are able to transfer their skills to industry and national lab partners **(Fall 2026).**

Plan: This deliverable relies on the plan for *Workforce Development Deliverable 2.1*, and includes student outreach visits to national labs and industry.

The Knowledge Transfer deliverables and their timelines are shown in Figure 14.

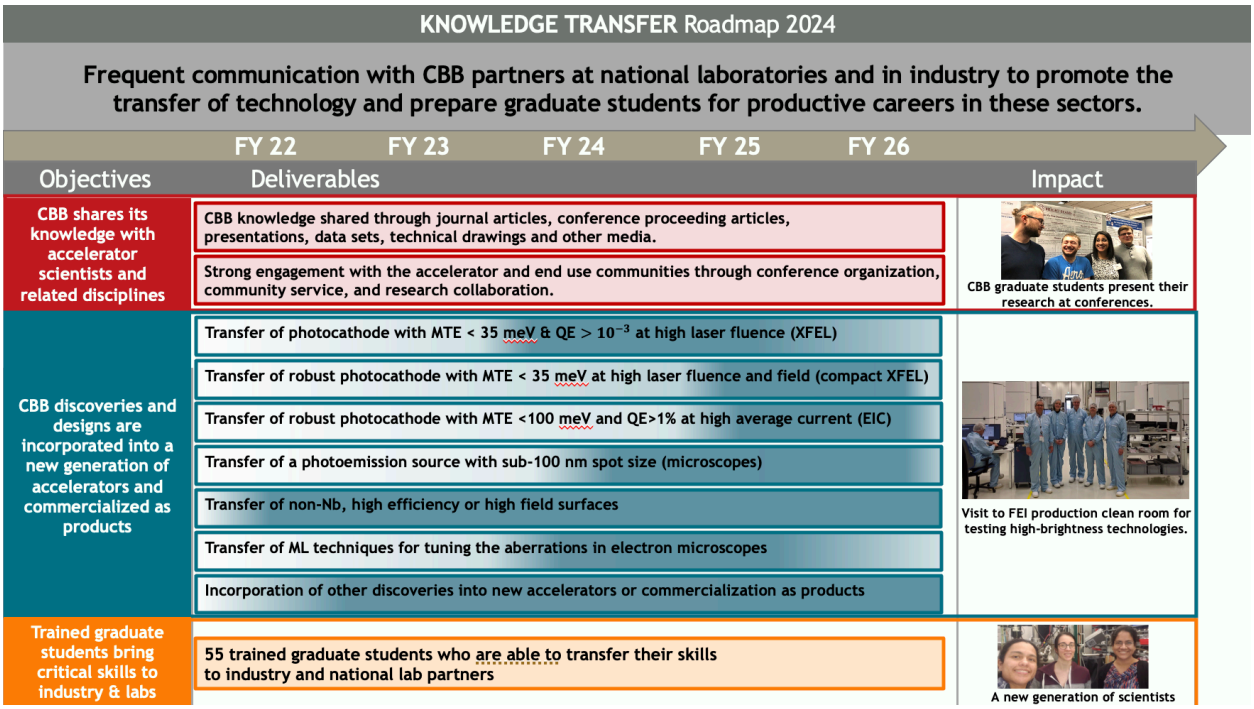

Figure 14. The Knowledge Transfer roadmap. Light shading indicates partner identification and research collaboration, and dark shading indicates method transfer.

References

[1] Dehmer, Pat, "Comments from the Office of Science," presented at the Meeting of the High Energy Physics Advisory Panel, Gaithersburg, MD, Dec. 2013. [Online]. Available: https://science.osti.gov/hep/hepap/Meetings/20131206

[2] A. M. Minor, P. Denes, and D. A. Muller, "Cryogenic electron microscopy for quantum science," *MRS Bull.*, vol. 44, no. 12, pp. 961–966, Dec. 2019, doi: 10.1557/mrs.2019.288.

[3] DOE Office of Science Report, "Accelerators for America's Future," 2009.

[4] HEPAP Subcommittee, "Review of the United States Particle Accelerator School," May 2015. [Online]. Available: https://science.osti.gov/-/media/hep/hepap/pdf/Reports/HEPAP_USPAS_Subcommittee_Final_Report.pdf

[5] "Funding Opportunity Announcement (DE-FOA-0002087): DOE Traineeship in Accelerator Science & Engineering." Department of Energy, Apr. 2019. [Online]. Available: https://science.osti.gov/-/media/grants/pdf/foas/2019/SC_FOA_0002087.pdf

[6] C. T. Parzyck *et al.*, "Single-Crystal Alkali Antimonide Photocathodes: High Efficiency in the Ultrathin Limit," *Phys. Rev. Lett.*, vol. 128, no. 11, p. 114801, Mar. 2022, doi: 10.1103/PhysRevLett.128.114801.

[7] J. K. Bae *et al.*, "Operation of Cs–Sb–O activated GaAs in a high voltage DC electron gun at high average current," *AIP Advances*, vol. 12, no. 9, p. 095017, Sep. 2022, doi: 10.1063/5.0100794.

[8] A. Kachwala, "Bright Electron Beams from Plasmonic Spiral Photocathode," presented at the Physics of Photocathodes for Photoinjectors (P3), Stony Brook University, Stony Brook, NY, Oct. 03, 2023. [Online]. Available: https://indico.bnl.gov/event/19730

[9] C. M. Pierce *et al.*, "Low intrinsic emittance in modern photoinjector brightness," *Phys. Rev. Accel. Beams*, vol. 23, no. 7, p. 070101, Jul. 2020, doi: 10.1103/PhysRevAccelBeams.23.070101.

[10] W. H. Li *et al.*, "A kiloelectron-volt ultrafast electron micro-diffraction apparatus using low emittance semiconductor photocathodes," *Structural Dynamics*, vol. 9, no. 2, p. 024302, Mar. 2022, doi: 10.1063/4.0000138.

[11] J. Jarvis *et al.*, "Experimental demonstration of optical stochastic cooling," *Nature*, vol. 608, no. 7922, Art. no. 7922, Aug. 2022, doi: 10.1038/s41586-022-04969-7.

[12] S. T. Wang *et al.*, "Simulation of transit-time optical stochastic cooling process in Cornell Electron Storage Ring," *Phys. Rev. Accel. Beams*, vol. 24, p. 064001, Jun. 2021, doi: 10.1103/PhysRevAccelBeams.24.064001.

[13] Piot, Philippe, "Simulation of Optical Stochastic Cooling in ELEGANT," in *In preparation*, 2021.

[14] C. Zhang *et al.*, "Aberration Corrector Tuning with Machine-Learning-Based Emittance Measurements and Bayesian Optimization," *Microscopy and Microanalysis*, vol. 27, no. S1, pp. 810–812, Aug. 2021, doi: 10.1017/S1431927621003214.

[15] D. Ma *et al.*, "Physics-informed Bayesian Optimization of an Electron Microscope," *Microscopy and Microanalysis*, vol. 29, no. Supplement_1, pp. 1875–1877, Jul. 2023, doi: 10.1093/micmic/ozad067.968.

[16] W. F. Bergan, I. V. Bazarov, C. J. R. Duncan, D. B. Liarte, D. L. Rubin, and J. P. Sethna, "Online storage ring optimization using dimension-reduction and genetic algorithms," *Phys. Rev. Accel. Beams*, vol. 22, no. 5, p. 054601, May 2019, doi: 10.1103/PhysRevAccelBeams.22.054601.

[17] A. Scheinker, F. Cropp, S. Paiagua, and D. Filippetto, "Demonstration of adaptive machine learning-based distribution tracking on a compact accelerator: Towards enabling model-based 6D non-invasive beam diagnostics," *arXiv:2102.10510 [physics]*, Feb. 2021, doi: 10.48550/arXiv.2102.10510.
[18] R. Roussel *et al.*, "Bayesian Optimization Algorithms for Accelerator Physics." arXiv, Dec. 09, 2023. doi: 10.48550/arXiv.2312.05667.
[19] L. Cultrera *et al.*, "Growth and characterization of rugged sodium potassium antimonide photocathodes for high brilliance photoinjector," *Applied Physics Letters*, vol. 103, no. 10, p. 103504, Sep. 2013, doi: 10.1063/1.4820132.
[20] C. T. Parzyck *et al.*, "Atomically smooth films of CsSb: A chemically robust visible light photocathode," *APL Materials*, vol. 11, no. 10, p. 101125, Oct. 2023, doi: 10.1063/5.0166334.
[21] A. J. Dick *et al.*, "Numerical modeling of a proof-of-principle experiment on optical stochastic cooling at an electron storage ring," *Phys. Rev. Accel. Beams*, vol. 27, no. 1, p. 012801, Jan. 2024, doi: 10.1103/PhysRevAccelBeams.27.012801.
[22] M. Gordon, S. B. van der Geer, J. Maxson, and Y.-K. Kim, "Point-to-point Coulomb effects in high brightness photoelectron beam lines for ultrafast electron diffraction," *Phys. Rev. Accel. Beams*, vol. 24, no. 8, p. 084202, Aug. 2021, doi: 10.1103/PhysRevAccelBeams.24.084202.
[23] Y. Gao *et al.*, "Bayesian optimization experiment for trajectory alignment at the low energy RHIC electron cooling system," *Phys. Rev. Accel. Beams*, vol. 25, no. 1, p. 014601, Jan. 2022, doi: 10.1103/PhysRevAccelBeams.25.014601.
[24] A. D. Cahill, J. B. Rosenzweig, V. A. Dolgashev, S. G. Tantawi, and S. Weathersby, "High gradient experiments with X-band cryogenic copper accelerating cavities," *Phys. Rev. Accel. Beams*, vol. 21, no. 10, p. 102002, Oct. 2018, doi: 10.1103/PhysRevAccelBeams.21.102002.

Appendix: Research Projects 2023-24

Beam Production

Optimal Outcome: The understanding, materials, and technology necessary to produce the brightest possible electron beams across the wide span of beam currents, pulse durations, and operating environments demanded by forefront scientific research and emerging technological applications.

Objective 1: Develop photocathodes for high peak-intensity beam generation with low Mean Transverse Energy (MTE) and good quantum efficiency (QE).

- Ab initio theory of many-body photoemission and of photomaterials (Arias/Wu)
- Monte Carlo modeling of photoemission from semiconductors (Chubenko/Franklin)

- Quantum machine learning for the synthesis of photocathodes by epitaxial growth (Hennig/Dong)
- Photoemission and surface characterization of Alkali-antimonides (Karkare/TBD)
- Cathode characterization in PEEM (Karkare/Kachwala)
- Measurements of low energy electron distributions and cryogenic MTE (Karkare/Owusu) (also BDC)
- MTE measurement of epitaxial alkali antimonides (Maxson/Zhang)
- Molecular beam epitaxy growth and characterization of bialkali antimonides (Maxson/Echeverria)
- Atomically Ordered & Engineered Materials for Photocathodes (Shen/Anil)

Objective 2: Design materials for long-lived cathodes in extreme electric field and high average current

- Photocathodes under realistic accelerator conditions (Chubenko/Hasan) (also BDC)
- Measurement of photocathode performance at high average current (Maxson/Levenson) (also BDC)
- Air-stable, high-performance photocathodes (Hines/Finsterer/Hasany/Zhu)
- Optimizing alkali antimonides for high QE, low MTE performance in low and high field electron guns (Maxson/Pennington)
- Testing of advanced photocathodes at UCLA Pegasus photoinjector (Musumeci/Garcia) (also BDC)

Objective 3: Approach fundamental brightness limits with nanostructured photoemitters

- Sub-100 nm sources and High field testing of Alkali-antimonide photocathodes (Karkare/Rizi) (also BDC)
- Extreme High Brightness Electron Source from Intense Laser Illumination of Nano-Blades (Rosenzweig/Yadav/Lawler/Mann)

Beam Acceleration

Optimal Outcome: The advanced methods and surfaces needed for next-generation SRF cavities that enable game-changing reduction of cooling power, higher temperature operation, and higher accelerating fields for lower cryogenic system costs, energy sustainability, and simpler refrigeration.

Objective 1: Advanced SRF materials growth: Developing improved growth methods and understanding the impact of realistic (non-ideal) surfaces on performance.

- Ab initio exploration of beyond-Nb SRF materials for low cooling power and high field performance (Arias/Mendez)
- Thermodynamics and Superconducting Properties of Novel SRF Superconductors (Hennig/Hire/Dong)
- High-performance Nb_3Sn (Liepe/Shpani)
- CVD Growth of Nb_3Sn Films (Liepe/Gaitan)
- Advanced Material Systems for Enhanced SRF Performance (LiepeSitaraman)
- Electron Microscopy characterization of the microstructure of materials for SRF cavities (Muller/Baraissov)
- Investigating the Atomic and Micron-Scale Morphological Development of Nb_3Sn Leading to Smooth Homogeneous Thin Films (Sibener/Willson/Do)
- In Situ Measurements of High Temperature Surface Structure, Bonding, and Dynamics of Alloying Sn, Nb, and Zr from Initial Behavior to Resulting Film Growth (Sibener/Van Duinen)
- Investigating the Effect of Atomic Scale Surface Structural Changes from Alloying, Doping, and Defects on the Superconductivity of Nb, Nb_3Sn and Zr with Simultaneous In Situ High Temperature Atomic-Scale Surface (Sibener/Thompson)
- Optimization of Nb SRF Surfaces: Atomic Visualization of Alloy Growth and Oxide Suppression (Sibener/Do/Willson)
- Mesoscopic models of superconductivity for realistic materials and surfaces (Transtrum/Harbick)

Objective 2: Multi-layers and inhomogeneous layers: Increasing RF performance via surfaces by design.

- Advancing RF Performance via Au Layering and Oxide Passivation (Liepe/Stettler)

Objective 3: Higher efficiency and higher fields: Demonstrate higher RF performance in proof-of-principle SRF cavities and study RF superconductivity under extreme conditions.

Beam Dynamics and Control

Optimal Outcome: Brightness conservation of beams from extreme-low MTE linac sources subject to intense Coulomb interactions (*Conserve*), increased brightness of beams in storage rings (*Cool*), and advanced techniques for the optimization of many-parameter accelerators (*Control*). By ensuring that CBB advances in beam production and beam acceleration are realized in brightness at the target, this theme unifies the center's research.

Objective 1 (Conserve): Probe the ultimate limits of brightness conservation in the presence of collective effects in low MTE photoinjector beamlines.

- Measurements of low energy electron distributions and cryogenic MTE (Karkare/Owusu) (also PHC)
- Noise in Intense Electron Bunches (Kim/Kladov)
- Demonstration of 100 nm transverse emittance with 100 pC beam charge (Musumeci/Kulkarni)
- Conserving 4-D brightness and enhancing 5-D brightness in integrated photoinjector beamlines (Piot/Al Marzouk/Frame)
- Optimization of ultra-compact free-electron laser performance with very low MTE photocathodes (Rosenzweig/Bosco/Lawler)
- Photocathodes under realistic accelerator conditions (Chubenko/Hasan) (also PHC)
- Measurement of photocathode performance at high average current (Maxson/Levenson) (also PHC)

- Testing of advanced photocathodes at UCLA Pegasus photoinjector (Musumeci/Garcia) (also PHC)

Objective 2 (Cool): Develop methods for cooling beams using optical stochastic cooling to increase beam luminosity in next-generation colliders.

Complete.

Objective 3 (Control): Investigate advanced optimization schemes, including ML and parameter reduction techniques, for precision phase-space control of particle accelerator systems.

- Applications of Machine Learning in Photoinjectors (Biedron/Aslam)
- ML/AI preparation of polarized proton beams for electron cooling (Hoffstaetter de Torquat/Lin)
- Auto-Differentiable Accelerator Modeling (Kim/Aguilera)
- Machine Learning for precise phase space control of electron microscopes (Muller/Ma)