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	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 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.

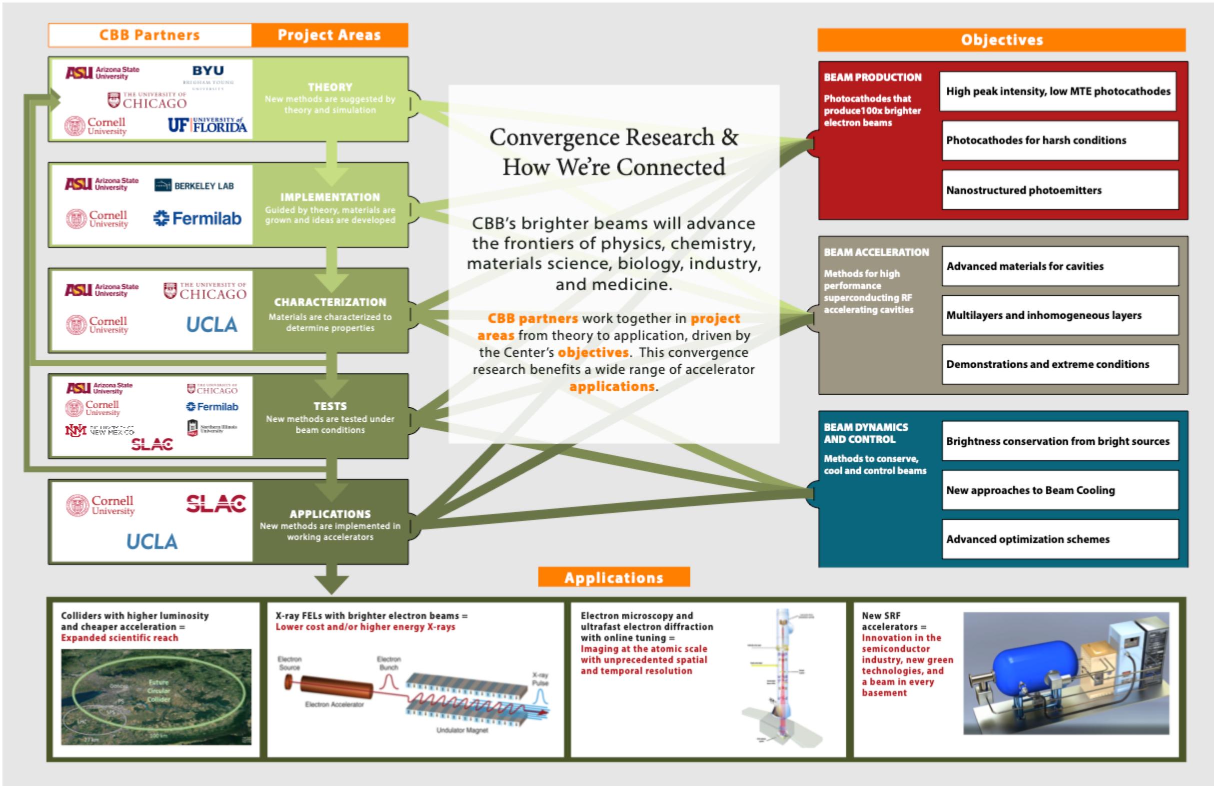

Figure 1. CBB research roadmap. CBB activities in the project areas (left) advance CBB towards it objectives (right). The objectives have been selected to benefit a wide range of beam applications (bottom).

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 < 10 meV 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 (**Summer 2022**)

> **Plan:** CBB recently grew an atomically ordered Cs_3Sb photocathode with near-zero physical and chemical roughness [6], and we will soon test it in an MTE measurement system (TEmeter). If ordering is sufficient, theory shows that CBB will meet this deliverable.

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 2024**)

> **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. Initial testing will be done at low laser fluence in MEDUSA (Cornell).
>
> **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 a 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 heterostructured 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, 1.4, 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.

Deliverable 1.4: A photocathode with MTE < 10 meV and QE $> 10^{-4}$ at laser fluences in excess of 50 μJ/cm^2 (**Fall 2026 stretch goal**)

Plan: This is likely to require an epitaxial, high quantum efficiency, semiconductor photocathode, ideally with significant response to visible or near-IR light. In addition, the sample will either need to be cryocooled to liquid nitrogen temperatures and below, and/or employ very low effective mass. Target materials include alkali antimonides, including Cs_3Sb, where epitaxial growth has been experimentally demonstrated.

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 mJ/cm^2 laser fluence and high field (>100 MV/m) for high peak current applications such as 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 like 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 is planned for the PEGASUS beamline at UCLA.

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, 1.4, 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 (>50 mA) conditions (**Summer 2026**)

Plan: CBB will pursue multiple approaches including developing 2-D material coatings like 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, developing new robust work function reducing layers for GaAs or other III-V materials. Testing will be done in a high-current DC gun at Cornell under *BDC Deliverable 1.3*.

End User: BNL electron cooler for RHIC and e-RHIC. 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: CBB plans to use plasmonic focusing, work-function patterning and/or immersion lenses to obtain sub-100 nm emission areas using photoemission from flat surfaces.

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.*

Risk: Impurities/imperfections in nanofabrication.

Mitigation: Identify the reason for imperfections and develop better nanofabrication processes. CBB is also pursuing multiple approaches simultaneously as stated in the plan to mitigate risks. Resources will be shifted from Deliverables 3.2 and 3.3 to this deliverable if needed.

Deliverable 3.2: 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**)

Plan: Use the small spot techniques in previous deliverables in conjunction with low MTE films under cryogenic conditions if necessary and possibly collimating apertures. This technology would benefit ultrafast electron microscopes operating in stroboscopic regime and ultrafast EELS systems. Continuous beam electron microscopy is a stretch goal.

Deliverable 3.3: Nano-structured arrays that deliver pm-emittances for higher charge per bunch (**Fall 2026, stretch goal**)

Plan: Experimental demonstration efforts have not yet started. CBB will re-evaluate the value and viability of this deliverable after making progress on *PHC Deliverables 3.1 and 3.2* in the next two years.

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

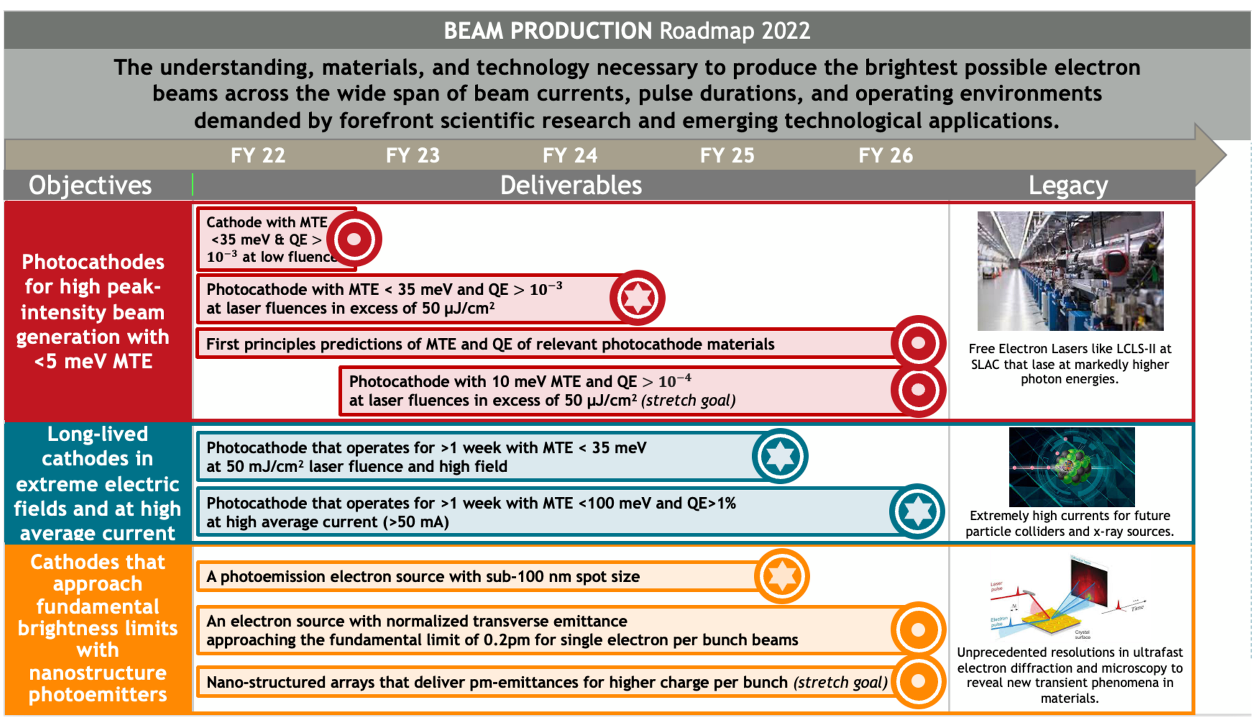

Figure 2. The Beam Production roadmap.

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 focussed on achieving highly efficient cavity operation at the cost of reducing effort on pushing maximum $_{\text{fields}}$ 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.

Deliverable 3.4: Documentation of best practices in specifying SRF material growth processes, critical material parameters, and material validation (**Fall 2026**)

Plan: An important component of the SRF Theme legacy will be to transfer the knowledge base that was developed by CBB for optimized materials growth for our most successful materials and processes to the end user accelerator community. To ensure the optimization of this handoff, CBB will develop and relate best practices. This documentation will span substrate preparation, material growth procedures, and deposition on substrates. Checkpoints in growth and superconducting performance will be documented, thereby enabling the ability of researchers elsewhere to duplicate our most important findings.

SRF materials researchers and growers will directly benefit from these legacy transfers via their ability to quantify when they are precisely creating the materials and coatings that were so very carefully refined as part of the CBB condensed matter, superconducting, surface chemistry, and theory unified effort in advancing this aspect of accelerator science.

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

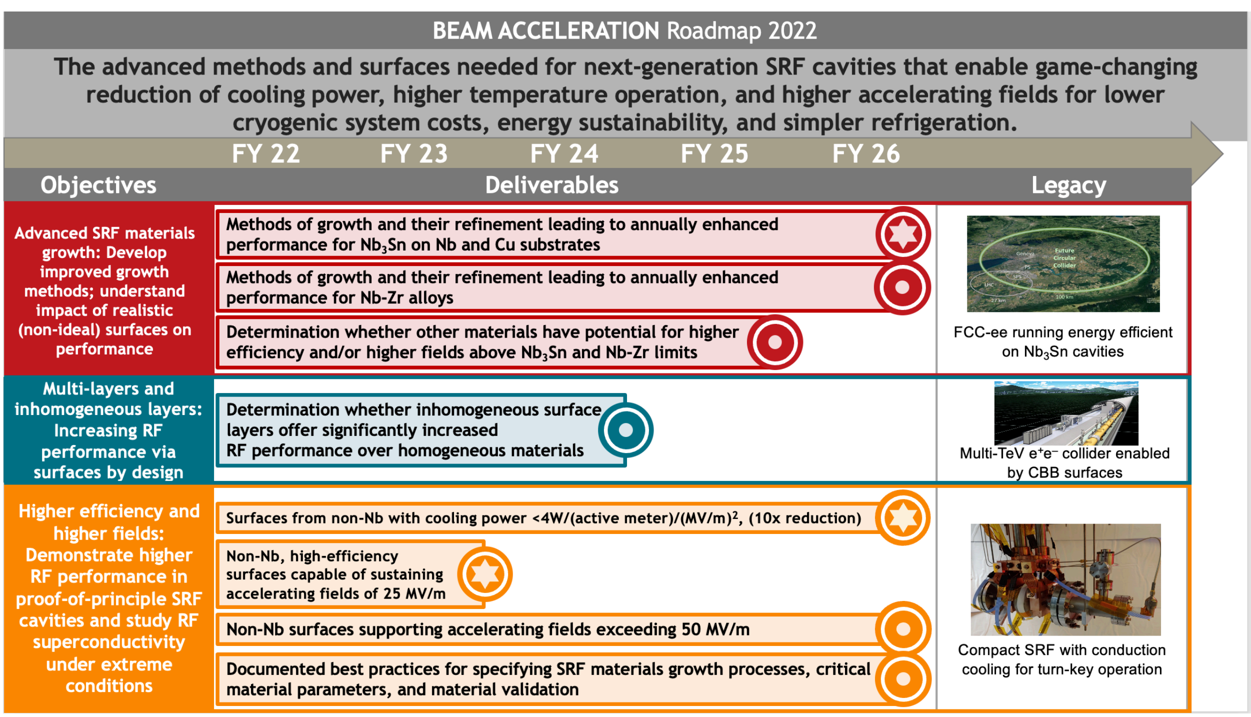

Figure 3. The Beam Acceleration roadmap.

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

> **Plan:** CBB recently demonstrated the generation of sub-nanometer emittances at the MEDUSA beamline at Cornell at low bunch charge (Q ~ 500 e) [7]. 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 1.2: 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:** CBB has demonstrated the impact of low MTE photocathodes in simulation for an SRF gun for LCLS-II-HE and a beamline for ultrafast electron diffraction (UED) [8]. Next, CBB will conduct simulations for beamlines to which CBB has access such as PEGASUS, the FAST-IOTA injector, AWA, and the UCLA C-band cryogun to determine whether CBB could conduct or participate in a convincing demonstration of the scientific reach of CBB low MTE photocathodes (*PHC Deliverable 1.2*). If a viable demonstration is identified, then CBB will develop a Deliverable to address it.

Deliverable 1.3: 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: Demonstrate high-current (≥10 mA) with robust photocathodes developed under *PHC Deliverables 2.1* and *2.2* using facilities such as the HERACLES beamline (Cornell). Demonstrate the transport of low-MTE cathode to geographically distant facilities such as FAST-IOTA or the PEGASUS facility (UCLA), and test and characterize their performance in a high-gradient gun, building on initial results obtained at PEGASUS. 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 [9] and the implementation of an OSC model in the popular codes BMAD [10] and ELEGANT [11].

Deliverable 2.2: Proof-of-principle demonstrations of key elements of *active* optical stochastic cooling at IOTA or CESR (**Summer 2025**)

Plan: Use numerical models developed by CBB to explore new lattice options for the IOTA active-OSC phase. Test low-gain optical amplifier. If possible, design conceptually and test the stability of the long-delay bypass lines, install and commission a long-delay light path in CESR to enable beam transport and stability studies related to optical stochastic cooling.

Deliverable 2.3: Configurations capable of the extremely high cooling rates needed for use in a future collider (**Summer 2026**)

Plan: Investigate the design of a high-gain active OSC system and demonstrate its practical application (via simulation) in a collider (or possible light-source) design. A preliminary study was performed for EIC but needs to be re-evaluated and finalized.

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 trained a convolutional neural network to determine the beam emittance in an STEM from a single ronchigram and applied gaussian processes to optimize corrector parameters [12].

Deliverable 3.2 (Priority): 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: CBB has already achieved performance comparable to that of traditional operator tuning using its ML techniques [12]. These techniques will continue to be improved and tested on the Cornell Titan and Spectra aberration correctors.

End User: Companies such as Thermo Fisher Scientific (TFS) that manufacture electron microscopes or Corrected Electron Optical Systems (CEOS), which manufactures the majority of aberration correctors. The transfer of this technology is *KT Deliverable 2.6*.

Risk: Progress may be slower than expected.

Mitigation: CBB may delay the schedule for this deliverable, and if needed, would redirect effort from *BDC Deliverables 3.3* and *3.4*.

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

Plan: CBB participants have applied ML to optimize and control accelerators [13], [14], 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, stretch**).

Plan: CBB participants are successfully applying 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. This rich and diverse experience will provide important input on the boundaries of applicability of ML in accelerators and will be summarized, most likely as a review article.

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

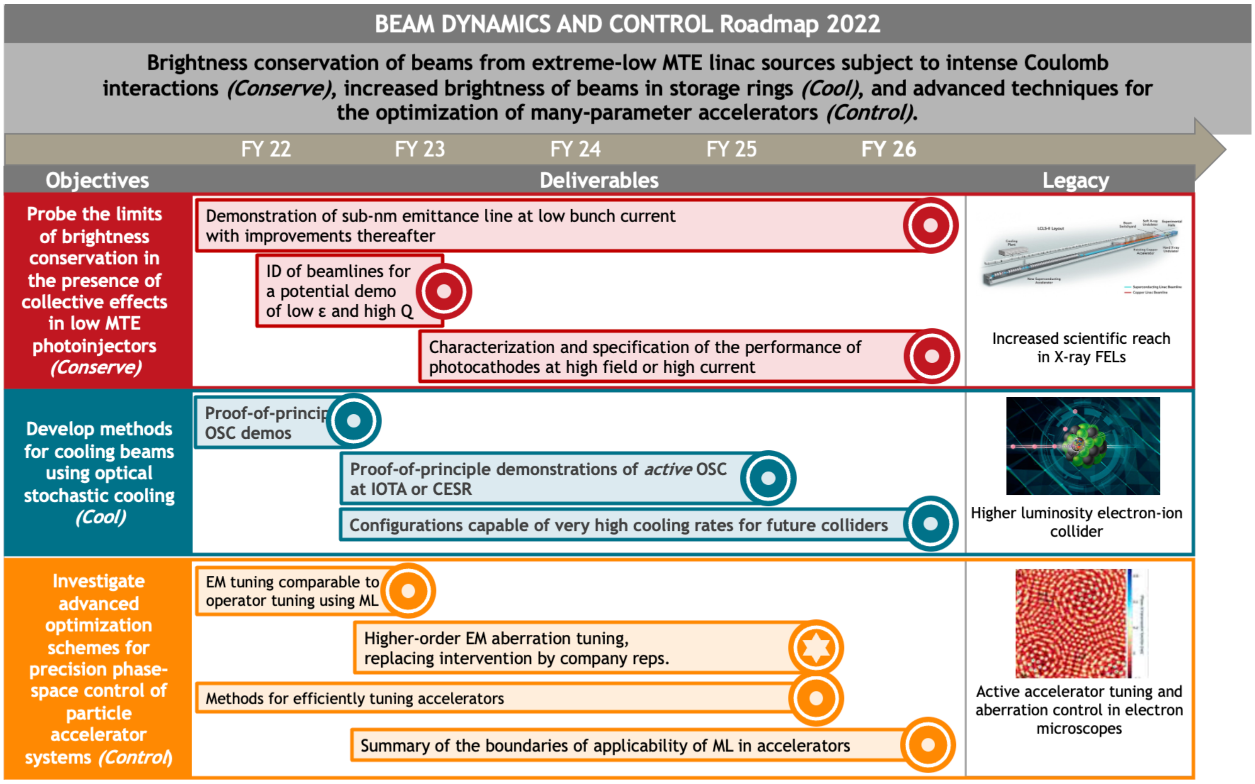

Figure 4. The Beam Dynamics and Control roadmap.

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.

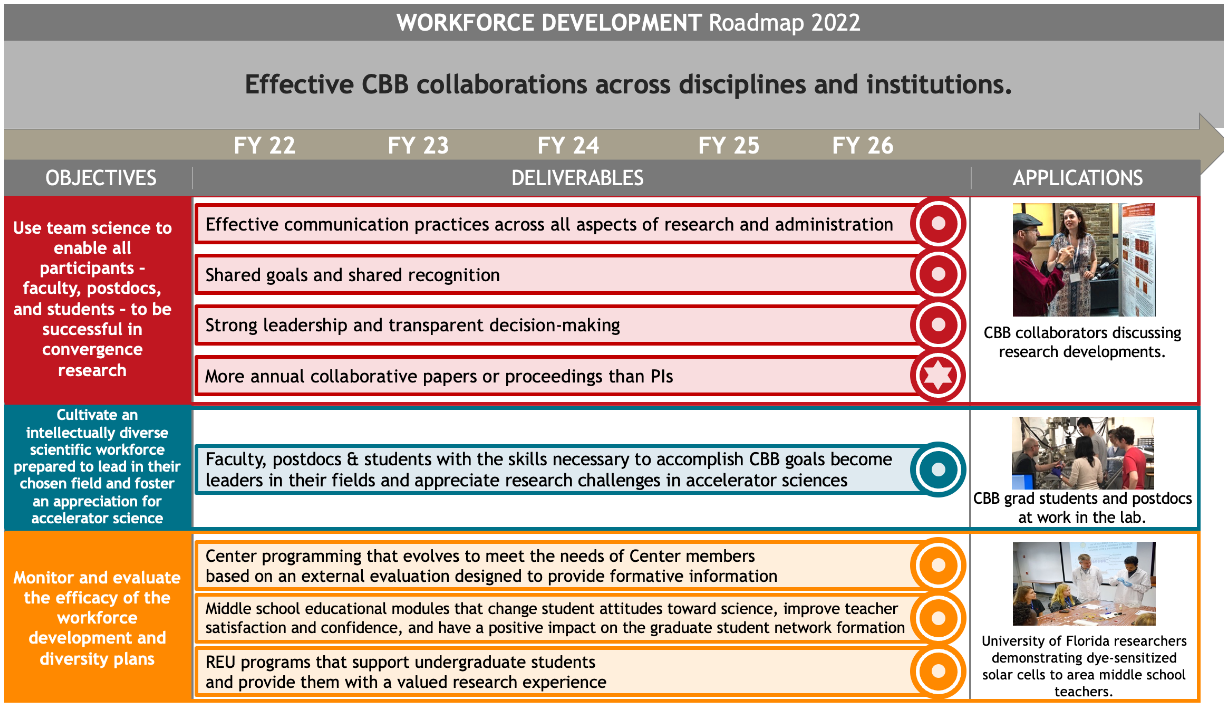

Figure 5. The Workforce Development roadmap.

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.

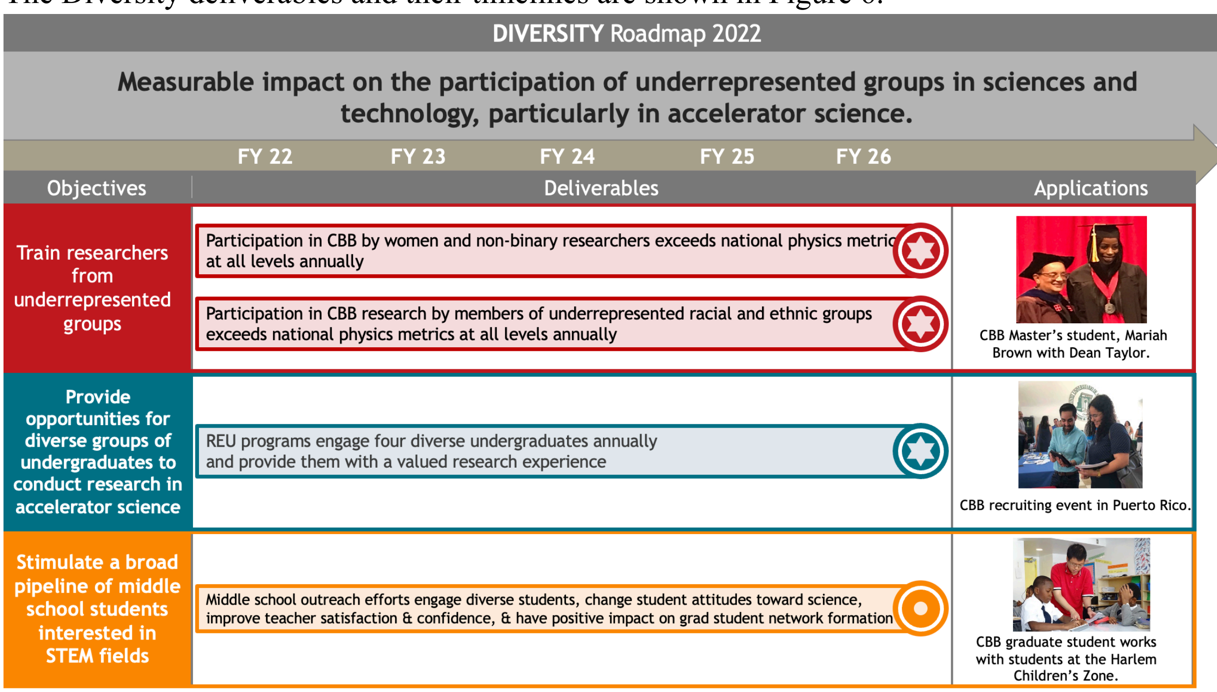

Figure 6. The Diversity roadmap.

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 (*PHC Deliverable 1.2*).

> **Plan**: This photocathode is aimed at the needs of the LCLS-II-HE SRF gun and electron microscopes. The LCLS-II-HE gun will deliver <100 μA beam current and, as an SRF gun, is expected to have good vacuum conditions. Past demonstrations indicate that MTE of 35 meV would be preserved in the LCLS-II-HE gun for the timescale of a day or more. CBB scientists (Karkare, Maxson, Musumeci) have submitted a joint proposal with scientists from SLAC (Dunham, Llewellyn, Vecchione) and LBNL (Filipetto) that would enable tests in Pegasus and at LBNL at high field and at low field in guns at Cornell and ASU. IDES/JEOL has also expressed interest in implementing such a photocathode in

one of its electron microscopes. 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.

Deliverable 2.2. The transfer of CBB methods for a photocathode that can operate for >1 week with MTE <35 meV at 50 mJ/cm2 laser fluence and high field (>100 MV/m) for high peak current applications such as compact XFELs (*PHC Deliverable 2.1*).

Plan: This photocathode is directed at the needs of advanced accelerators such as compact X-ray FELs. CBB is connected with the compact X-ray FEL community, and the leader of one design (UCXFEL) is a CBB participant.

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 (*PHC Deliverable 2.2*).

Plan: This photocathode would benefit a BNL electron cooler for RHIC or e-RHIC. BNL is exploring the use of GaN-based cathodes or applying a robust coating to GaAs cathodes. CBB is collaborating with BNL scientist and CBB affiliate Luca Cultrera on this work. Another approach is to coat Cs_3Sb with graphene (at CBB, Euclid Lab and LANL); here CBB brings unique expertise in graphene coating techniques. If successful, CBB's close ties with Cultrera will facilitiate adoption by BNL.

Deliverable 2.4: The transfer of CBB technology for a photoemission source with sub-100 nm spot size (*PHC Deliverable 3.1*).

Plan: IDES/JEOL and CBB are in discussions about the transfer of such a source, pending demonstration in a photoemission gun.

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 (*SRF Deliverables 3.1 and 3.2*).

Plan: CBB scientists will continue regular meetings 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. In addition, CBB scientists (Bazarov, Hoffstaetter, Liepe and Maxson) have submitted a joint proposal with scientists at Ion Linac Systems for beam testing a conduction cooled cavity and initiating tech transfer. CBB will share documentation of best practices in specifying SRF material growth processes, critical material parameters, and material validation (*SRF Deliverable 3.4*).

Deliverable 2.6: The transfer of CBB ML techniques for tuning the higher-order 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*).

Plan: CBB scientist David Muller (Cornell) will collaborate closely with teams led by Heiko Muller at Corrected Electron Optical Systems (CEOS) and Dmitri Klenov at Thermo Fisher Scientific (TFS). Already, 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. The software will be tested on the Cornell Titan and Spectra aberration correctors repeatedly through the development process, and following completion of the software in Summer 2025, Muller will test the package on instruments at TFS R&D facility in Aacht (with Klenov).

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

Plan: CBB collaboration with industry and lab scientists has already resulted in the incorporation of CBB technology and methods in operating accelerators. An SRF cavity incorporating CBB advances is now in operation at NSLS-II, a copper CBB photocathode demonstrated MTE of 5 meV at the HI-RES beamline at LBNL, and a CBB-contributed delay system enabled the demonstration of optical stochastic cooling at Fermilab's IOTA. Future possibilities for transfer into operating accelerators beyond those highlighted in *KT Deliverables 2.1-2.6* include ML techniques applied to cooling at RHIC and laser pulse shaping controls for the Accelerator Test Facility's main accelerator at BNL.

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 7.

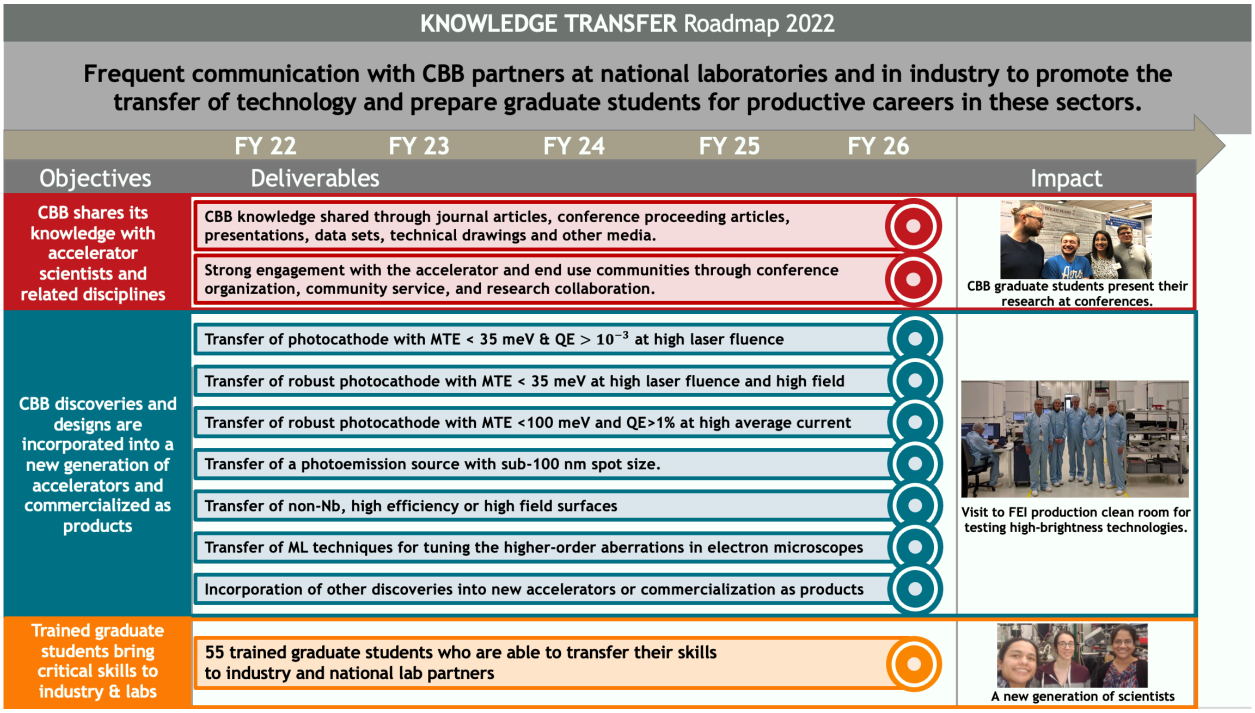

Figure 7. The Knowledge Transfer roadmap.

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Appendix: Research Projects 2021-22

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 < 5 meV MTE

- Atomically Ordered & Engineered Materials for Photocathodes (Shen / Anil)
- Growth and Characterization of the Epitaxial Alkali Antimonides: Exploring growth parameters, MET, QE, and robustness (Maxson / Echeverria)
- Ab initio theory of photoemission and of photomaterials (Arias / Nangoi)
- Computational synthesis of photocathodes by epitaxial growth (Hennig / Gibson)
- Measurements of low energy electron distributions (Karkare / Knill)
- Optical, X-ray and surface characterization of Alkali-Antimonides (Karkare / Saha)
- Cryogenic photocathode characterization in a low voltage electron gun (Bazarov / Pierce)

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

- Air-stable, high performance photocathodes (Hines / Somaratne, Zhu)
- MTE of easily oxidizable photocathodes both with and without protection coatings (Maxson / Li)
- High Gradient Testing and the Brightness of Epitaxial Alkali Antimonides (Maxson / Pennington) (also BDC)
- Advanced photocathodes testing in high gradient RF gun at the UCLA Pegasus Laboratory (Musumeci / Garcia) (also BDC)

Objective 3: Approach fundamental brightness limits with nanostructured photoemitters

- Extreme High Brightness Electron Source from Intense Laser Illumination of Nano-Blades (Rosenzweig / Lawler, Mann)
- Nanoscale photoemitters (Karkare / Chubenko)

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* study of Nb and Nb_3Sn surfaces and interfaces relevant to SRF performance (Arias / Sitaraman)
- Advanced Growth Methods for Next-Gen SRF Surfaces (Liepe / Gaitan)
- Detecting and Visualizing Alloy Growth Mechanisms of Nb_3Sn and Zr_xNb_7 that inform Optimal Growth Procedures for Next-Generation SRF Materials (Sibener / Farber, Willson)
- Electroplating based Growth and Surface Oxides (Liepe / Sun)
- High-field Nb_3Sn (Liepe / Shpani)
- Investigating the Atomic and Micron-scale Morphological Development of Nb_3Sn leading to Smooth Homogeneous Thin Films (Sibener / Farber, Willson)
- Optimizing surface layers for SRF Performance (Transtrum / Francis)
- Surface scattering studies that connect Atomic-Scale Structure and Dynamics to the Superconductivity of SRF Materials by Design (Sibener / McMillan, Thompson, Van Duinen)
- Time-Dependent Ginzburg-Landau studies of realistic materials and surfaces (Transtrum / Harbick)
- Thermodynamics and superconducting properties of novel SRF superconductors (Hennig / Hire)

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

- *Ab initio* studies of lattice and electron excitations relevant to SRF performance and inverse-Q behavior (Arias / Kelley)
- SRF Surfaces by Design (Liepe / Oseroff)

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.

- Brightness limiting effects of point to point space charge (Kim / Gordon)
- Demonstrating Emittance Preservation in Ultrafast Electron Micro-Diffraction (Maxson / Duncan)
- Development of the ASU-DC cryogun (Karkare / Gevorkyan)
- Exploring the Impact of Radiation Field on Brightness (Piot / Al Marzouk)
- Optimization of ultra-compact free-electron laser performance with very low MTE photocathodes (Rosenzweig / Majernik, Lawler)
- Strongly nonlinear space-charge in photoinjectors with collimating apertures (Maxson / Li)
- High Gradient Testing and the Brightness of Epitaxial Alkali Antimonides (Maxson / Pennington) (also PHC)
- Advanced photocathodes testing in high gradient RF gun at the UCLA Pegasus Laboratory (Musumeci / Garcia) (also PHC)

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

- Feedback System and Isochronous Lattice Development towards an Optical Stochastic Cooling Stability Experiment (Bazarov / Levenson)
- Optical Transport and Beam Manipulation for Optical Stochastic Cooling (Piot / Dick)

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

- Advanced beam manipulations enabled by novel computational techniques in beam physics (Musumeci / Cropp, Isen, Guo)
- Application of Machine Learning in Compact Photoinjectors (Biedron / Aslam)
- Auto-differentiable accelerator modeling for high-dimensional optimization (Kim / Aguilera)
- Microscope Tuning by ML and Emittance Optimization (Muller / Zhang)
- Operating hadron coolers with Machine Learning (Hoffstaetter / Lin)