THE CENTER FOR BRIGHT BEAMS*

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Abstract

The Center for Bright Beams (CBB) is a new National Science Foundation Science and Technology Center. CBB's research goal is to increase the brightness of electron beams by a factor of up to 100 while reducing the cost and size of key technologies. To achieve this, it will join the capabilities of accelerator physicists with those of physical chemists, materials scientists, condensed matter physicists, plasma physicists, and mathematicians. This Center has the potential to increase the brightness of electron sources through better photocathodes, the efficiency and gradient of SRF cavities through deeper understanding of superconducting compounds and their surfaces, and better understanding of beam storage and transport and the associated optics by using new mathematical techniques. The Center currently involves ten universities and three national labs in the US and Canada, including a large and diverse team of students and postdocs.

INTRODUCTION

The NSF *Science and Technology Center (STC): Integrative Partnerships* program supports "innovative, potentially transformative, complex research and education projects that require large-scale, long-term awards." The **Center for Bright Beams (CBB)** is a new STC with the mission to gain the fundamental understanding required to increase electron beam brightness by a factor of up to 100 while decreasing the size and cost of the key underlying technologies. The goal is to remove the brightness barriers to progress for a broad range of electron beam applications in science and industry, including FELs and synchrotron light sources, particle colliders, electron microscopes, and semiconductor fabrication and quality assurance. For each of these applications, the available beam brightness (current/emittance) limits progress.

In order to achieve its goal, CBB will combine the expertise of accelerator physicists, physical chemists, materials scientists, condensed matter physicists, plasma physicists, and mathematicians. It will tackle areas where better understanding of the underlying science has the potential for significantly improving the design or treatment of devices such as photoemission sources, superconducting cavities, and nonlinear optics. CBB will also focus on accelerator workforce development and increasing the diversity of accelerator scientists.

CBB is a collaboration of Brigham Young University, University of California Los Angeles, University of Chicago, Chicago State University, Clark Atlanta University, Cornell University (CU) (lead), University of Florida, University of Maryland at College Park, Morehouse College, University of Toronto, Fermi National Accelerator Laboratory, Lawrence Berkeley National Laboratory and TRIUMF.

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RESEARCH PROGRAM

CBB has three Research Themes: Beam Production, Beam Acceleration, and Beam Storage and Transport.

Beam Production

The *Beam Production* theme will increase the brightness of electron sources by up to a factor of 100 by advancing the science of photocathodes. In a bright photoemission source, the electrons are emitted with small mean transverse energy (MTE) and experience a large accelerating field E_z. The transverse emittance $\varepsilon_{2D,n}$ and 4-D brightness B_{4D} are given by

$$\epsilon_{2D,n} = \sigma_x \sqrt{\mathrm{MTE}/mc^2} \propto \sqrt{\mathrm{MTE}}$$

and

$$\mathcal{B}_{4D} \propto \frac{E_z}{\mathrm{MTE}}$$

respectively. CBB has identified four photocathode objectives shown in Fig. 1. At each stage, it will conduct beam tests. The ultimate goal will be a proof of principle experiment that uses record coherence length beams for ultrafast electron diffraction.

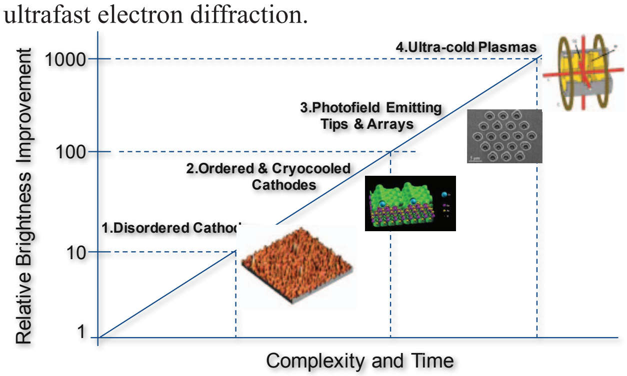

Figure 1: The Beam Production objectives, shown in order of increasing risk. In addition to these, CBB will demonstrate high resolution ultrafast electron diffraction.

Achieving these objectives requires an interdisciplinary approach. For example, materials scientist Hennig (Florida) will screen candidate photocathode materials, condensed matter physicist Arias (CU) will apply density functional theory to predict performance, Bazarov (CU) and physical chemists Hines (CU) and Padmore (LBNL) will synthesize photocathodes, and condensed matter physicists Muller (CU) and Shen (CU), together with Hines (CU), will characterize them using Scanning Tunneling Microscopy and ARPES respectively. Musumeci

(UCLA) and Bazarov (CU) will do beam tests. Applied physicist Kourkoutis (CU) and chemist Miller (Toronto) will apply the new photocathodes for ultrafast electron diffraction.

Beam Acceleration

Today, the typical quality factor of 1.3 GHz Niobium SRF cavities at medium fields is ~$2x10^{10}$ at 2 K [1]. The RF penetration layer of the cavity (the inner 40 - 200 nm) determines the RF losses; however, this layer is complex and its surface morphology, topology and chemistry are poorly understood.

The gradient barrier of SRF cavities, which is about 50 MV/m for niobium, arises from the superheating critical field, H_{sh}, which is the flux-free field limit of the cavity material. Some compound superconductors such as Nb_3Sn have higher values of H_{sh} than niobium, and therefore promise larger gradients. Compound superconductors can also deliver high quality factors at 4.2 K [2], as shown in Fig. 2. Achieving the promise of compound superconducting cavities requires improved understanding of synthesis processes for alternative high quality thin film compound superconductors.

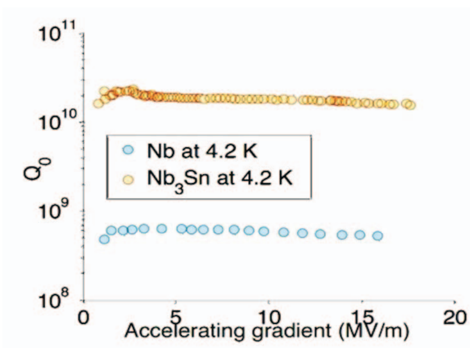

Figure 2: Quality factor as a function of accelerating gradient for Cornell Nb and Nb_3Sn 1.3 GHz test cavities.

The *Beam Acceleration* theme is aimed at increasing the quality factor of niobium cavities by a factor of 10, doubling the accelerating gradient, and enabling the acceleration of high power beams with systems operating at 4.2 K, making them more widely accessible.

Advance the Theory of RF Superconductivity Condensed matter physicists Arias (CU), Sethna (CU), Transtrum (Brigham Young), Wang (Clark Atlanta) and Japaridze (Clark Atlanta) will advance the theoretical tools for calculating H_{sh}, and Liepe (CU) will test them.

Develop More Efficient Niobium Cavities This team will investigate the physics that underlies surface resistance, its strong field dependence and the impact of doping by nitrogen and other impurities; quantify the impact of surface crystal morphology and topology; and identify treatment protocols that yield optimal surfaces, and ultimately work with vendors. It will supplement theoretical advances and RF measurements with the use of TEM and other surface characterization techniques by chemist Sibener (Chicago) and applied physicist Muller (CU) and on ARPES by Shen (CU).

Develop Processes for Fabricating Cavities from Compound Superconductors This team will identify best synthesis processes that yield phase-pure and defect free materials; synthesize cavities with Nb_3Sn, NbN and MgB_2 surfaces; analyze microstructures, measure critical temperatures, fields, and chemical concentration profiles, and measure surface resistance and flux entry fields; and localize limiting areas for post-mortem analysis. In addition to the techniques used for earlier objectives, it will rely on muon spin rotation and relaxation techniques by Laxdal (TRIUMF), materials theory calculations by Hennig (U Florida) and experimental tests by Liepe (CU) and Posen (FNAL).

Beam Storage and Transport

The *Beam Transport and Storage* theme will develop a) *beam transport systems* that preserve beam brightness in electron microscopes and in linear accelerators and b) *beam optics* that increase equilibrium beam brightness in electron *storage* rings for light sources and high energy physics.

Develop Mathematical Tools to Characterize Dynamic Aperture This work will seek a metric to identify resonances and dynamic aperture by representing the relevant dynamics with an effective Hamiltonian. The goal is to design and optimize strong focusing, low emittance, high brightness storage ring optics with reduced reliance on multi-turn tracking.

Develop Instrumentation for Measuring & Correcting Nonlinearities High brightness storage rings require hundreds of sextupole magnets to compensate chromatic effects, and their nonlinearities often limit the design's dynamic aperture. Here the goal is an experimental method to determine optimal sextupole distributions from resonance driving terms.

Develop Concepts for Novel Beam Line Elements that Compensate Nonlinearities, Space Charge, etc. Guide fields in storage rings and beam lines consist of sequences of multipole magnets. CBB will provide theoretical guidance for the development of non-standard optics, such as commoving beams and plasma lenses, which could extend the stable region of phase space, and will model them in a ring.

Demonstrate Tuning Algorithms that Optimize Performance High brightness storage rings require hundreds of corrector magnets to compensate field errors and misalignments, and often these must be tuned empirically. The CBB goal is to develop automated tuning algorithms that can be incorporated into the accelerator control system to minimize emittance and maximize brightness. Continuous tuning of this type promises to preserve brightness in the face of time-dependent noise.

Mitigate Collective Effects that Diminish Brightness Collective effects degrade the brightness of electron beams during transport from the source to the target in electron microscopes and energy recovery linacs. Space charge, wakefields, and ions all degrade the temporal and spatial resolution in microscopes, and limit the useful current. The CBB goal is to develop optics that mitigate collective effects and preserve brightness.

Compensate Aberrations with Time-Dependent Fields The resolution in electron microscopes is limited by chromatic and spherical aberrations of cylinder-symmetric electro-magnetic lenses. These aberrations are unavoidable [3] for fields that are constant in time, for beam pipes that are free of ions, and for beams that do not reverse their directions. While high-resolution electron microscopes compensate these aberrations by non-cylinder-symmetric fields and electrostatic mirrors that reverse the beam's direction, simpler and more robust compensation may be possible by using cylinder-symmetric but time-dependent electro-magnetic fields.

In order to achieve these Beam Storage and Transport-goals, Hoffstaetter (CU), Kim (Chicago), Nagaitsev (FNAL/Chicago), and Rubin (CU), will contribute expertise in beam dynamics, mathematicians Kaloshin (Maryland), Rand (CU) and Wilkinson (Chicago) and condensed matter physicist Sethna (CU) will develop mathematical tools, Rosenzweig (UCLA) will apply techniques for beam manipulation, and Bazarov (CU), Muller (CU), Musumeci (UCLA) and Wan (LBNL) will implement solutions in beam lines and microscope columns.

EDUCATION AND BROADENING PARTICIPATION

CBB goals include workforce development and broadening participation in accelerator physics and science writ large.

Workforce Development

The CBB workforce development goals are integrated with its research program, in which students and postdocs will play leading roles. They are:

Prepare Students to Participate Successfully in Interdisciplinary Team Science Scientific research increasingly relies on the coherent effort of large, interdisciplinary teams. CBB will train graduate students, postdocs and undergraduates to function effectively in such teams, overcoming barriers such as discipline-specific terminology, infrequent face-to-face meetings, and large group size. [4].

Cultivate an Intellectually Diverse Workforce of Accelerator Scientists who are Well Prepared for a Broad Set of Career Paths CBB speakers will describe their career paths to help students and postdocs envision themselves in academia, policy, national labs, industry and elsewhere. Students will maintain an individual development plan and develop skills in proposal writing, learn communication, entrepreneurship, and innovation skills, and have opportunities for internships in industry and national laboratories.

Broadening Participation

CBB will strive to establish a diverse research team. In addition to attention to diversity in hiring and support, three programs address broadening participation.

Train Graduate Students from Underrepresented Minority Groups Graduate students from Clark Atlanta University will join projects in the Beam Acceleration theme alongside other graduate students at CBB universities. At meetings such as the National Society of Black Physicists, we will recruit students to apply for graduate study at CBB universities.

Provide Opportunities for a Diverse Group of Undergraduates to Conduct Research in Accelerator Science Students from Morehouse College, Chicago State University, Clark Atlanta University and other minority-serving institutions will be recruited to join summer undergraduate research programs at CBB universities.

Stimulate Middle School Student's Interest in Science with STEP UP! STEP UP! will pair graduate students with middle school teachers to develop classroom learning kits tailored to meet the Next Generation Science Standards. These will be available to Middle School Science teachers nationwide through a lending library, and trainings will be offered in Los Angeles, Chicago, Atlanta, Washington DC, Gainesville, Provo and Ithaca, NY.

CONCLUSION

The new Center for Bright Beams, an NSF Science and Technology Center, brings together scientists from diverse disciplines to tackle challenges in accelerator science that may be overcome through deeper understanding of the underlying science. Nine universities and three US and Canadian national labs are participating. The program and team outlined here will evolve over time to reflect advances at CBB and elsewhere and new opportunities. CBB's priorities include the effective transfer of its results to national labs and industry, and the education of a diverse pool of accelerator scientists with broad interdisciplinary training and team experience.

ACKNOWLEDGMENT

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