Vision and Mission

Vision

Transform society by revolutionizing the brilliance of 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 will extend the capabilities of the 10,000 U.S. researchers who rely on beams of electrons or photons to advance the frontiers of physics, chemistry, materials science, biology, and medicine. The proposed research will lead to new methods that reduce the cost and improve the performance of small laboratory instruments and industrial tools as well as large colliders and X-ray sources. Brighter beams for ultrafast electron diffraction will enable synthetic chemists to probe processes such as photocycle dynamics in larger, more complex molecules. Brighter beams will allow applied physicists and biologists to access new regions of phase space and to image directly the atomic motions in high-temperature superconductors or folding proteins. Brighter beams will enable transformative methods for studying the full dynamics of single macromolecules, such as proteins, as they respond to stimuli, providing insights into structural biology and biodynamics that we can only envision. Compact, high-flux, hard X-ray sources from Compton backscattering will enable materials scientists to conduct precision microscopy of structural materials. Coherent continuous-wave hard X-ray sources with brighter beams will enable condensed matter physicists to study nanoscale phase separation in correlated electron systems. Linear, circular, and energy-recovered colliders with brighter beams will allow particle physicists to probe nearer the big bang and nuclear physicists to peer deeper inside the proton.

CBB will transfer its bright beam technology to the national laboratories that build large-scale accelerators and to market leaders in areas such as accelerator components (Radiabeam),
electron microscopy (FEI), and wafer inspection (Applied Materials). These companies recognize that the proposed work can help them gain competitive advantages in the marketplace. By increasing the resolution and throughput of critical semiconductor manufacturing equipment, our work will satisfy a necessary condition for continued growth of the $300B integrated circuit industry and the $2T electronics industry.

The effort of young scientists will be essential to achieving these goals. We will provide students with experience in effective team science, and a program that integrates professional development with their research. The outcome will be a new generation of scientists, drawn from a diverse population, and prepared for leadership in a broad range of career paths.

**Guiding Principles**

1. Research 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. 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. 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. 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. 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.

**Research**

**Introduction**

The Research Optimal Outcomes address three major challenges in achieving bright electron beams.

*Theme 1 -- Beam Production Optimal Outcome:* Methods for x100 brighter electron beams through better photocathodes, enabling better X-ray sources, colliders and electron imaging.
Theme 2 -- *Beam Acceleration Optimal Outcome*: Methods for x10 lower power losses and x2 higher accelerating fields in RF cavities made of niobium and compound superconductors, for lower costs, simpler refrigeration and wider access to high-power beams.

Theme 3 – *Beam Storage and Transport Optimal Outcome*: 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.

*All Themes – Integration*: Integration of these methods for optimization of high performance of accelerator systems.

The Beam Production theme joins materials scientists, chemists, condensed matter physicists and accelerator scientists to invent photocathode materials capable of producing beams with low mean transverse momentum. These beams will improve X-ray sources, particle colliders and electron imaging.

The Beam Acceleration theme will enable superconducting accelerating cavities with x10 lower power losses for lower costs, simpler refrigeration and wider access to high-power beams. It also aims to double the available accelerating gradient for less expensive, more compact accelerators. To achieve these goals, it will harness the expertise of condensed matter physicists and physical chemists to understand RF superconductivity, and learn to control the surfaces of niobium and compound superconductor cavities.

The Beam Transport and Storage theme will direct its efforts toward the mastery of non-linear effects that reduce brightness and destabilize stored beams for better, less expensive control of beams in electron microscopes and storage rings. To reach this goal, it will use the tools of nonlinear dynamics to analyze dynamic aperture and test the strategies they suggest for limiting emittance growth.

In order to deliver optimized beams to their target, the Beam Production, Beam Acceleration, and Beam Transport and Storage systems must work symbiotically. Our final Research Optimal Outcome is therefore the Integration of these methods for the optimization of high performance of accelerator systems.

We anticipate that these activities, which integrate the expertise of many disciplines to deliver transformative accelerator technologies, will reshape the field of accelerator science. Interest in accelerators by university researchers across the physical sciences will grow, expanding the pipeline of young accelerator scientists and increasing the pace of progress in the field.

The leaders of the research teams are Siddharth Karkare, Jared Maxson and Howard Padmore (Beam Production), Steve Sibener and Matthias Liepe (Beam Acceleration) and Young Kee Kim and Ivan Bazarov (Beam Transport and Storage). In each case, at least one co-leader brings expertise in accelerator science and another brings expertise in a related essential discipline.
The research team includes senior participants, affiliates, postdoctoral associates and graduate students. The senior participants and affiliates (denoted with “(A)”) are:

<table>
<thead>
<tr>
<th>Last</th>
<th>First</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arias</td>
<td>Tomas</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Bazarov</td>
<td>Ivan</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Barletta (A)</td>
<td>William</td>
<td>Lawrence Berkeley National Lab</td>
</tr>
<tr>
<td>Biedron (A)</td>
<td>Sandra</td>
<td>University of New Mexico</td>
</tr>
<tr>
<td>Cultrera (A)</td>
<td>Luca</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Filippetto (A)</td>
<td>Daniele</td>
<td>Lawrence Berkeley National Lab</td>
</tr>
<tr>
<td>Gulliford (A)</td>
<td>Colwyn</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Hartill (A)</td>
<td>Donald</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Hennig</td>
<td>Richard</td>
<td>University of Florida</td>
</tr>
<tr>
<td>Hoffstaetter (A)</td>
<td>Georg</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Hines</td>
<td>Melissa</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Japaridze</td>
<td>George</td>
<td>Clark Atlanta University</td>
</tr>
<tr>
<td>Kaloshin (A)</td>
<td>Vadim</td>
<td>University of Maryland</td>
</tr>
<tr>
<td>Karkare</td>
<td>Siddharth</td>
<td>Arizona State University</td>
</tr>
<tr>
<td>Kim</td>
<td>Young-Kee</td>
<td>University of Chicago</td>
</tr>
<tr>
<td>Kourkoutis (A)</td>
<td>Lena</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Laxdal (A)</td>
<td>Robert</td>
<td>TRIUMF</td>
</tr>
<tr>
<td>Liepe</td>
<td>Matthias</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Maxson</td>
<td>Jared</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Meller (A)</td>
<td>Robert</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Miller (A)</td>
<td>Dwayne</td>
<td>University Toronto</td>
</tr>
<tr>
<td>Muller</td>
<td>David</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Musumeci</td>
<td>Pietro</td>
<td>University of California Los Angeles</td>
</tr>
<tr>
<td>Nagaitsev (A)</td>
<td>Sergei</td>
<td>Fermi National Accelerator Laboratory/U. Chicago</td>
</tr>
<tr>
<td>Padmore</td>
<td>Howard</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td>Patterson</td>
<td>J Ritchie</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Posen</td>
<td>Sam</td>
<td>Fermi National Accelerator Laboratory</td>
</tr>
<tr>
<td>Rand (A)</td>
<td>Richard</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Rosenzweig</td>
<td>James</td>
<td>University of California Los Angeles</td>
</tr>
<tr>
<td>Rubin (A)</td>
<td>David</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Sagan (A)</td>
<td>David</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Sethna</td>
<td>James</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Shen</td>
<td>Kyle</td>
<td>Cornell University</td>
</tr>
<tr>
<td>Sibener</td>
<td>Steven</td>
<td>University of Chicago</td>
</tr>
</tbody>
</table>
Research Optimal Outcome 1 – Beam Production

Methods for x100 brighter electron beams through better photocathodes, enabling better X-ray sources, colliders and electron imaging.

Objective A. Demonstrate mean transverse energy (MTE) of 10 meV and understand the tradeoffs required to reach this goal without sacrificing the beam brightness (year 5). For example, photocathodes with a very long response time can give lower MTE’s, but at the expense of reduced peak brightness.

Interim goal: Demonstrate 50 meV MTE under realistic photoemission conditions (pulse energy, pulse length) to extend the baseline photon energy reach and flux of next generation FELs and inverse Compton scattering X-ray sources.

In the first three years, CBB has developed and characterized the extreme low MTE performance (<20 meV) of both semiconductor and metallic photocathodes at low laser pulse energies, with the role of band structure and many-body effects investigated both experimentally and in first-principles modeling. Last year we have demonstrated an MTE of 5 meV from the ordered Cu(100) surface cooled to liquid helium temperatures completing this objective. Additionally, we have measured the energy spread from such a source to be 10 meV, making it the most monochromatic electron source. Such a low MTE and monochromatic cathode will have a transformative impact of high repetition rate UED/UEM and will enable new techniques like time resolved EELs with a 10 meV scale energy resolution.

A simultaneous effort has shown that electron heating and multi-photon emission effects will degrade the brightness of electrons emitted from this source if used for applications like single-shot UED and FELs that require a large charge density. The highest priority for Year 4 continues to be quantitatively characterizing ultrafast heating and multi-photon effects in low-MTE cathodes and determine their effect on beam brightness. This will require addressing the impact of these effects on MTE in semiconductors both via simulation and experimentally, by performing time resolved pump-probe measurements. This remains unchanged from last year.

Activities needed to reach Objective A for single shot UED and XFEL applications include using computational modeling to predict emission properties of new and designed materials, characterizing the chemical and morphological heterogeneity of as-grown photocathodes and
develop processes to improve them, growing materials using Molecular Beam Epitaxy (MBE) and characterizing them in-situ, and developing methods to measure MTE in the lab and in photoguns.

To achieve the interim goal, CBB will continue to evaluate both disordered alkali antimonides and ordered semiconductors. In particular, understanding the role of multiphoton/heating effects will be critical. These activities and goals are largely the same as year 3 and we are making good progress on them.

Objective B. Demonstrate 1 nm-rad emittance from a photoemission gun for bunches containing 10^5 electrons. (Year 4)

Interim goal: Measure <1 nm photocathode emittance with few electrons per pulse by exploring photoemission at threshold, novel laser coupling geometries, and low emittance beam diagnostics.

Successful completion of this interim goal can have immediate impact on the coherence of high repetition rate accelerator-based ultrafast electron diffraction, where bunches with <10^5 electrons are commonly employed. In addition to the photocathode development described above, achieving this objective requires testing photocathode materials in realistic photoemission gun setting, including in high fields that are characteristic of RF photo-injectors. This year we have successfully demonstrated the capability to measure sub-nm emittances in an accelerator environment using knife edge scans. This demonstration was performed at the APEX photoinjector at LBNL with CBB members and affiliates. In this experiment, the small emittances were obtained by using a series of apertures in the beamline, and we continue to make progress towards demonstrating these emittances directly from the source.

Objective C. Demonstrate brightness increase by another factor of 5 or more using nanostructured cathodes, for a) single point emitters suitable for ultrafast electron diffraction and microscopy, and b) arrays of point emitters for higher charge operation. Devices would be demonstrated in the lab by the end of year 7.

In Year 4, we will begin to increase the emphasis of this goal. This stretch goal will begin with numerical studies of single tips-structures and small source structures, which will be followed by experimental demonstrations, first with high brightness single tips, and later with tip arrays. The activities in year 4 towards this goal will include designing a nano-meter sized photoemission-based electron source using various techniques to couple light into nano-meter sized spots or by developing nano-meter sized low work function patches.
Research Optimal Outcome 2 – Beam Acceleration

Methods for x10 lower power losses and x2 higher accelerating fields in RF cavities made of niobium and compound superconductors, for lower costs, simpler refrigeration and wider access to high-power beams.

Objective A. Fundamental Superconductivity and Nb₃Sn: Current Nb₃Sn films produced via vapor diffusion are limited to maximum surface field of ~80mT at 4.2K, and a 1.3GHz surface resistance of ~25nOhm. Develop and use experimental methods and advance fundamental theory of superconductivity to identify the sources of these Nb₃Sn performance limitations.

(Year 4)

In the first three years, CBB has achieved significant advances in determining the sources of current Nb₃Sn performance limitations. CBB has developed a weak pinning theory, (explaining for the first time the observed strong RF field dependence of the residual resistance due to trapped vortices, and giving guidance for reducing these losses), has determined how the Nb₃Sn layer grows from initial nucleation to forming a polycrystalline film (showing initial upward and later downward growth, and illuminating the processes by which thick oxide layers optimize growth conditions), has performed detailed surface characterization and DFT calculations (showing potentially performance degrading tin-depleted regions that are not a phase, but result of tin-starved growth), has analyzed the quench region of a Nb₃Sn cavity (indicating that field enhancement is a likely player in lowering the quench field of current Nb₃Sn cavities, together with a defect causing early vortex entry), has quantified the effect of surface roughness on RF performance (showing >50% field enhancement), has developed a post-coating method for reducing roughness, has developed a critical droplet theory for flux entry at defects (showing that new materials are not more sensitive to dirt), and has performed time dependent Ginzburg Landau simulations of magnetic vortex entry at grain boundaries at large applied magnetic fields (which uncovered a sequence of material parameters that lead to qualitatively different behaviors, and gave important new insight into this likely source of quench in Nb₃Sn).

Additional activities needed to complete Objective A will focus on further studies of the quench mechanism in current Nb₃Sn cavities. These activities will include experimental and theoretical studies on the growth kinetics and energetics of the niobium-tin system, characterization of the microstructure for the vapor-based growth process of Nb₃Sn, especially grain boundaries, and studies to understand – using theory and experiment – the impact of different types of defects on the superconducting performance of Nb₃Sn, especially on early vortex entry. Additional activities will address the experimentally observed two-gap behavior of current Nb₃Sn films as well as the weak frequency dependency of trapped flux losses in Nb₃Sn.
Objective B. Fundamental Superconductivity and Niobium: Improve fundamental understanding and control of the field-dependent surface resistance of niobium and use these advances to develop R&D surfaces, which at 2K, 1.3GHz, and 100mT have surface resistances reduced to <5nOhm, and at 150mT to <10nOhm. (Year 4).

In the first three years, CBB has studied impurity diffusion in niobium, has performed detailed analysis of field and frequency dependence of the anti-Q slope in the BCS surface resistance (showing strong dependence of the anti-Q slope strength on electron mean free path, frequency, and temperature), has demonstrated that theoretical descriptions of the anti Q slope of SRF cavities that currently are proposed in literature are based either on incorrect assumptions or incomplete calculations, has designed and fabricated a special setup for measuring the DC field dependence of the BCS surface resistance to test theoretical predictions, has completed DFT studies on the electronic structure and scattering in the presence of interstitials in niobium, has gained new fundamental understanding of nano-hydride formation on niobium surfaces during cryogenic cool down, and has demonstrated that nitrogen doping of niobium can suppress formation of these performance-impacting surface hydrides.

CBB will continue to address this objective through activities such as characterizing the microstructure and superconducting properties of impurity doped and low-temperature baked niobium surfaces, further developing improved understanding of impurity diffusion at low temperatures, analyzing the impact of impurities on heat flow, developing theory for the origin of the anti-Q slope observed in doped niobium cavities, further studying the frequency and field dependence of the RF surface resistance, studying the impact of hydrides on surface resistance and maximum fields, controlling hydride formation via impurities, and designing an ideal RF penetration layer. CBB will then synthesize knowledge gained from these activities to design an optimized treatment protocol for niobium that then can be applied to niobium SRF cavities to reach performance meeting the specifications of this objective.

Objective C. Newer Material Options: Use experimental results and theoretical predictions to identify promising material options and arrangements for high gradient and/or high efficiency SRF operation. (Year 4).

In the first three years, CBB has developed theoretical tools to estimate the superheating field, critical temperature and other relevant parameters (e.g. electron-phonon scattering) of candidate superconductors, has studied anisotropy effects (indicating that anisotropy likely limits usefulness of some materials), has developed a new test setup for measuring flux-entry fields of small material samples under RF conditions, has optimized a system to measure the RF surface resistance of material samples, and has used this system to perform first RF performance measurements of new materials (NbN and MgB2), of films grown via new growth methods (CVD and ALD), and of multi-layer structures (superconductor – insulator – superconductor).
Harnessing newer materials will require activities such as developing and using theory to estimate RF performance of various material candidates and arrangements, developing and characterizing alternative thin-film growth methods, understanding surface properties of next generation high temperature superconductors, and RF performance testing of various material options and arrangements using small material samples to validate and guide theory and to demonstrate RF performance beyond the limits of niobium. CBB will then synthesize knowledge gained from these activities to create a list of most promising materials for further development and to define a roadmap for experimental and theoretical work to fully explore these candidate materials.

Objective D. Factor of 5 Increased Efficiency: Improve fundamental understanding and control of the synthesis kinetics of compound superconductors required to develop R&D surfaces, in order to support higher (>3K) temperature cavity operation at medium fields (15 to 20 MV/m), and reduce cooling power in large-scale systems to <3 kW/(active cavity meter) at 20 MV/m operating field. (Year 5)

In the first three years, CBB has performed experimental studies and DFT calculations on the layer growth dynamics, indicating that the tin depleted regions are likely a result of kinetic processes (varying tin chemical potential) during layer growth, and has used this new insight to alter the Nb3Sn coating procedure to ensure a steady supply of liquid tin to the growing later, has started to determine the benefit of surface oxide on the Nb3Sn growth process, has performed Sn nucleation studies to improve film uniformity, has developed a new electroplating process for growing a uniform Sn film on Nb, and has analyzed the frequency dependence of trapped flux losses in Nb3Sn. With the recent improvements in film growth and control of ambient conditions, Nb3Sn films now support 15 MV/m cavity operation at 3.5 to 4.2K with cooling power ~3 kW/(active meter).

Advancing Nb3Sn is currently the most promising path towards meeting this objective, and will be the focus during years 4 and 5. For Nb3Sn, achieving an additional factor of 2 increase in efficiency to meet the specifications of this objective will require further optimizing the Nb3Sn vapor diffusion protocol (using theory and experiment) to mitigate the limiting mechanisms identified in objective (A), exploring alternative nucleation and Nb3Sn growth methods, and then testing these on small material samples via surface characterization and RF performance measurements. In addition, CBB will synthesize knowledge to optimize synthesis of other high Tc compound superconductors.

Objective E. Increased Accelerating Field: Demonstrate fundamental understanding and control of the synthesis of a compound superconductor required to develop R&D surfaces that reach surface fields above the fundamental field limit of niobium (~200mT) in pulsed mode operation (Year 7).
Nb₃Sn is currently the only compound superconductor that has reached RF fields above 100 mT. CBB has demonstrated that magnetic surface field enhancement due to surface roughness can be reduced via optimized chemical etching of the Nb₃Sn film, and also has started development of laser annealing of Nb₃Sn films.

This Objective builds on Objectives A, C and D, and will require further optimization of the synthesis of compound superconductors (especially Nb₃Sn) for increased surface fields. The stretch goal of this objective is a demonstration of RF performance meeting the specification using small material samples (Years 5-7).

Research Optimal Outcome 3 – Beam Storage and Transport

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.

The Objectives for this Research Optimal Outcome fall into three interconnected domains. One is “Conserve”, which refers to the preservation of already bright beams in the face of the phenomena that tend to disrupt them. The second is “Control”, which is concerned with applying novel algorithms and state of the art methods to improve accelerators and controlling transport nonlinearities and beam instabilities. The third one is “Cool”, which addresses strategies for increasing the brightness of beams with initially large emittance.

**Conserve**: source emittance preservation, physics of space charge, binary collisions, beam demonstration.

**Objective A.** Identify and quantify 6D emittance dilution mechanisms from x100 brighter sources to the application point along with methods to mitigate them (Year 3). This includes detailed beam physics simulations of successful preservation of the transverse emittance from very low-MTE photocathodes (Year 4) and corresponding beam measurements aimed at demonstrating improved brightness from photoemission guns (Year 5).

**Interim Goal 1:** Characterize emittance preservation in the next generation of photoinjectors along with the photocathode MTE’s required for improved performance (as soon as Year 3, and surely by Year 4).

Various efforts are underway to increase electron source brightness, including exhaustive simulations of space charge dominated beams, introducing new analytical tools to evaluate and characterize emittance degrading phenomena in intense bunches, developing new beam diagnostics capable of probing record low emittances. Next activities to meet the objectives will continue to build on these capabilities and the collaborative network formed during first two years of the CBB research.
**Control:** advanced tuning algorithms, control of nonlinearities, collective effects, and new diagnostics.

**Objective B.** Introduce new methods that capitalize on machine learning and other advanced techniques in order to improve the transport and storage of high brightness beams.

*Interim Goal 1:* Implement in modeling (Year 3) and demonstrate in experiment (Year 4) algorithms for online correction of aberrations in electron microscopes.

Electron microscope column transport has been reconsidered from a different perspective utilizing advanced techniques and methods developed for accelerator applications. This unconventional approach opened a way towards significant increase in accuracy of characterizing aberrations in 4D-STEM. We successfully identified a strategy that enables fast online corrections using effective dimensionality reduction of control knobs.

*Interim Goal 2:* Evaluate machine-learning based methods for live accelerator performance improvements (Year 4) - starting year 3.

Machine learning methods are particularly attractive whenever the simulation model is not sufficiently accurate to fully describe the real-world complexities of the accelerator machine, or alternatively when simulation models, in order to take into account all physics effects, become so CPU-expensive to require weeks of computer cluster use. In all these cases, we plan to use the output of simulations as well as online experimental data to train neural networks and enable fast prediction of beam dynamics for live accelerator performance improvements and optimization.

*Interim goal 3:* Demonstrate that special quasi-integrable arrangement of octupole magnets in IOTA ring located at Fermilab can produce much large betatron tune spread in a beam than any conventionally designed accelerator lattice (Year 4).

This goal continues an ongoing project that is yielding promising results. Fast coherent beam instabilities that may limit accelerator performance can be significantly suppressed by introducing specially designed nonlinear elements in the accelerator lattice. The key feature behind such insertions is the complete or partial integrability of the Hamiltonian associated with the beam motion. Additionally, this strategy can eliminate destructive resonances in beam motion, further improving beam stability.

**Cool:** emittance reduction via cooling.

**Objective C.** Develop methods for cooling beams using optical stochastic cooling to increase beam luminosity in next generation colliders.
Interim goal 1: Exploration of a novel bypass method enabling the design of a high gain optical amplifier with existing laser technology (Year 4).

Ordinary microwave based stochastic cooling has proven to be an effective tool to damp the emittance of charged particle beams. Being limited by a bandwidth of the microwave system, this technique can be expanded into the optical regime. This optical stochastic cooling (OSC) can increase the cooling rate by 4 orders of magnitude paving a way to cooling of all type of high brightness beams, including electrons and positrons. OSC holds great promise, however, it has not yet been experimentally demonstrated. To this end both Cornell University and Fermi National Laboratory/University of Chicago are working on proof of principle state of the art experiments to be performed at CESR and IOTA accelerator facilities respectively. In order to take advantage of this approach one must address the question of how to introduce high-gain light amplification required for optimal cooling rate into the light bypass section.

Research Optimal Outcome 4 – Integration

Integration of these methods for optimization of high performance of accelerator systems.

This Research Optimal Outcome captures the progress made in the individual theme areas for integration in full accelerator systems.

Objective A. CBB validates computational methods for the thermo-kinetics and electronic properties of surfaces and films grown for photocathodes and superconductors. (Research Outcomes 1 & 2)

This objective ensures that the computational methods developed to treat the materials used in photocathodes and superconductors for superconducting RF cavities will be captured in widely available codes.

Objective B. CBB integrates its developed photocathodes into ultrafast electron diffraction and microscopy setups to utilize x10 improvement in resolving power or coherence length compared to the existing state-of-the-art. (Research Outcomes 1 & 3) (Year 6)

CBB will develop a sample set-up in preparation for experimental assessment of coherence length in Ultrafast Electron Diffraction.

Objective C. CBB captures new approaches in documented software modules that can be used in full accelerator simulations and control. (Research Outcomes 1-3)

As new modeling tools and device technologies are developed, CBB will interface them into the appropriate software simulations of single particle and collective phenomena to enable a seamless start-to-end optimization and control. (Year 3; pending other developments)
Team Science

In many fields of science and engineering, the size of research teams has grown steadily over the past few decades, driven principally by the need for complex instruments and broad expertise. The growth of scientific teams has stimulated a new research field, the science of team science. Scientists in this field endeavor to identify the challenges associated with team science and to establish best practices for meeting them.

A 2015 NRC report lists the challenges of team science: high diversity of membership, difficulty of deep knowledge integration, large size, goal misalignment, permeable boundaries, geographic dispersion, and a high degree of task interdependence. We will implement targeted strategies to address each of these challenges. Success in forming and maintaining a coherent team is essential to CBB impact in research.

Through continuous improvement of its Team Science processes, CBB will arrive at a set of best practices for Team Science, which it will share with other Science and Technology Centers and may publish for the broader scientific community.

Team Science Optimal Outcome

*CBB Team Science practices enable effective collaborations across disciplines and institutions.*

**Objective A. CBB engages in open, inclusive multi-modal communications.**

In its first two years, CBB has established platform for team science based on frequent scientific meetings, the appointment of theme leaders from a variety of disciplines, extensive face-to-face interaction at the annual meeting, publicizing of this Strategic Plan, and clear expectations for participants, including a standard onboarding procedure.

In the third year, CBB released its Handbook, overhauled its internal website, and held workshops on Team Science at the Annual meeting led by EAB member and Team Science expert Kara Hall. In addition, with the assistance of Hall and Evaluator Sara Woodruff, CBB has developed a model for evaluating the quality of our communication and team science practice, which is now in the implementation phase.

**Objective B. CBB promotes authentic collaboration among participants across disciplines and institutions.**

Achieving this Objective requires a coherent planning process that relies on teamwork from the outset. In 2017, CBB developed a process for funding allocation based on internal proposal alignment with CBB goals, its use of the synergies of a Center, and the engagement of the team.
In 2018, this process was expanded to include an update of the Strategic Plan, so that it responds to discovery and the evolving priorities in the world of accelerators. The revision is based on discussion at Theme Meetings, guidance by the Theme Leaders, and the advice of the External Advisory Board. CBB PIs voted unanimously in favor of adoption of the revised Strategic Plan at the 2018 Annual Meeting, and then served as the basis for project planning for Year 3. The same process will be followed in Year 4. The Strategic Plan is available to all participants on CBB’s internal wiki.

Objective C. CBB ensures opportunities for all participants to develop cross-disciplinary knowledge.

To improve communication across disciplines, CBB has created an ontology, a formal naming and definition of the types, properties and interrelationships of the concepts and objects that exist in accelerator science and related fields (Year 1) and is expanding it annually (Years 2-10). To establish a common knowledge base, CBB offers pedagogical lectures at each Annual Meeting, which are then made available on the CBB YouTube channel. CBB also established a monthly students-only meeting where students present tutorials, their own work, or a recent important publication. Faculty are generally excluded from these meetings to encourage a relaxed atmosphere in which students can freely exchange ideas.

Objective D. CBB provides and inclusive and supportive research culture for all CBB participants.

Ethics training is essential to a positive research culture and productive collaboration. In addition to requiring completion of the online Responsible Conduct of Research Course, CBB’s 2018 annual meeting included a well-received workshop on scientific ethics by CK Gunsalus.

CBB students have the experience of working in a coherent, interdisciplinary team with highly engaged mentors. In addition, they get training in the skills and practices necessary for the promotion of such high-performance, inclusive, and supportive research environments. All CBB participants are required to complete implicit bias diagnostics regarding race and gender. Additional training includes activities that promote awareness of implicit bias, that address research ethics, that promulgate best practices in research mentoring, and that promote effective team science. Some training in these areas are offered every year — either at the annual meeting, during the year, or asynchronously — with the goal of providing complete coverage over a period of ~3 years, at which point the cycle will begin again.

Workforce Development
Workforce Development Optimal Outcome 1
CBB students are well-prepared to become leaders in their chosen fields and have an appreciation of accelerator science.

**Objective A. CBB facilitates graduate students’ development, revision of, and reflection on professional and career goals.**

CBB has identified MyIDP (https://myidp.sciencecareers.org), which was developed by the American Academy for the Advancement of Science, and all students complete it during their first year and then update it annually. After this, all students discuss their plans with their faculty advisors annually. The IDP explores the student’s career goals and identifies her strengths, weaknesses, and objectives, and suggests learning activities designed to exploit her strengths, bolster her weaknesses, achieve her objectives, and explore potential career paths.

In order to help students and postdocs envision themselves in academia, national labs, industry, and elsewhere including public service, teaching, consulting, engineering, computer software, business, and finance, CBB invites speakers who describe their career paths. So far, these speakers have been from industry, academia, and national labs, and an upcoming speaker will speak about his transition from physics to finance.

**Objective B. CBB provides relevant and effective professional development opportunities to enhance graduate students’ skills.**

Oral presentation is an essential skill for almost any career path and is among the skills covered by the CBB professional development program. Theme meetings provide an opportunity to develop communication skills by including at least one talk, on average, by a student or post-doc. At the annual Symposium, all students present posters, and each gives a 1-minute advertisement for their poster in a preceding Poster Blitz. Students also have the opportunity to present their work at a national or international conference or workshop each year.

To give students experience in written communication relevant to report and proposal preparation, CBB has organized a system in which students prepare annual reports that describe their work and accomplishments. We also offer students the opportunity to submit proposals for funding for events such as guest speakers or professional development at their home institution.

Since many careers require communication with non-experts, CBB students present their work to other students at the monthly students-only meeting. This setting requires them to address people with expertise in different fields.

To further improve graduate students’ communication with non-experts while simultaneously improving the nation’s infrastructure for STEM education, all graduate students are expected to perform educational outreach at least once per year. To satisfy this requirement, many CBB graduate students are working through our STEP UP! program to develop new middle school
educational modules aligned with the Next Generation Science Standards. The topics covered by these modules are chosen in consultation with teachers to meet current educational needs. After field tests in K-12 classrooms and at teacher workshops, the refined experiments are assembled into kits and placed in an online Lending Library, where they are available at no cost to any teacher in the US. Starting in 2019, CBB will also offer teacher workshops based on these kits at non-Cornell CBB universities to train local teachers in the use of the kits and to advertise their availability. In 2019, this program has already reached high needs classrooms in New York City and Washington DC. Additional workshops are planned for high needs school districts in Chicago, Los Angeles, Atlanta and other cities.

To develop other professional skills, CBB has offered a workshop on Entrepreneurship and Innovation at each annual meeting. As described above, the students have had multiple opportunities to meet with industrial lab scientists, not only at the Symposium, but also by meeting with seminar speakers. CBB practice is to invite speakers to give their talk from any CBB institution, and these regularly include student meetings. For example, Bill Barletta, the former Director of the US Particle Accelerator School, gave a seminar on Accelerators in Industry, and it was followed by a well-attended get together with students.

In addition to the CBB-wide programs described here, CBB encourages its investigators to organize professional development workshops or speakers at their home institutions, and provides funds to support these activities. One university used these funds to organize a luncheon for graduate students with an industrial accelerator scientist; another invited an Improv group to work with their physics graduate students on teamwork and inclusion.

Objective C. CBB ensures that all graduate students receive appropriate mentoring and networking opportunities.

While a student’s faculty advisor is a student’s primary mentor, mentorship by other figures can also be important. In CBB, the intensive interaction within the themes means that every student works closely with one or more additional faculty or postdocs. Their guidance can take the form of constructive feedback at meetings or more personal one-on-one guidance.

CBB also connects students with potential external mentors. It invites industry participation in the annual Symposium and organizes a lunch where the students have an opportunity to interact with them. The Symposium also includes a poster session, with a prize to the best student poster, and industry and national lab scientists are among the judges.

Last year, two internship opportunities in industry were organized and advertised to students. In addition, CBB advertises the Science Graduate Student Research (SCGSR) program for graduate students and the Science Undergraduate Laboratory Internship (SULI) or undergraduates, both sponsored by the DOE Office of Science.

This year, we have scheduled several industry visits in which students will participate.
**Objective D. CBB promotes students’ learning about and appreciation of accelerator science.**

Accelerator science is the context for all CBB research. CBB offers education through its pedagogical lectures, which have now been viewed on YouTube more than 1800 times (apparently, we are educating others too). CBB also encourages graduate students and postdocs to get formal education by taking at least one course at the US Particle Accelerator School. Six CBB students attended the session in January 2019.

CBB has provided six students with hands-on accelerator operation at UCLA, SLAC and Cornell, and that number is growing. Next year we hope to expand that figure considerably by offering training at CBETA, which is a high brightness test accelerator that combines a photoinjector, superconducting RF linac and fixed field alternating gradient return arcs. The goal of this new device, which is currently being commissioned, is to produce high average current, low emittance electron beams. CBB graduate students and postdocs will gain experience in commissioning and operating this accelerator as they evaluate CBETA as a platform for strong electron cooling of ions.

**Objective E. CBB builds the pipeline of accelerator scientists.**

Today, accelerator scientists are educated either on the job, or at one of the small number of universities with a graduate program in the field. According to the 2015 HEPAP Subpanel Report on the US Particle Accelerator School, there are roughly a dozen graduate programs in accelerator science nationwide, which award roughly 15 to 20 doctoral degrees each year (See https://science.energy.gov/hep/hepap/reports/). The experience at Cornell is that graduates are in high demand at national labs and in industry. CBB is broadening this pipeline by engaging faculty from a broad range of disciplines in the physical sciences in accelerator research. Already, CBB is providing accelerator science training to students in chemistry, materials science, condensed matter physics and mathematics, and we hope that the numbers will increase further as CBB research becomes more visible in these allied disciplines. Through professional development workshops, training in team science, active mentoring, and internships, CBB prepares students to become leaders in their fields.

Already, two CBB postdocs have moved on (Karkare and Maxson), and both have accepted faculty appointments in accelerator science. We are delighted that both continued in CBB, now as senior investigators and theme leaders.

**Workforce Development Optimal Outcome 2**

*CBB has measurable impact on the participation of underrepresented groups in sciences and technology, particularly in accelerator science.*

**Objective A. CBB engages a diverse group of researchers at all levels in the Center through effective recruiting, supporting and retention of women and other underrepresented groups.**
This year, two CBB students from minority-serving Clark Atlanta University expect to earn doctoral degrees. Both students, Aron Tesfamichael and Frank Ikponmwen, have conducted significant portions of their research at Cornell working under the guidance of Cornell faculty members. CBB is also recruiting students from URM groups to its summer programs. We work to make the CBB environment one in which every student can reach her or his maximum potential. CBB is also proactive in increasing the diversity of its senior researchers.

CBB diversity data are summarized in the table below (compiled September 2018). In almost every category, CBB exceeds the target, in some cases by a wide margin. The targets are set based on national statistics in the level of physics as a whole, compared to which accelerator science lags. In the longer term (our lifetimes), CBB hopes to achieve participation of women and underrepresented minorities at levels comparable to society at large.

<table>
<thead>
<tr>
<th>Total</th>
<th>% female Achieved</th>
<th>% female Target</th>
<th>% URM Achieved</th>
<th>% URM Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undergraduate researchers</td>
<td>16</td>
<td>38%</td>
<td>20%</td>
<td>25%</td>
</tr>
<tr>
<td>Graduate students (includes CAU summer students)</td>
<td>25</td>
<td>20%</td>
<td>20%</td>
<td>28%</td>
</tr>
<tr>
<td>Postdocs</td>
<td>5</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Faculty/senior scientists</td>
<td>21</td>
<td>14%</td>
<td>20%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Objective B.  **CBB diversifies the field of accelerator science and associated STEM disciplines.**

CBB hosted 16 undergraduates in summer research in 2017, including two URM undergraduates. In addition, it hosted three URM Master’s students from Clark Atlanta University, one of whom has stayed on as a PhD candidate, and another of whom returned in summer 2018. In the future, we intend to maintain the number of undergraduate researchers, while increasing the number of participating URM undergraduates or Master’s students to seven. Similarly high levels were achieved in Summer 2018 and are expected in Summer 2019.

CBB is active in recruiting URM students. Last year, three Clark Atlanta Master’s students participated in summer research and two undergraduates from Chicago State University; both institutions are minority-serving institutions (MSIs). We hope to begin working with additional MSIs in the future. Anitra Douglas of the Cornell graduate school last year recruited for CBB at four major events that attract URM students in STEM. This exceeds our original goal of recruiting at two minority-serving institutions and/or conferences.
CBB is working to diversify the faculty by seeking female and minority faculty to join CBB, in part through targeted hires in accelerator science at Cornell and UCLA and seed projects. This year, we have recruited a female accelerator physicist who is interested in submitting a CBB proposal in the 2019 cycle.

**Knowledge Transfer**

Knowledge Transfer Optimal Outcome 1

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

The overarching knowledge transfer goal of CBB is to transfer the technology we develop to other research groups, to national laboratories, and to industry. CBB will communicate frequently with our partners in companies and national laboratories to ensure that we understand their requirements. CBB will negotiate commercial licenses for technologies with immediate applications. For example, ultra-bright, ultra-fast sources will enable diffraction and microscopy at currently inaccessible combinations of length and time.

**Objective A. CBB builds partnerships with at least one company and one national lab.**

Two-way conduits of people and ideas lay the groundwork for the transfer of CBB discoveries to our partners in national labs and industry. To that end, CBB has appointed one industrial scientist and three scientists from national laboratories to the External Advisory Board. The 2017 and 2018 Symposia included speakers from industry.

Host international workshops, possibly in conjunction with the annual Symposium, to share CBB developments and broaden engagement by the scientific community. (3 during the 5-year award period.)

**Objective B. CBB technologies/discoveries are incorporated into at least one real world device. (Year 5)**

CBB has identified technologies that are potentially transferrable, has identified potential client labs and companies, and has introduced them to CBB technology through events such as the Symposium. These include, for example, new tuning codes for electron microscopes produced by Thermo-Fisher, Inc., and 2) improved photocathodes for LCLS-II-HE. When the technologies are mature, CBB will sign MOU for partnership, and enter a period of joint development to transfer the technology. CBB has won a separate grant from New York State to foster this partnership with in-state companies. CBB will also identify SBIR/STTR opportunities to leverage early tech transfer for commercialization, and continue consulting as technology is scaled up to production.
Knowledge Transfer Optimal Outcome 2

A trained graduate student cohort is capable of recognizing and transferring these skills to industry and national lab partners.

Objective A. CBB ensures that all graduate students receive appropriate mentoring and networking opportunities.

This Objective is part of the CBB workforce development plan, and specific activities are discussed in that section.

Objective B. CBB promotes students’ learning about and appreciation of accelerator science.

This Objective is part of the CBB workforce development plan, and specific activities are discussed in that section.