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

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 xFELs 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 New Mexico, aa Minority Serving Institution (MSI), a Hispanic Serving Institution (HSI) and an MI (Minority Institution). In addition, CBB is collaborating with University of Puerto Rico at Mayagüez, Clark Atlanta University, Morehouse College, Chicago State University, and Spelman College in its research and educational programs. As a result, CBB is bringing welcome diversity to accelerator science and other 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	Artificial Intelligence, FELs
NIU	Piot	Beam dynamics

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 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, and genders can thrive.

Optimal Outcomes

1. **Beam Production**: 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:** 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:** 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.

> 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:** Be a leader in convergence research by developing effective means of communicating across disciplines and institutions that includes providing scientific, technical, and professional skills trainees need to be successful in chosen careers.

5. **Diversity:** Have a measurable impact on the field of accelerator science and the pipelines that feed accelerator science, particularly with respect to the participation of underrepresented groups, with the goal of exceeding national metrics in the field of physics.

6. **Knowledge Transfer:** Frequent communication with CBB partners at national laboratories and in industry to promote the transfer of technology and prepare graduate students for productive careers in these sectors.

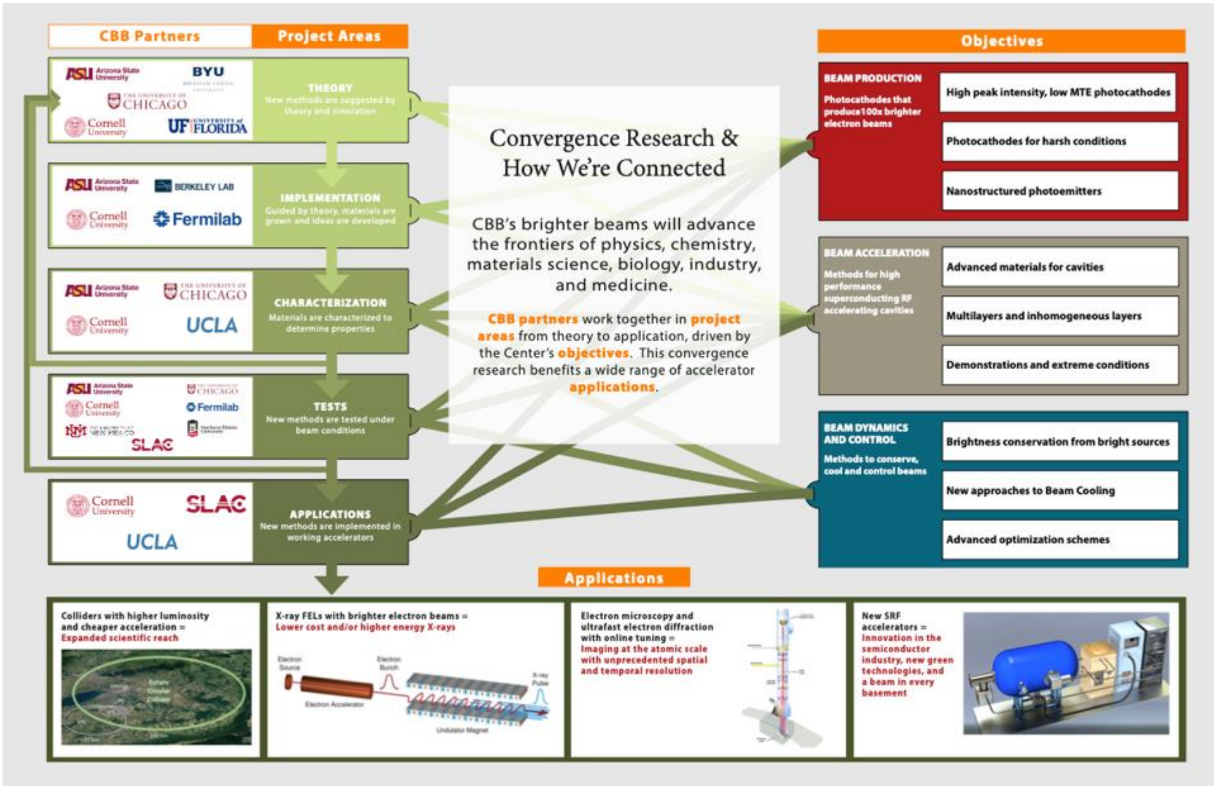

Figure 1. CBB research roadmap. CBB activities in the project areas (left) advance CBB towards it objectives (right). The objectives have been selected to benefit a wide range of beam applications (bottom).

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: Generate 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 < 5 meV MTE

Deliverable: A photocathode with 20 meV MTE at operational laser fluences, for example, by developing single-crystal, epitaxial alkali antimonides or other materials (October 2024).

Deliverable: A photocathode with 5 meV MTE at operational fluences by enhancing QE of ordered III-V and alkali antimonide photocathodes or other single crystals at threshold by engineering the density of states using dopants, heterostructure growth, and quantum-confined structures **(Fall 2026)**

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

Deliverable: Develop highly robust protective coatings or new materials that extend the photocathode lifetimes with little degradation in either QE or MTE. **(Fall 2025).**

Objective 3: Approach fundamental brightness limits with nanostructured photoemitters

Deliverable: An electron source with normalized transverse emittances approaching the fundamental limit of 0.2 pm set by the uncertainty principle for single electron per bunch beams **(Fall 2026).**

Deliverable: Use nano-structure arrays to deliver pm-emittances for higher charge per bunch. **(Fall 2026).**

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

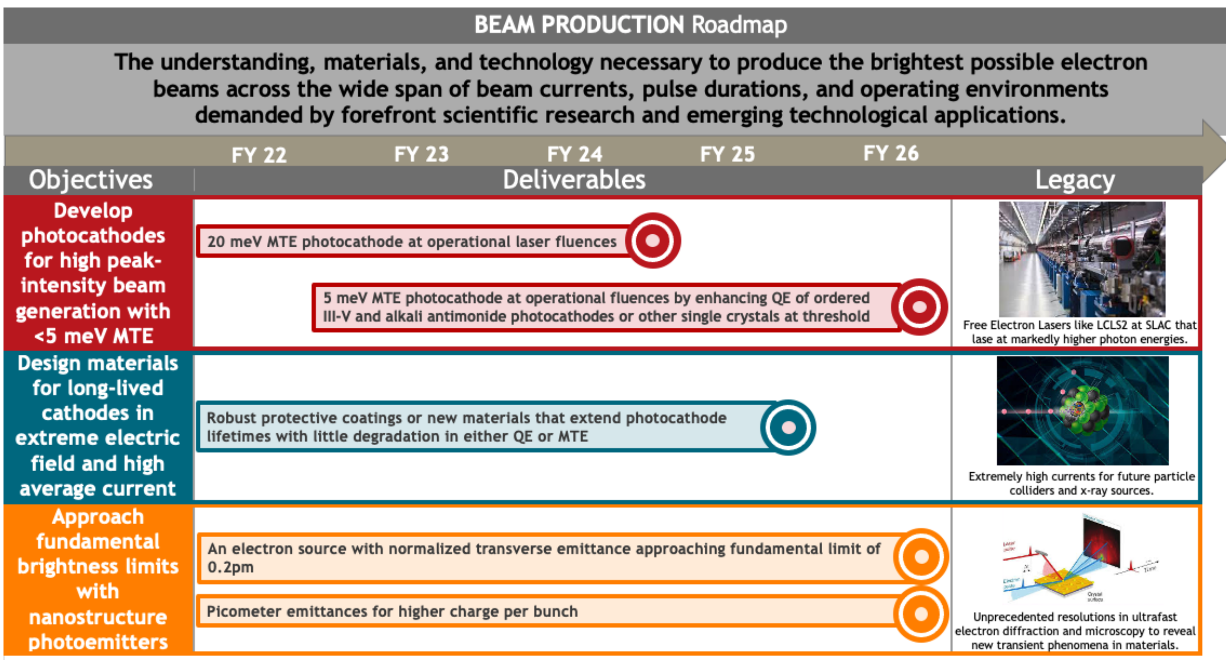

Figure 2. The Beam Production roadmap.

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: New and improved growth methods and alternative materials for increased cavity efficiency and operating temperature **(Fall 2026).**

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

Deliverable: Optimized inhomogeneous surface layers for increased cavity efficiency and increased accelerating fields (**Fall 2026**).

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: Surfaces from non-Nb at 20 MV/m with cooling power <1.5 kW/(active meter), corresponding to a 10× reduction in cooling power (relative to a 1.3 GHz Nb cavity with Q_0=2x10^{10} at 2K) **(Fall 2024).**

Deliverable: Surfaces capable of sustaining higher accelerating field (from 20MV/m toward 40 MV/m) with ultra-high efficiencies (>10x reduction in cooling power), and surfaces approaching 400 mT (corresponding to 2× accelerating field increase) **(Fall 2026).**

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

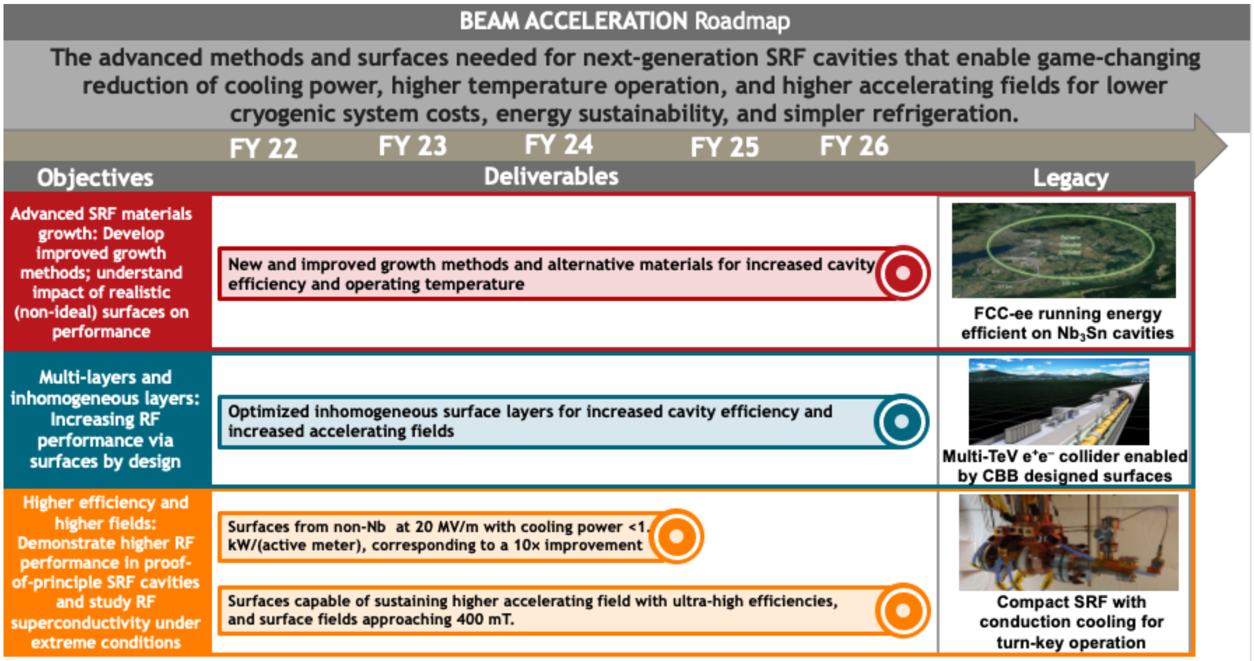

Figure 3. The Beam Acceleration roadmap.

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: The sources of residual emittance growth in select optimized beam lines **(Spring 2022).**

Deliverable: Cathode longevity testing capability with beam to support Theme 1 developments **(Fall 2023)**.

Deliverable: A list of the parameters that determine emittance growth in low MTE photoinjector beam lines **(Fall 2024).**

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

Deliverable: Proof of principle demonstrations of key elements of optical stochastic cooling at IOTA and CESR **(Spring 2023)**

Deliverable: Configurations capable of the very high cooling rates needed for use in a future colliders. **(Fall 2025)**

Deliverable: Single-pass correction of beam distortions and beam diagnostics using techniques developed for OSC **(Summer 2026)**

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

Deliverable: Methods for efficiently tuning an accelerator **(Summer 2026)**

Deliverable: Summary of the boundaries of applicability of ML in accelerators with varying noise types and data availability **(Summer 2026).**

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

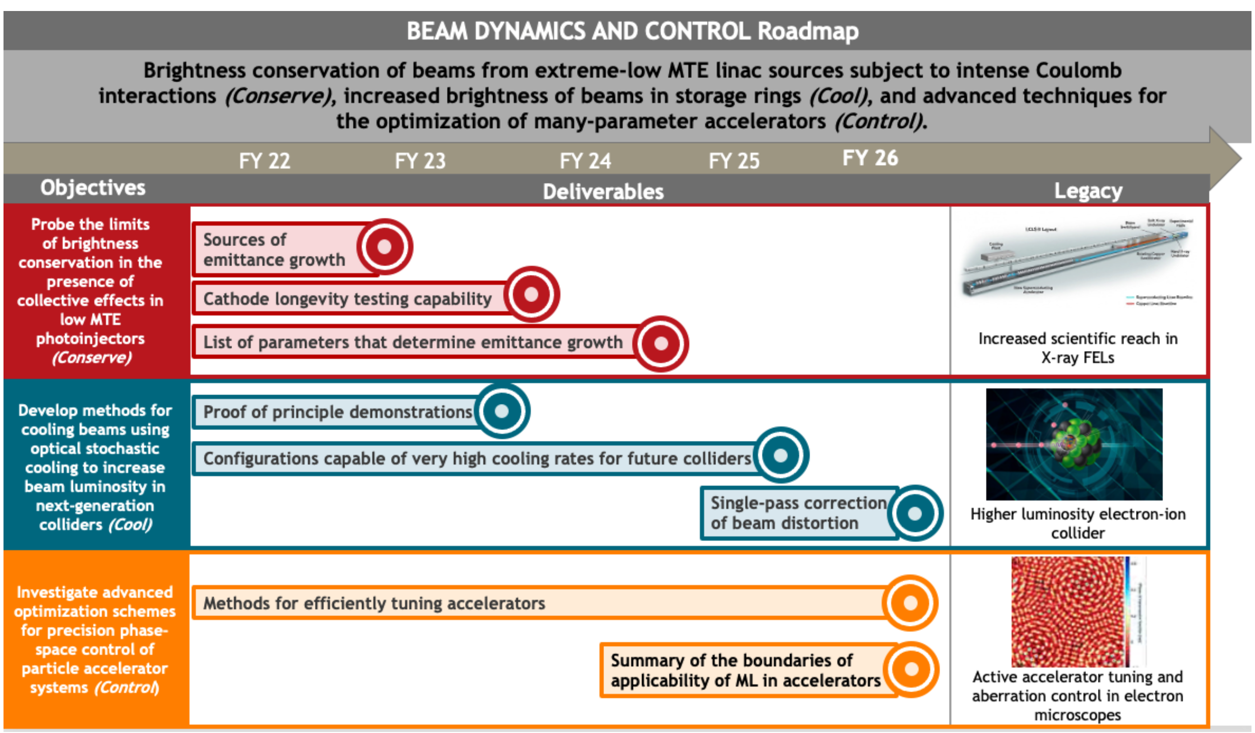

Figure 4. The Beam Dynamics and Control roadmap.

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: Effective communication practices across all aspects of research and administration **(Fall 2026)**.

Deliverable: Shared goals and shared recognition **(Fall 2026)**.

Deliverable: Strong leadership and transparent decision-making **(Fall 2026)**.

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: Faculty, postdocs, and students with the skills necessary to accomplish CBB goals, become leaders in their fields, and appreciate research challenges in accelerator sciences **(Fall 2026).**

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

Deliverable: Center programming that evolves to meet the needs of Center members based on an external evaluation designed to provide formative information (**Fall 2026**).

Deliverable: 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 **(Fall 2026).**

Deliverable: Research Experiences for Undergraduates (REU) programs that support undergraduate students and provides them with a valued research experience **(Fall 2026).**

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

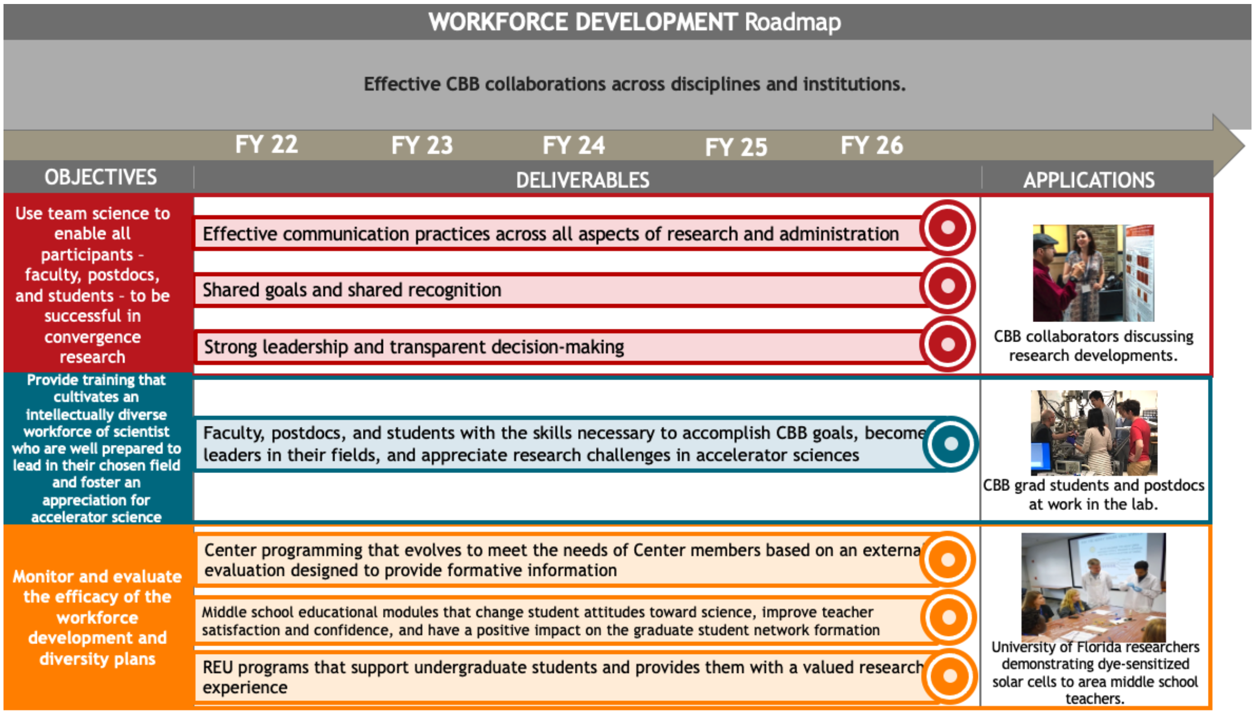

Figure 5. The Workforce Development roadmap.

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: Graduate students from underrepresented groups engaged in CBB research **(Fall 2026)**.

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

Deliverable: Research Experiences for Undergraduates (REU) programs that engage six diverse undergraduates annually and provide them with a valued research experience **(Fall 2026)**.

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

Deliverable: 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)**.

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

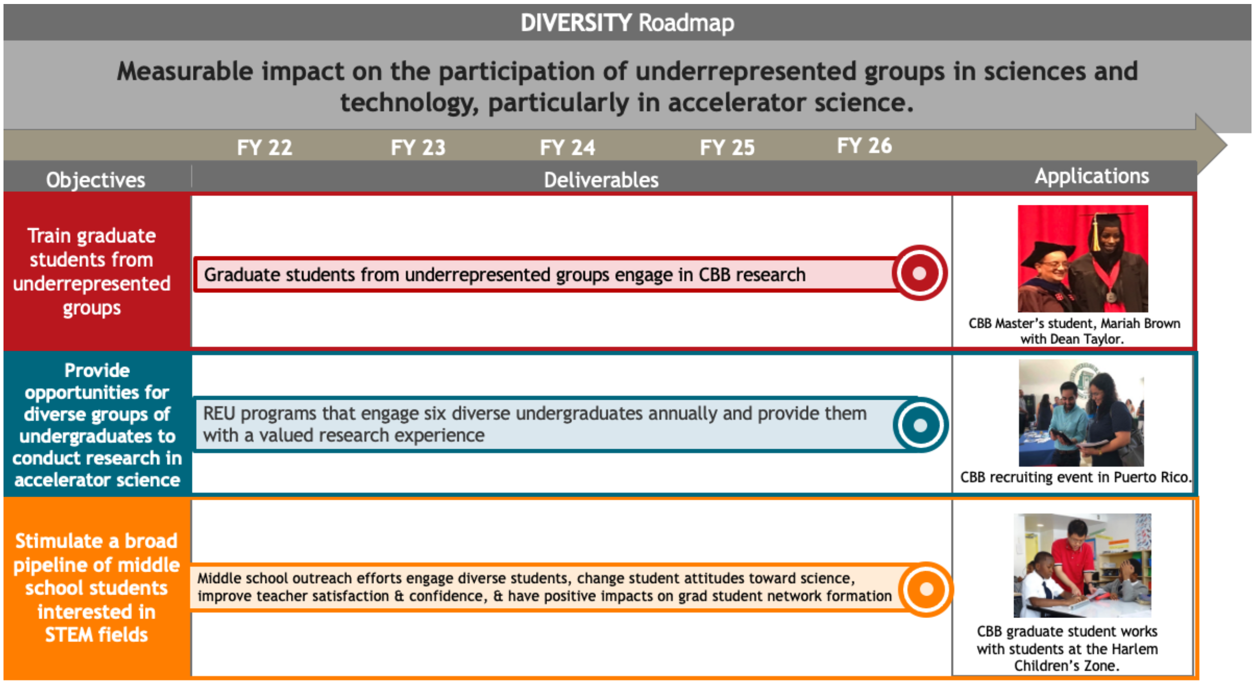

Figure 6. The Diversity roadmap.

KNOWLEDGE TRANSFER
Performance Objectives and Deliverables

Optimal Outcome: Frequent communication with CBB partners at national laboratories and in industry to promote the transfer of technology and prepare graduate students for productive careers in these sectors.

Objective 1: CBB discoveries and designs are incorporated into a new generation of accelerators and commercialized as products.

> **Deliverable**: CBB advances are incorporated into at least two accelerators or their applications (**Fall 2026).**

Objective 2. Trained graduate students are capable of recognizing and transferring critical skills to industry and national lab partners.

> **Deliverable**: Forty trained graduate students who are able to transfer their skills to industry and national lab partners **(Fall 2026).**

The Knowledge Transfer deliverables and their timelines are shown in Figure 7.

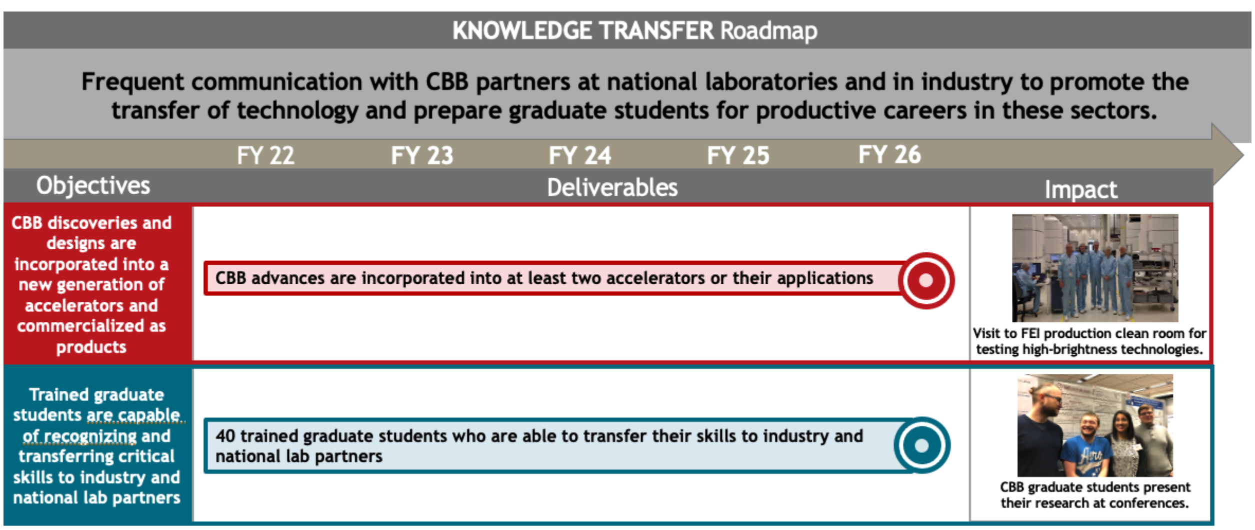

Figure 7. The Knowledge Transfer roadmap.

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.

Appendix A: Deliverables and Supporting Activities

Beam Production

Deliverable: A photocathode with 20 meV MTE at operational laser fluences, for example, by developing single-crystal, epitaxial alkali antimonides or other materials (October 2024).

Activity: Grow alkali-antimonides and other materials using molecular beam epitaxy (Karkare, Hines, Maxson, Shen) (Year 2021 – 2024)

Activity: Using advanced growth diagnostics such as *in-situ* electron and X-ray diffraction and *ex-situ* X-ray photoemission and optical characterization to develop single-crystal, epitaxial alkali antimonides (Maxson, Karkare, Hines, Shen) (Year 2021 – 2024)

Activity: Characterize structures with AFM/STM (Karkare, Hines, Padmore) and MTE and QE (Karkare, Maxson, Musumeci, Bazarov) to identify growth conditions that minimize MTE-increasing chemical and physical heterogeneities (Year 2021 – 2024)

Activity: Predict surface phase diagrams and MTE's to guide synthesis efforts and understand materials limits (Hennig, Arias)

Deliverable: A photocathode with 5 meV MTE at operational fluences by enhancing QE of ordered III-V and alkali antimonide photocathodes or other single crystals at threshold by engineering the density of states using dopants, heterostructure growth, and quantum-confined structures **(Fall 2026)**

Activity: Predict the effects of doping or layered structures computationally (Arias, Hennig, Karkare) (Year 2023 – 2026)

Activity: Grow structures using molecular beam epitaxy (Karkare, Hines, Maxson, Shen) **projects not yet started* (Year 2023 – 2026)

Activity: Characterize structures with AFM/STM(Karkare, Hines, Padmore) and MTE and QE (Karkare, Maxson, Musumeci, Bazarov) **projects not yet started* (Year 2023 – 2026)

Deliverable: Develop highly robust protective coatings or new materials that extend the photocathode lifetimes with little degradation in either QE or MTE. (Fall 2025).

Activity: Design coatings such as two dimensional materials or CsSb-based materials (Hines, Arias, Hennig) (Year 2021 – 2025)

Activity: Grow coated photocathodes (Karkare, Maxson, Padmore, Shen, Hines) (Year 2021 – 2025)

Activity: Test photocathodes in operating beam lines for robustness (Bazarov, Musumeci, Rosenzweig) (Year 2021– 2025)

Deliverable: An electron source with normalized transverse emittances approaching the fundamental limit of 0.2 pm set by the uncertainty principle for single electron per bunch beams **(Fall 2026).**

Activity: Use nanofabricated cathodes with embedded nanofocusing structures, nanostructured work function, and/or plasmonic optical confinement to enable sub-100-nm emission areas (Karkare, Padmore, Maxson, Muller) (Year 2021 – 2026)

Deliverable: Use nano-structure arrays to deliver pm-emittances for higher charge per bunch. **(Fall 2026).**

Activity: Produce ordering in the transverse plane using low MTE nanoscale tip emission arrays (Rosenzweig) (Year 2021 – 2026)

Activity: Produce ordering using plasmonic structuring of the light field using low MTE on planar photocathodes (Arias, Padmore) (Year 2023 – 2026)

Beam Acceleration

Deliverable: New and improved growth methods and alternative materials for increased cavity efficiency and operating temperature **(Fall 2026).**

Activity: Advance growth methods to achieve surfaces with the quality needed for high RF performance (Elam, Liepe, and Sibener). (Year 2022 – 2026)

Activity: Measure the superconducting surface resistance of these materials on small samples and determine field limitations and localize RF performance impacting regions (Liepe). (Year 2022 – 2026)

Activity: Characterize the performance impacting regions at the meso- to atomic-scale via FIB/STEM, XRD, EBSD, STM, AFM, XPS, supersonic atomic beam scattering, and other state-of-the-art tools and identify different types of defects (Liepe, Muller, Sibener). (Year 2022 – 2026)

Activity: Develop theory of defects that explains their formation, predicts their impact on vortex nucleation and RF dissipation, and guides refining growth methods (Hennig, Arias, Transtrum, Sethna). (Year 2022 – 2026)

Deliverable: Optimized inhomogeneous surface layers for increased cavity efficiency and increased accelerating fields (**Fall 2026**).

Activity: Develop theoretical models of structured layers to determine the best solutions at high field and high frequency (multi-GHz) (Arias, Transtrum, Sethna). (Year 2022 – 2026)

Activity: Synthesize inhomogeneous surfaces using optimized growth methods (Elam, Liepe, Sibener). (Year 2022 – 2026)

Activity: Characterize these surfaces across multiple length scales (Liepe, Muller, Sibener) (Year 2022 – 2026)

Activity: Measure performance to evaluate the extent to which surfaces can reach predicted ultimate performance (Liepe, Laxdal). (Year 2022 – 2026)

Deliverable: Surfaces from non-Nb at 20 MV/m with cooling power <1.5 kW/(active meter), corresponding to a 10× reduction in cooling power (relative to a 1.3 GHz Nb cavity with Q_0=2x10^{10} at 2K) **(Fall 2024).**

Activity: Synthesize and test compact proof-of-principle SRF cavities using the optimal protocols, laminates, and materials developed under Objectives 1 and 2 (Liepe, Posen). (Year 2022 – 2024)

Activity: Develop theories of superconductivity to calculate surface resistance under high-field and high-frequency conditions (Transtrum, Sethna, Arias). (Year 2022 – 2024)

Activity: Characterize low- and high-resistance regions to identify origin of inhomogeneities that limit performance (Liepe, Muller, Sibener). (Year 2022 – 2024)

Deliverable: Surfaces capable of sustaining higher accelerating field (from 20MV/m toward 40 MV/m) with ultra-high efficiencies (>10x reduction in cooling power), and surfaces approaching 400 mT (corresponding to 2× accelerating field increase) **(Fall 2026).**

Activity: Synthesize and test compact proof-of-principle SRF cavities using the optimal protocols, laminates, and materials developed under Objectives 1 and 2 (Liepe, Posen). (Year 2024 – 2026)

Activity: Develop theories of superconductivity to calculate surface resistance under high-field and high-frequency conditions (Transtrum, Sethna, Arias). (Year 2024 – 2026)

Activity: Characterize low- and high-resistance regions to identify origin of inhomogeneities that limit performance (Liepe, Muller, Sibener). (Year 2024 – 2026)

Beam Dynamics and Control

Deliverable: The sources of residual emittance growth in select optimized beam lines **(Spring 2022).**

Activity: Explore emittance preservation limits in UED (Musumeci, Karkare, Maxson) and xFEL (Piot, Rosenzweig) beamlines. (Year 2021 – 2024)

Activity: Observe global emittance trends as a function of operational parameters via multi-objective genetic optimization and will seek to identify the sources of residual emittance growth (Bazarov, Maxson, Musumeci, Piot). (Year 2021 – 2023)

Deliverable: Cathode longevity testing capability with beam to support Theme 1 developments **(Fall 2023)**.

> **Activity:** Study the limits of irreversible emittance growth in optimized cases (Kim, Maxson). (Year 2021 – 2022)

Deliverable: A list of the parameters that determine emittance growth in low MTE photoinjector beam lines **(Fall 2024).**

> **Activity:** Demonstrate high current (≥10 mA) with e.g. robust photocathodes developed by Theme 1 researchers using a new 400 kV electron photogun beamline (Bazarov, Maxson). (Year 2021 – 2023)

Deliverable: Proof of principle demonstrations of key elements of optical stochastic cooling at IOTA and CESR **(Spring 2023)**

> **Activity:** Design conceptually and test the stability of the long-delay bypass line for CESR (Bazarov, Maxson). (Year 2021 – 2022)
>
> **Activity:** Numerical models of optical stochastic cooling at IOTA and CESR (Bazarov, Maxson, Piot). (Year 2021 – 2023)
>
> **Activity:** Test a low-gain amplifier at IOTA (Piot, Nagaitsev, Valishev, Kim). (Year 2021 – 2023)
>
> **Activity:** Diagnostics for precise electron-light, spatio-temporal overlap at IOTA and CESR (Bazarov, Kim, Maxson, Piot). (Year 2021 – 2023)

Deliverable: Configurations capable of the very high cooling rates needed for use in a future colliders. **(Fall 2025)**

> **Activity:** Investigate the design of a high-gain amplifier based on an OPA at IOTA (Piot) (2022-2023) with possible demonstration in (2024-2025).

Deliverable: Single-pass correction of beam distortions and beam diagnostics using techniques developed for OSC **(Summer 2026)**

> **Activity:** Explore application of OSC-like technique to correct the beam in a single pass (Maxson, Piot). (Year 2026)

Deliverable: Methods for efficiently tuning an accelerator **(Summer 2026)**

> **Activity:** Compare performance of deterministic ML algorithms in a high gradient pulsed accelerators (Musumeci, Edelen) (Year 2021 – 2025)
>
> **Activity:** Apply ML to precise tailoring of the beam phase-space distribution at the Argonne Wakefield Accelerator and investigate efficacy of parameter reduction on ML performance. (Kim, Rosenzweig, Piot). (Year 2021 – 2026)

Activity: Implement tuning in an electron microscope based on CBB's 4D-STEM aberration measurement and minimization (Muller) (Year 2021 – 2025)

Activity: Investigate using both parameter reduction and ML-based surrogate modeling or reinforcement learning to diagnose and correct drift in a high repetition rate accelerator (Muller, Hoffstaetter, Kim) (Year 2021 – 2024)

Deliverable: Summary of the boundaries of applicability of ML in accelerators with varying noise types and data availability **(Summer 2026).**

Activity: Summarizing findings by the CBB ML team (Year 2025 - 2026)

Workforce Development

Deliverable: Effective communication practices across all aspects of research and administration **(Fall 2026)**.

Activity: Hold biweekly theme meetings(Year 2021 – 2026)

Activity: Convene Grad-to-grad meetings where graduate students present updates on their research (Year 2022 – 2026)

Activity: Program seminars featuring speakers from academia, national labs, and industry.

Activity: Arrange three 30-minute pedagogical talks each year, providing background knowledge necessary to understand and advance CBB research.

Activity: Share electronic copies of all slides, meeting agendas, and written reports and documents on protected web sites, Indico and Box platforms.

Activity: Formally onboard all new CBB members.

Deliverable: Shared goals and shared recognition **(Fall 2026)**.

Activity: Hold an annual meeting that consists of a one-day of research planning, a day of student training, one-day collaboration meetings, and a one-day annual symposium. (Year 2022 – 2026)

Activity: Host seminars, annual meetings, and other activities at rotating CBB venues (Year 2022 – 2026)

Activity: Facilitate research at other institutions through a travel grant program. ((Year 2022 – 2026)

Activity: Invite national lab and industrial researchers to share perspectives and needs at the annual symposia and through the seminar series (Year 2022 – 2026)

Activity: Support travel for all CBB members to present their results at conferences and workshops. (Year 2022 – 2026)

Deliverable: Strong leadership and transparent decision-making **(Fall 2026)**.

Activity: Yearly review process that considers research progress, research promise, and previous year's participation in CBB activities (Year 2021 – 2026)

Activity: Review and revise the Strategic Plan annually based on discussion with all CBB members and input from the EAB. (Fall 2026)

Deliverable: Faculty, postdocs, and students with the skills necessary to accomplish CBB goals, become leaders in their fields, and appreciate research challenges in accelerator sciences **(Fall 2026).**

Activity: Provide communications workshops each year for students and postdocs (Year 2022 – 2026)

Activity: Students and postdocs will practice communicating their science and receive feedback (e.g., theme meetings, annual collaboration meetings, and symposia). (Year 2022 – 2026)

Activity: Students will participate in a yearly "Poster Blitz" competition, in which every student is given up to 60 seconds and one slide to advertise their research. (Year 2022 – 2026)

Activity: Build persistence with educational outreach activities

Activity: Encourage students and postdocs to take at least one course at the US Particle Accelerator School.

Activity: Require that all graduate students develop an Individual Development Plan discussed with their advisor and updated annually.

Activity: Provide three 30-minute pedagogical talks annually to provide background knowledge necessary to understand and advance CBB research.

Activity: Require that all CBB participants complete the Harvard Implicit Bias diagnostics for race and gender in science.

Activity: Host speakers with experiences in entrepreneurship and technology transfer to give researchers a clear-eyed view of the challenges and rewards of commercializing research and the mechanism for doing so.

Activity: Require that all CBB researchers engage in case-based discussions of research ethics drawn in part from real-life misconduct investigations.

Activity: Provide mentoring training, often using case-based discussion, to all CBB members mentoring undergraduates, graduate students or postdocs.

Activity: Invite a wide cross-section of speakers to present seminars and Q&A session on their career paths to help students and postdocs envision themselves in a wide variety of careers including national labs, public service, teaching, R&D, consulting, business, and finance.

Deliverable: Center programming that evolves to meet the needs of Center members based on an external evaluation designed to provide formative information (**Fall 2026**).

> **Activity:** Yearly external evaluation that includes quantitative and qualitative instruments and data, including an annual climate survey, trainee and faculty surveys, team science survey, and interviews and focus group activities (Year 2022 – 2026)

Deliverable: 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 **(Fall 2026).**

> **Activity:** Create new modules, field test them in classrooms and with teachers, and train teachers to use existing ones.
>
> **Activity:** Perform student and teacher evaluations to determine efficacy of middle school modules (Year 2022 – 2025)
>
> **Activity:** Perform evaluation of the educational outreach activities on graduate students (Year 2022 – 2026)

Deliverable: Research Experiences for Undergraduates (REU) programs that support undergraduate students and provides them with a valued research experience **(Fall 2026).**

> **Activity:** Perform an evaluation of the Cornell REU program to compare and contrast REU student preparation and expectations prior to entering the program to their status after program completion. Results will be used to formulate program improvements. (Year 2022 – 2026)

Diversity

Deliverable: Graduate students from underrepresented groups engaged in CBB research **(Fall 2026)**

> **Activity**: Anitra Douglas McCarthy coordinates recruiting activities and travel with faculty to recruiting events, particularly those at minority-serving conferences and institutions (Year 2022 - 2025)

Deliverable: Research Experiences for Undergraduates (REU) programs that engage six diverse undergraduates annually and provide them with a valued research experience. **(Fall 2026)**

Deliverable: 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)**

Knowledge Transfer

Deliverable: CBB discoveries are incorporated into new generations of accelerators and commercialized as products **(Fall 2026).**

> **Activity**: Identify potentially transferable technologies and introduce them to client companies with the aim of joint development and pursuing SBIR/STTR opportunities. (Year 2022 – 2026)
>
> **Activity:** CBB work will be presented at the International Particle Accelerator Conference and at other international conferences.

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

> **Activity:** Students evaluate their aspirations early, and work with advisors to prepare ((Year 2022 – 2026)
>
> **Activity:** Provide workshops on topics such as mentoring and science communications. (Year 2022 – 2026)
>
> **Activity:** Match CBB graduate students with a mentor (Year 2022 – 2026)
>
> **Activity:** Develop internship opportunities for students, such as the Department of Energy's Science Graduate Student Research program. (Year 2022 – 2026)

Appendix B: Research Projects 2021

Beam Production

- Photocathodes for high peak-intensity beam generation with < 5 meV electron mean transverse energy
    - 3-D energy-momentum distribution measurements from single crystal metals (Karkare / Knill)
    - Ab initio theory of photoemission and of photomaterials (Arias / Nangoi)
    - Study of Alkali Antimonide photoemission characteristics in very high gradient electron guns (Musumeci / TBD)
    - Computational synthesis of photocathodes by epitaxial growth (Hennig / Gibson)
    - Improving the structural quality of alkali antimonide photocathodes via MBE growth and advanced characterization (Maxson / Galdi)
    - Optical and X-ray characterization of Alkali-antimonides (Karkare / Saha)
- Materials design for long-lived cathodes in extreme electric field and high average current
    - Air-stable, high performance photocathodes (Hines / Somaratne, Zhu)
    - Cryogenic photocathode characterization in a low voltage electron gun (Bazarov / Pierce)
    - Femtosecond Nonequilibrium Multi-photon Photoemission near Threshold, Improving robustness of photocathodes (Bazarov / Bae)
    - Atomically Ordered & Engineered Materials for Photocathodes (Shen / Parzyck)
    - Development of the ASU-DC cryogun (Karkare / Gevorkyan)
    - Alkali Antimonides at High Gradients (Maxson / Pennington)
    - Optimization of ultra-compact free-electron laser performance with very low MTE photocathodes (Rosenzweig / Lawler, Majernik)
- Approaching fundamental brightness limits with nanostructured photoemitters
    - Extreme High Brightness Electron Source from Intense Laser Illumination of Nano-Blades (Rosenzweig / Lawler, Mann)
    - Zone Plate Based Nano-emitters (Padmore / Chubenko)

Beam Acceleration

- Advanced SRF materials growth: Developing improved growth methods and understanding the impact of realistic (non-ideal) surfaces on performance.
    - Alternative Growth Methods of Nb3Sn and other Materials based on CVD and ALD (Liepe / Gaitan)
    - Alternative Growth Methods of Nb3Sn based on Electroplating and Sputtering (Liepe / Sun)

- Growth and spatially resolved surface characterization of smooth homogeneous Nb3Sn thin films (Sibener / Farber, Willson)
- Improving Vapor Diffusion Nb3Sn Growth to Increasing Maximum Fields in Nb3Sn (Liepe / Porter)
- Nb3Sn Composition and Strain (Muller / Baraissov)
- Nb3Sn interfaces: importance to growth and inverse-Q behavior (Arias / Kelley)
- Nucleation of Nb3Sn and impact of point defects on electron scattering (Arias / Sitaraman)
- Sn Nucleation, diffusion, and Nb3Sn Alloying mechanisms studies to inform optimal Nb3Sn growth (Sibener / Farber, Willson)
- Surface scattering studies of alloying mechanisms, diffusion and modification of interfacial forces of Sn on oxidized Nb (Sibener / Graham, Thompson)

- Multi-layers and inhomogeneous layers: Increasing RF performance via surfaces by design.
    - Next-Gen SRF Surfaces (Liepe / Oseroff)
    - Optimizing surface layers for SRF Performance (Transtrum / Francis)
    - Thermodynamics and superconducting properties of novel SRF superconductors (Hennig / Hire)
    - Time-Dependent Ginzburg-Landau studies of realistic materials and surfaces (Transtrum / Harbick)
- 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

- Exploration of the ultimate limits of brightness conservation in the presence of collective effects in low mean transverse energy photoinjector beamlines (Conserve).
    - Beam Dynamics for Ultrafast Electron Diffraction with High QE cathodes: Charge Density and Laser fluence effects (Maxson / Li)
    - Brightness limiting effects of point to point space charge (Kim / Gordon)
    - Microscope Tuning by ML and Emittance Optimization (Muller / Zhang)
    - Ultrafast electron diffraction as an application demonstration of CBB photocathodes, and transmission electron microscope modelling for online optimization (Maxson / Duncan)

- Methods for cooling beams using optical stochastic cooling to increase beam luminosity in next-generation colliders (Cool).
    - Optical Stochastic Cooling in CESR and development of the 400 kV electron photoemission gun diagnostics beamline (Bazarov / Andorf)

    - Optical Transport and Beam Manipulation for Optical Stochastic Cooling (Piot / Dick)
    - Studies for optical stochastic cooling and development of the 400 kV electron photoemission gun diagnostics beamline (Bazarov / Levenson)

- Investigation of advanced optimization schemes, including machine learning and parameter reduction techniques, for precision phase-space control of particle accelerator systems (Control).
    - Experimental nonlinear integrable optics studies at the integrable optics test accelerator (Kim / Kuklev)
    - Extensible software tools and methods for using surrogate modeling in injector and FEL systems (Kim / Gupta)
    - Intelligent laser control with uncertainty quantification for electron beam generation (Biedron / Aslam)
    - Large scale multi-objective Bayesian optimization for online accelerator control and tuning (Kim / Roussel)
    - Machine-learning assisted high brightness photoinjector optimization (Musumeci / Cropp)
    - Operating hadron coolers with Machine Learning (Hoffstaetter / Lin)