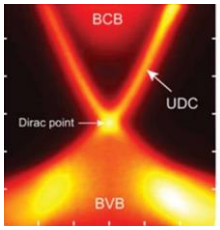
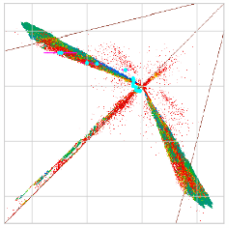
The Center for BRIGHTBEAMS
A National Science Foundation Science & Technology Center

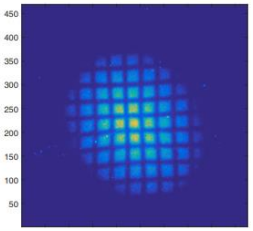
An Introduction to the CBB and its Research

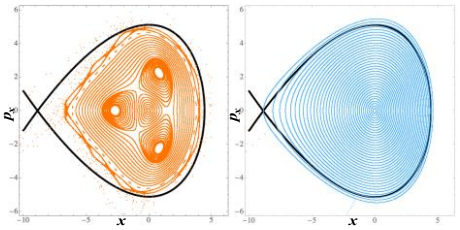
Jared Maxson, Cornell University

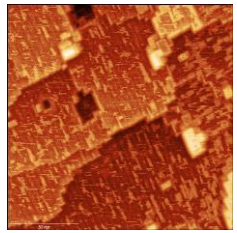
With many thanks to Center Director J.R. Patterson for many of these slides

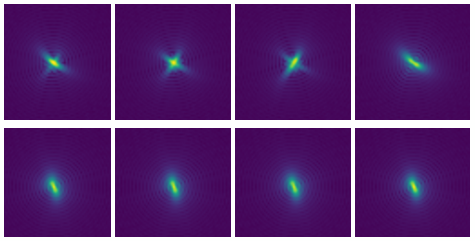


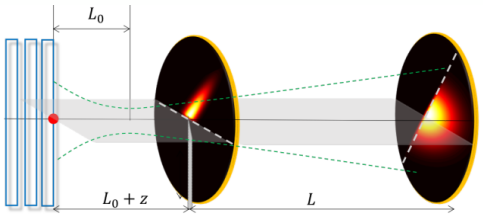


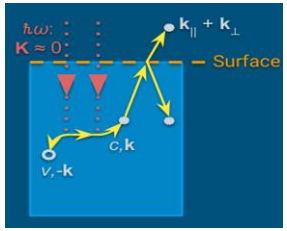


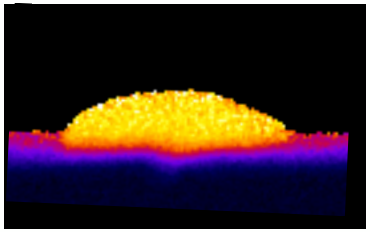












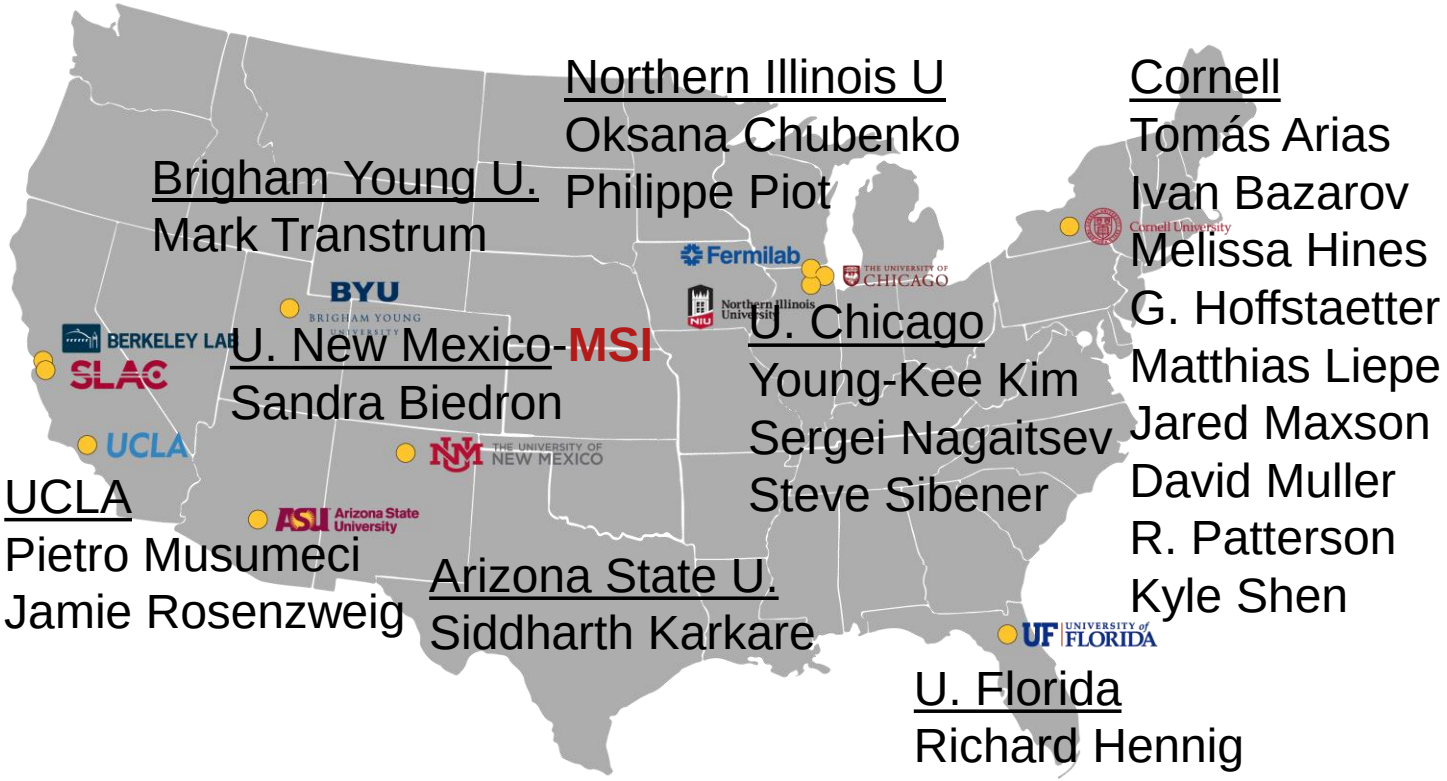
An NSF Science and Technology Center

- The US National Science Foundation (NSF) issues a regular call for proposals for *Science and Technology Centers,* which (from NSF)

  - Conduct world-class research through partnerships among academic institutions, national laboratories, industrial organizations and other entities, both domestically and internationally.
  - Undertake significant investigations at the interfaces of disciplines and/or using fresh approaches within disciplines.
  - Can involve any areas of science and engineering that NSF supports.

- Up to $5.0M/year of funding for up to 10 years.
- CBB is one of these Centers.
- Federal funding for physical science research in the US is largely provided by the U.S. Department of Energy and the NSF.
- CBB is one of the few NSF grants dealing with accelerator science.

CBB institutions



<u>Brigham Young U.</u>
Mark Transtrum

<u>Northern Illinois U</u>
Oksana Chubenko
Philippe Piot

<u>U. New Mexico</u>-**MSI**
Sandra Biedron

<u>U. Chicago</u>
Young-Kee Kim
Sergei Nagaitsev
Steve Sibener

<u>Cornell</u>
Tomás Arias
Ivan Bazarov
Melissa Hines
G. Hoffstaetter
Matthias Liepe
Jared Maxson
David Muller
R. Patterson
Kyle Shen

<u>UCLA</u>
Pietro Musumeci
Jamie Rosenzweig

<u>Arizona State U.</u>
Siddharth Karkare

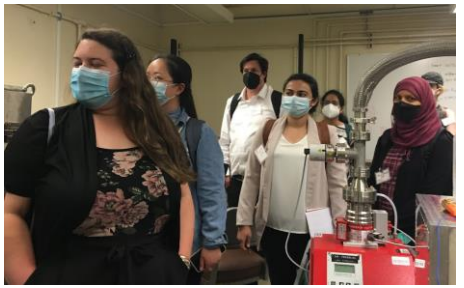
<u>U. Florida</u>
Richard Hennig

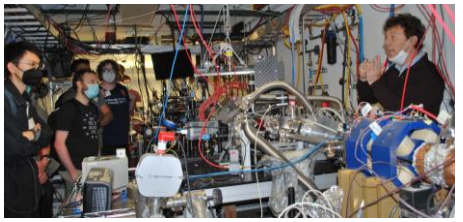
CBB joins chemists, surface scientists, condensed matter physicists, ab initio physicists, electron microscopists, and accelerator scientists

Our Team

Our return to person meetings!

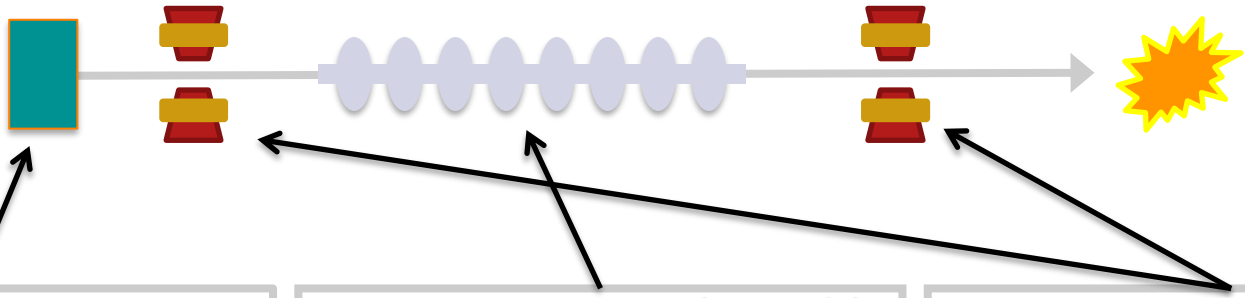
June 1-3, 2022, UCLA





CBB Research Topics

- CBB Research is broken down into three themes with *specific aims*:



Beam Production with Photocathodes

Goal: Methods to dramatically enhance photoemission brightness

Beam Acceleration with SRF

Goal: Methods for superconducting RF accelerating cavities with lower losses and higher gradient

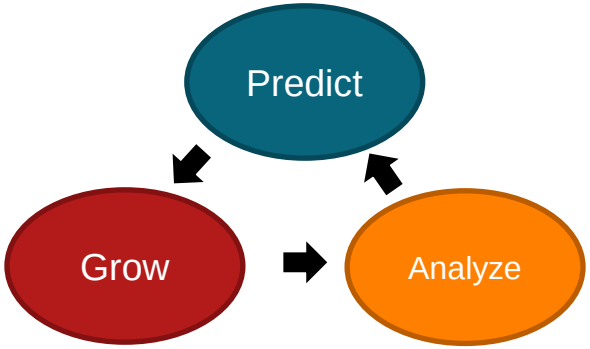
Beam Dynamics and Control

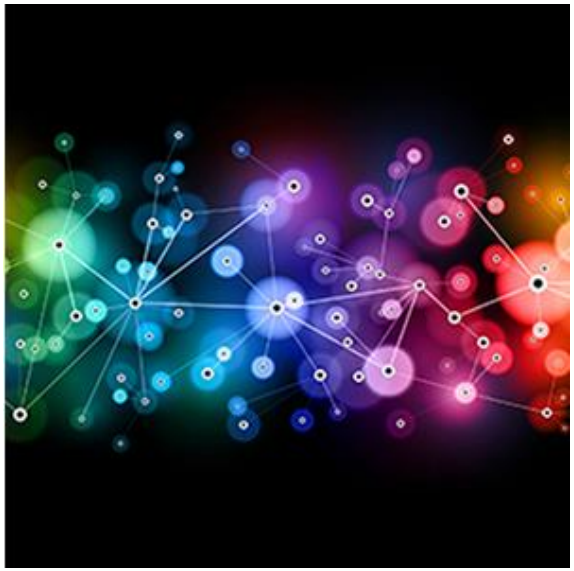
Goal: Methods for beam transport that preserve and optimize brighter beams

Integration of these methods in order to optimize high performance accelerator systems.

An NSF “Big Idea”

- The *convergence of multiple disciplines*, such that the “whole is greater than the sum of it’s parts,” is a CBB guiding principle.
  - In the photocathode and SRF research themes:
    - The link between materials and surface science (both theory and expt) is the foundation.





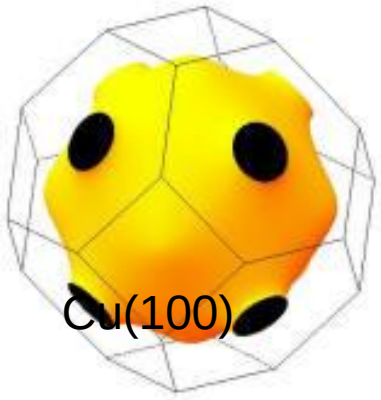
NSF Illustration of convergence research

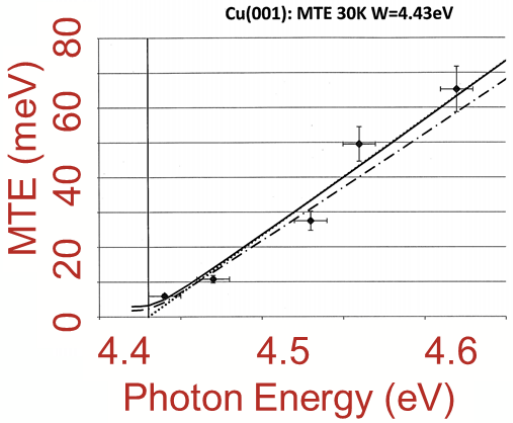
- Beam Dynamics and Control :
  - Integrate advances of other themes → brightness *optimization and preservation*
  - brings together accelerator physicists and electron microscope optics community
  - an important aspect: advanced methods for optimization (AI/ML)

Some research highlights from the past few years

The Coldest Photoelectrons to Date

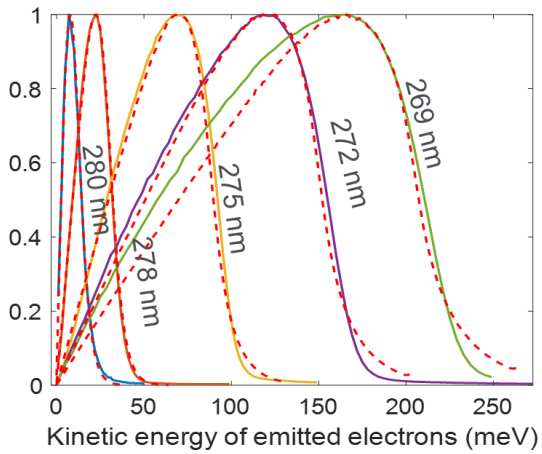
- We use a quantity called the Mean Transverse Energy (MTE) to characterize the momentum spread/temperature of photoemitted electrons.





5 meV MTE measured from Cu(100)
Most photoinjectors use MTE ~500 meV

- Photoemission at the threshold
- Cooled to LHe (30K)
- Atomically ordered flat surface
- Good band-structure
- **New techniques to measure low energy distributions**



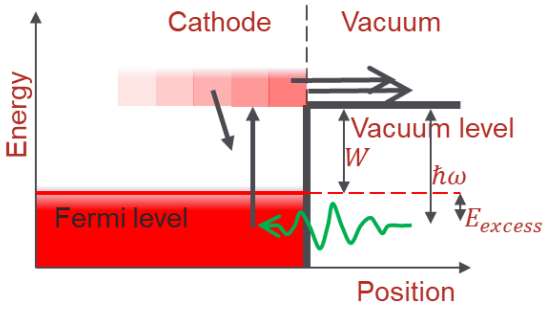
10 meV total energy spread
More than **1 order of magnitude smaller than any existing electron source (not just photoemission)**

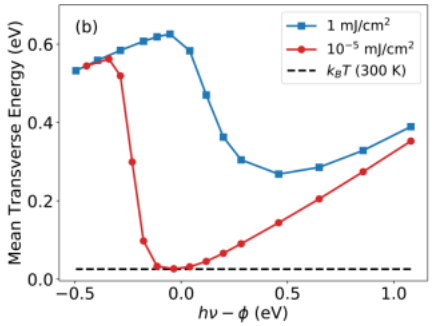
PRL 125 (5), 054801 (2020)

Deep Theoretical Understanding of Photoemission

Theoretical calculations of non-linear photoemission effects

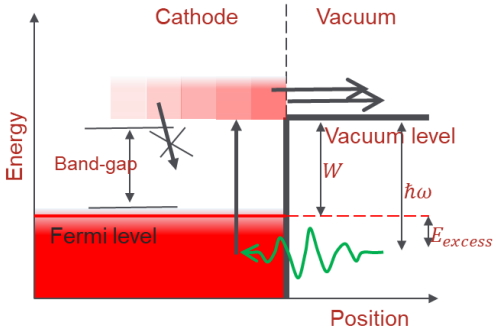
Electron heating in metals



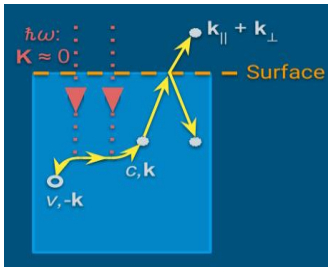


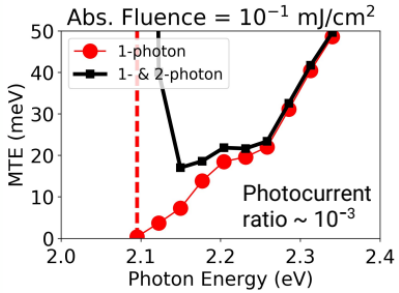
Non-linear effects will **limit MTE in metals to few 100 meV** for large charge densities

Heating suppressed in semiconductors



Multiphoton effects





Solution: use low-electron affinity semiconductors E.g. Alkali-antimonides, NEA-GaAs

Preliminary results indicate MTE < 20 meV even at large laser fluence

Kevin Nangoi

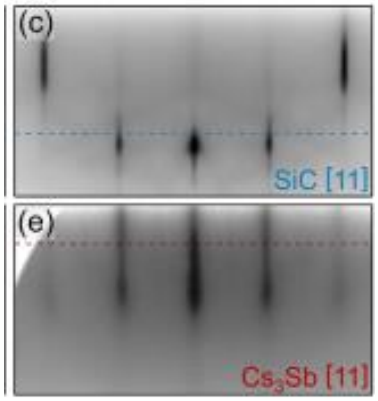
Jai Kwan Bae

Oksana Chubenko

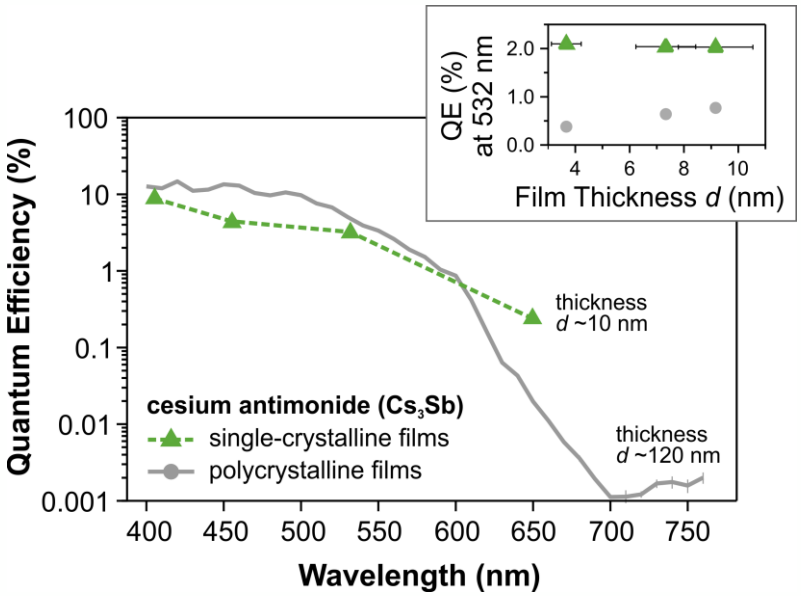
An Atomically Ordered Visible-light Cathode

- The first atomically-ordered visible light photocathode achieved using molecular beam epitaxy

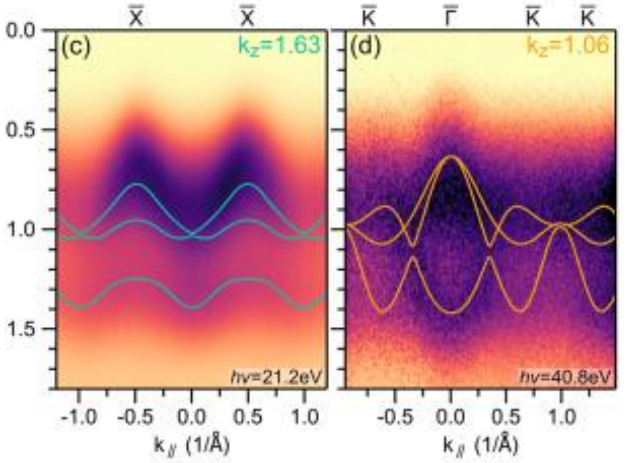
RHEED image of Cs3Sb on ordered surface



Ultrathin with enhanced red efficiency



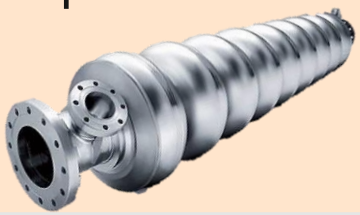
ARPES Measurements of Band Structure + DFT



Phys. Rev. Lett., 128, 114801 (2022).

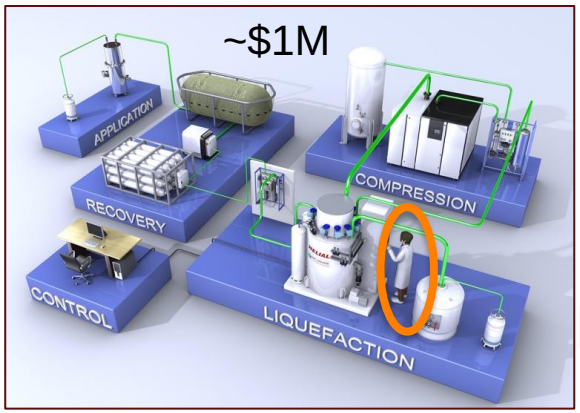
New Materials For SRF (1)

Superconducting RF (SRF) cavities



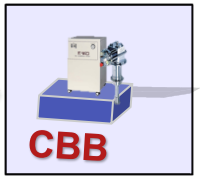
Niobium → Nb_3Sn

Nb_3Sn has higher critical temperature and is therefore far simpler to operate → A high power beam in every basement ... or industrial plant



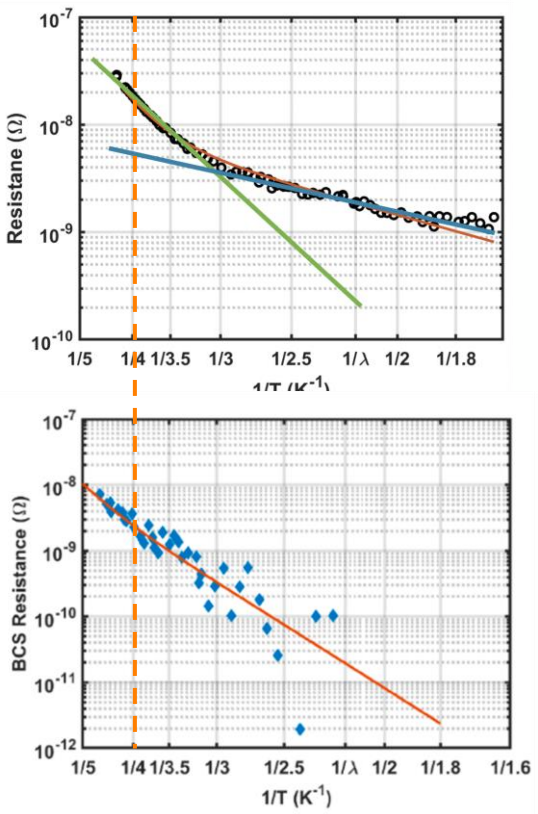
Cooling for one cavity

$50k



Earlier: CBB PI (Liepe) first successful growth of Nb_3Sn

Recent progress: Eliminated a second band gap, for 50% reduction in BCS resistance

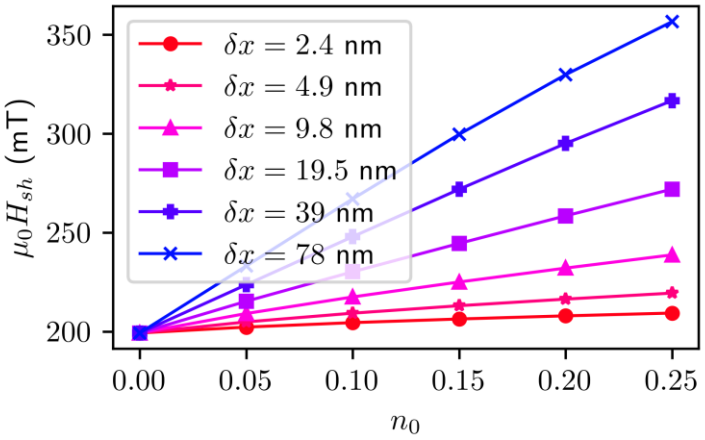


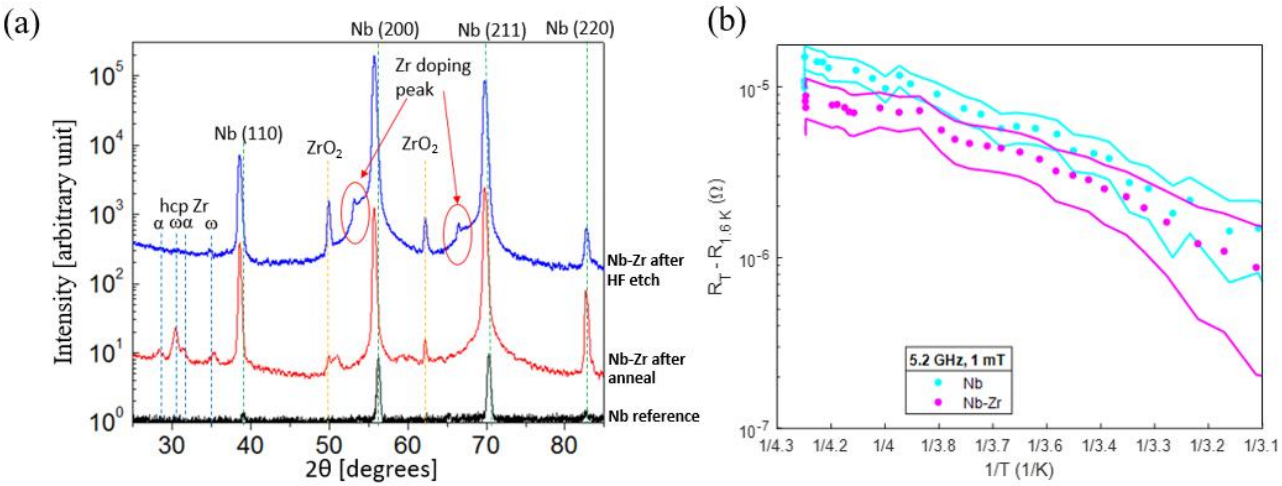
Team: Surface chemistry, electron microscopy, accelerator science, ab initio physics, materials engineering, condensed matter physics, and computational physics.

New Materials For SRF (2)

A promising new material for SRF: Nb-Zr *alloys*

- Multi-scale theoretical modeling predicts nearly a factor of 2 potential enhancement of **Nb-Zr** over Nb.
- Proof of principle Nb-Zr surfaces



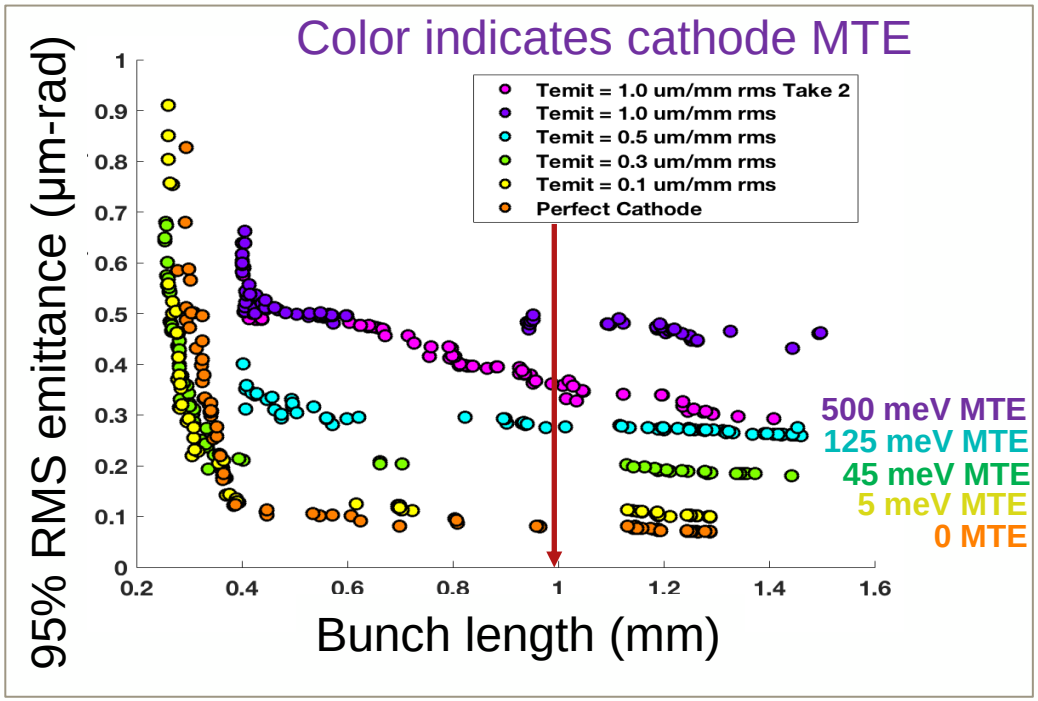


Sitaraman et al. arXiv:2208.10678 (2022).

Photoinjector optimization

Can photoinjectors benefit from high-performance photocathodes? Genetic optimizations say YES.

Application: Lepton linear colliders
Cross-cut: Single shot UED/UEM, xFELs



The effect of the photocathode photoinjector emittance

Application: XFEL eg LCLS-II-HE
Gun: 1.5-cell SRF gun (KEK)
Bunch charge: 100 pC

Pierce et al., Phys. Rev. Accel. Beams, **23**, 070101 (2020)

Groups: CBB, SLAC (Norvell, Dunham (now NNSS), Raubenheimer)

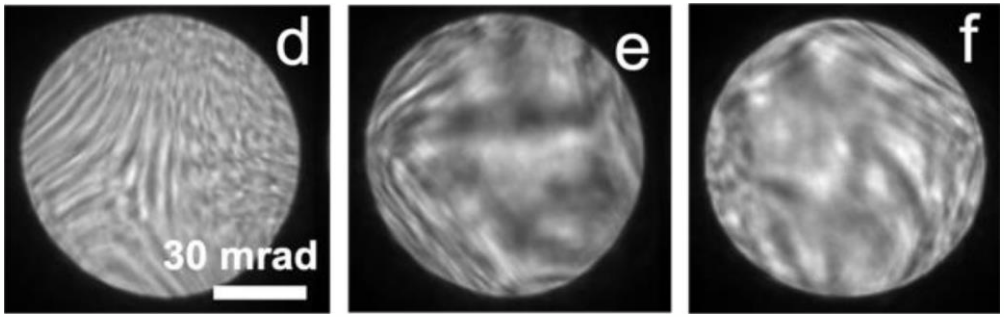
Accomplishment: Microscope tuning

Nion UltraSTEM microscope
Atom-scale imaging

2022: We used machine learning to tune the octupole aberration corrector (81 lenses)

Microsc. Microanal. ***28*** *(S1), 3146 (2022)*

Ronchigrams
Smoother is better



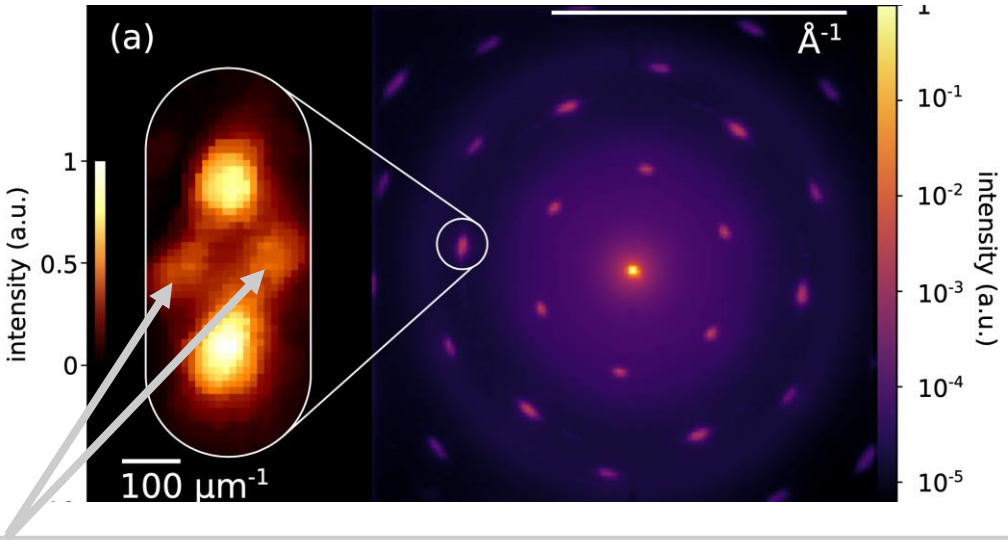
Initial state | After new auto-tuning | After standard tuning

Auto-tuning performs as **well or better** than standard tuning, is **faster** (2 minutes), and **doesn't rely on human judgement**

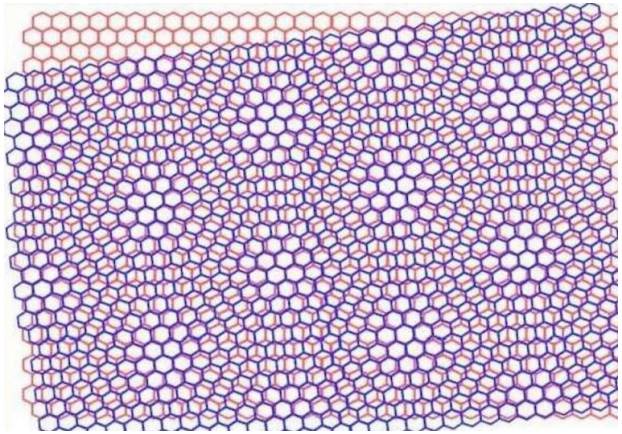
Groups: CBB, SLAC (Edelen, Hanuka)

Improved Ultrafast Electron Diffraction

Single hexagonal atomic layers → twist → Moiré pattern



$MoSe_2$
WSe_2



10 nm periodicity of the Moiré superlattice.
First observation in an ultrafast setup

Large coherence length (10 nm)
enabled by small emittance
ε = 0.7 ± 0.1 nm (500 e^-)
Arxiv: 2206.08404

Tech Details

- MEDUSA UED Beamline (Cornell)
  1kz rep rate
- EMPAD high dynamic range detector

CBB and DOE Early Career award (BES)

Optical Stochastic Cooling

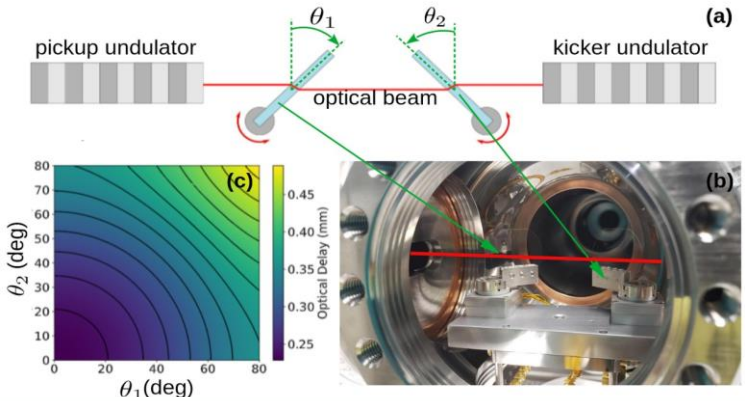
CBB contributions to the IOTA demonstration

Groups: CBB, FNAL, ANL

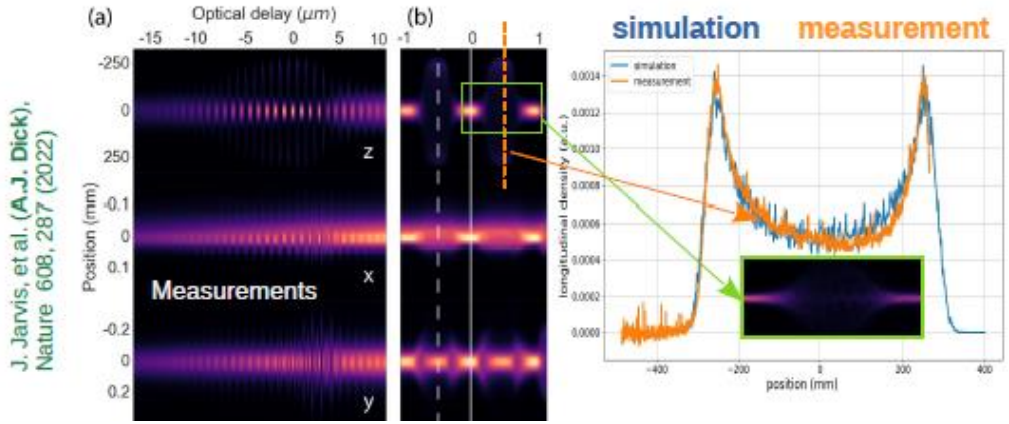
J. Jarvis, et al., Nature 608, 287 (2022)

Optical-delay stage

A. J. Dick et al., IPAC2021, WEPAB270 (2021)



OSC simulation in ELEGANT and BMAD



ELEGANT validation

BMAD: S. T. Wang, M.B. Andorf, et al., Phys. Rev. Accel. Beams 24, 064001 (2021)

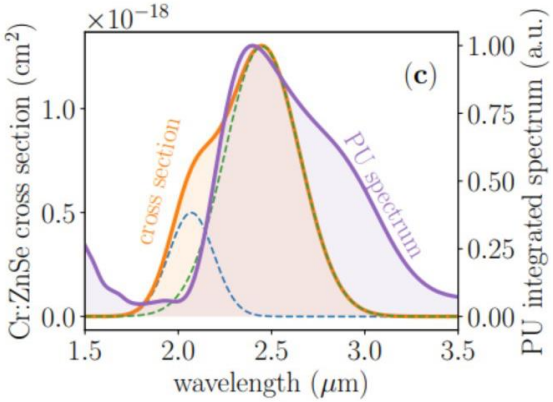
Optical Stochastic Cooling

Future: Active cooling

Preliminary design of a Cr:ZnSe single-pass amplifier
Compact, high gain,with wavelength tuned for IOTA, tested at APS.

Andorf, Lebedev, Piot, Optics Express 28, 26601 (2020)

Groups: CBB, FNAL

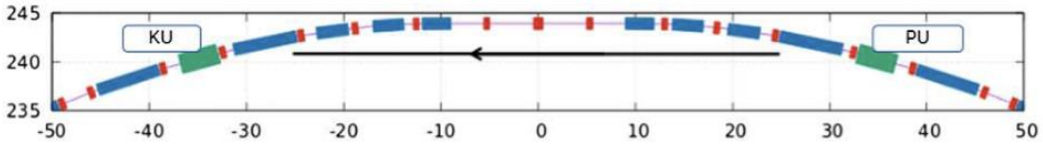


Preparing for a high-gain OSC experiment at IOTA

CESR-based OSC

Design of scalable bypass beamline to enable high-gain active OSC

M.B. Andorf, W. F. Bergman, et al., Phys. Rev. Accel. Beams 23, 102801 (2020)



70 m

ΔL = 20 cm for amplifiers

Developed and lab tested an active stabilization system for long delay lines [**2020**], now installed in CESR

CBB Nuts and Bolts

- We are guided by a Strategic Plan—we update it annually based on our progress and other developments in the field.
- The majority of CBB funding goes to supporting graduate student and postdoc research projects.
- Capital funding is very limited. Deployment of CBB ideas on actual accelerators typically relies on partnership, for example with national laboratory *affiliates*.
- We have a proposal process for university PIs—typically one proposal per graduate student or postdoc.
- The PI team is not static, but changes slowly over time as needs and interests evolve.

Grad Students and Postdocs I

Current Graduate Students


JP Gonzalez Aguilera, Chicago


Vivek Anil, Cornell


Asma Aslam, New Mexico


Zhaslan Baraissov, Cornell


Eric Cropp, UCLA


AJ Dick, Northern Illinois


Gabriel Gaitan, Cornell


David Garcia, UCLA


Gevork Gevorkyan, ASU


Jason Gibson, Florida


Aiden Harbick, BYU


Mariam Hasany, Cornell


Ajinkya Hire, Florida

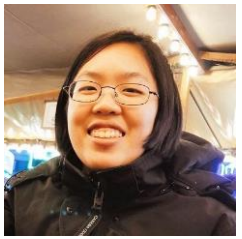

Ali Kachwala, ASU


Michelle Kelley, Cornell


Chris Knill, ASU


Gerald Lawler, UCLA


Samuel Levenson, Cornell


Lucy Lin, Cornell


Desheng Ma, Cornell

Grad Students and Postdocs II

Current Graduate Students

Joshua Mann, UCLA

Chad Pennington, Cornell

Christopher Pierce, Cornell

Pallavi Saha, ASU

Annabel Selino, Cornell

Liana Shpani, Cornell

Nathan Sitaraman, Cornell

Caleb Thompson, Chicago

Michael Van Duinen, Chicago

Sarah Willson, Chicago

Tyler Wu, Cornell

Charles Zhang, Cornell

Amy Zhu, Cornell

Current Postdocs

Elena Echeverria Cornell

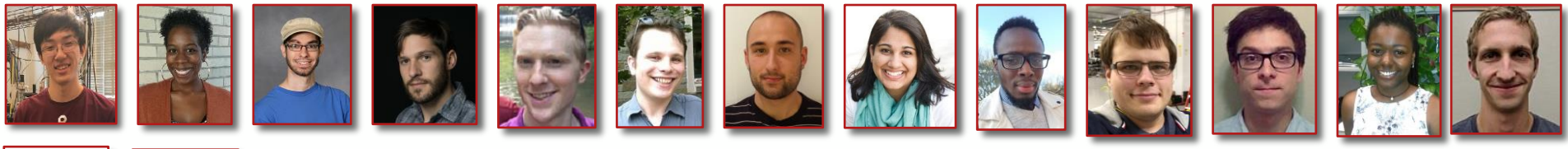
Nathan Majernik UCLA

Afnan Marzouk NIU

CBB Alumni

41 highly-trained scientists by the end of year 5 Interdisciplinary team science, plus training in entrepreneurship, communication, ethics, mentorship, diversity & inclusion....

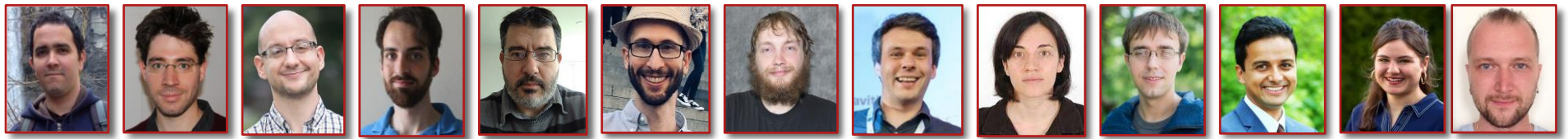
CBB priority: **Diversity** Accelerator Division of the American Physical Society has the lowest female representation of all 16 APS units except one (10%)



20% URM and 22% female

MS	Maria	
	Brian	
	Eylen	
	Nilanj	
	Alex I	
Ph. D.	Alex Cahill	Varian Medical Systems, Eng. Physicist
	Colin Clement	Microsoft, Data Scientist
	Paul Cueva	Corning, Scientist
	Will DeBenedetti	Pacific Northwest Nat. Lab., Postdoc
	Cameron Duncan	EPFL, Postdoc
	Lipi Gupta	Lawrence Berkeley Nat. Lab, Postdoc
	Matthew Gordon	National Lab, Postdoc
	Daniel Hall	ASML, Sr. Design Engineer
	Frank Ikponmwen	FDA, Analytical Chemist
	Nikita Kuklev	Argonne Nat. Lab., Postdoc
	William Li	Brookhaven Nat. Lab., Postdoc
	James T. Maniscalco	SLAC, SRF Engineer
	Allison McMillan	Interviewing
	J. Kevin Nangoi	UC Santa Barbara, Postdoc
	Alden Pack	Sandia Nat. Lab, Albuquerque, Postdoc
	Joshua Thomas Paul	Argonne Nat. Lab, Postdoc
	Ryan Porter	SLAC, Postdoc
	Darren Veit	TBD
Postdoc	Matthew Andorf	Cornell U. , Res. Assoc.
	Jan Balajka	TU Wien, Postdoc
	Stanislav Baturin	Northern Illinois U., Asst. Professor
	Oksana Chubenko	Northern Illinois U., Asst. Professor
	Rachael Farber	University of Kansas, Asst. Professor
	Alice Galdi	U. of Salerno, Italy, Assoc. Professor
	Jacob Graham	NASA Goddard, Space Res. Scientist
	Siddharth Karkare	Ariz. State U., Asst. Professor
	Danilo Liarte	Cornell U. , Res. Assoc.
	Andy Linscheid	Tom Tom, Germany
	Jared Maxson	Cornell U., Asst. Professor
	Jorge Giner Navarro	CIEMAT, Madrid, Researcher
	Ryan Roussel	SLAC, Postdoc
	Dulanga Somartne	Unknown
	Chenyu Zhang	ASML, Sr. Software Engineer
RA	Luca Cultrera	Brookhaven Nat. Lab., Scientist

Academia/Education
Industry
Gov't/ National Lab



CBB Workforce Development

CBB Young Scientists

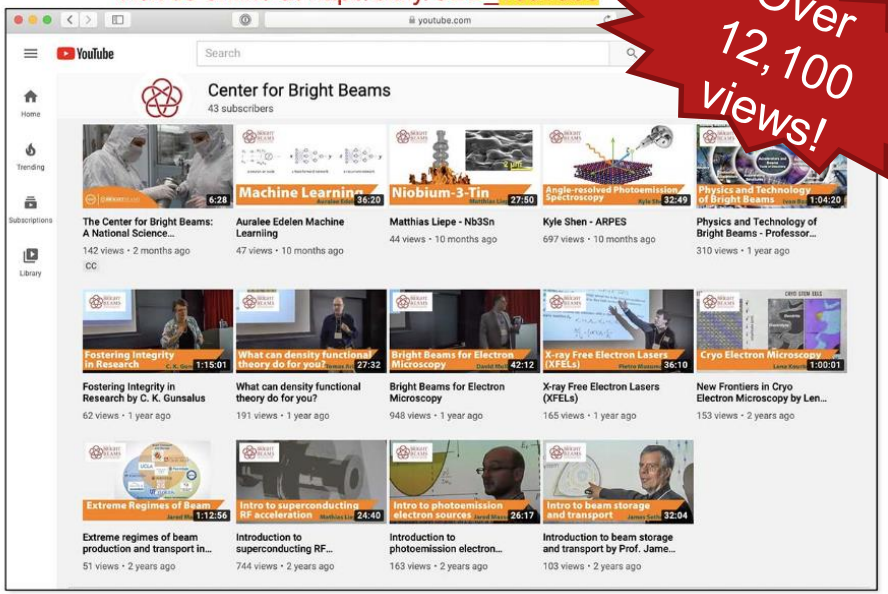
- **30 grad students**
- **9 postdocs**
- **20 undergraduates**
  includes ~8 in REU programs

Accelerator Education

- **Accelerator and related lectures on YouTube**
- **Hands-on accelerator training**
  Cornell Cryo DC gun, CESR, Advanced Photon Source (ANL), IOTA (FNAL), Pegasus (UCLA), HiRES (LBNL), CBETA, MEDUSA (Cornell).
- **University courses**
  Last year: U Chicago, UCLA
- **USPAS** and **NAPAC schools**

Every annual meeting features three 30-minute pedago

Visit us online at http://bit.ly/CBB_YouTube



9

Developing the path to DOE labs:

- Lab affiliates (SLAC, FNAL, ANL, BNL, LBNL)
- SCGSR
- DOE lab speakers and poster judges at CBB Symposium
- DOE lab career panel
- Student co-mentors from DOE labs

Pubs/proceedings this year

Colors show the univ. **departments/institutions** of the authors.

P. Denham and P. Musumeci, “Analytical Scaling Laws for Radiofrequency Based Pulse Compression in Ultrafast Electron Diffraction Beamlines.” arXiv, Jun. 03, 2021	UCLA
M. Gordon, S. B. van der Geer, J. Maxson, and Y.-K. Kim, “Point-to-point Coulomb effects in high brightness photoelectron beam lines for ultrafast electron diffraction,” *Phys. Rev. Accel. Beams*, vol. 24, no. 8, p. 084202, Aug. 2021	Chicago LEPP
A. Dick, J. Jarvis, and P. Piot, “Characterization of the Sub-mm Delay Plates for the IOTA Optical-Stochastic-Cooling Experiment,” FERMILAB-FN-1130-AD, 1827262, oai:inspirehep.net:1950815, Jul. 2021	NIU FNAL
L. Cultrera, E. Rocco, F. Shahedipour-Sandvik, L. D. Bell, J. K. Bae, I. V. Bazarov, P. Saha, S. Karkare, and A. Arjunan, “Photoemission characterization of N-polar III-nitride photocathodes as candidate bright electron beam sources for accelerator applications,” *Journal of Applied Physics*, vol. 131, no. 12, p. 124902, Mar. 2022	BNL LASSP LEPP ASU
A. A. McMillan, C. J. Thompson, M. M. Kelley, J. D. Graham, T. A. Arias, and S. J. Sibener, “A combined helium atom scattering and density-functional theory study of the Nb(100) surface oxide reconstruction: Phonon band structures and vibrational dynamics,” *J. Chem. Phys.*, vol. 156, no. 12, p. 124702, Mar. 2022	Chicago LASSP
C. T. Parzyck, A. Galdi, J. K. Nangoi, W. J. I. DeBenedetti, J. Balajka, B. D. Faeth, H. Paik, C. Hu, T. A. Arias, M. A. Hines, D. G. Schlom, K. M. Shen, and J. M. Maxson, “Single-Crystal Alkali Antimonide Photocathodes: High Efficiency in the Ultrathin Limit,” *Phys. Rev. Lett.*, vol. 128, no. 11, p. 114801, Mar. 2022	LASSP LEPP CHEM
W. H. Li, C. J. R. Duncan, M. B. Andorf, A. C. Bartnik, E. Bianco, L. Cultrera, A. Galdi, M. Gordon, M. Kaemingk, C. A. Pennington, L. F. Kourkoutis, I. V. Bazarov, and J. M. Maxson, “A kiloelectron-volt ultrafast electron micro-diffraction apparatus using low emittance semiconductor photocathodes,” *Structural Dynamics*, vol. 9, no. 2, p. 024302, Mar. 2022	LASSP AEP BNL
J. Jarvis, V. Lebedev, A. Romanov, D. Broemmelsiek, K. Carlson, S. Chattopadhyay, A. Dick, D. Edstrom, I. Lobach, S. Nagaitsev, H. Piekarz, P. Piot, J. Ruan, J. Santucci, G. Stancari, and A. Valishev, “First Experimental Demonstration of Optical Stochastic Cooling,” *arXiv:2203.08899 [physics]*, Mar. 2022	FNAL NIU
J. B. Gibson, A. C. Hire, and R. G. Hennig, “Data-Augmentation for Graph Neural Network Learning of the Relaxed Energies of Unrelaxed Structures,” *arXiv:2202.13947 [physics]*, Feb. 2022	Florida
J. N. Nelson, N. J. Schreiber, A. B. Georgescu, B. H. Goodge, B. D. Faeth, C. T. Parzyck, C. Zeledon, L. F. Kourkoutis, A. J. Millis, A. Georges, D. G. Schlom, and K. M. Shen, “Interfacial charge transfer and persistent metallicity of ultrathin $SrIrO_3$/$SrRuO_3$ heterostructures,” *Science Advances*, vol. 8, no. 5, p. eabj0481, Feb. 2022	AEP LASSP
S. Deyo, M. Kelley, N. Sitaraman, T. Oseroff, D. B. Liarte, T. Arias, M. Liepe, and J. P. Sethna, “Dissipation by surface states in superconducting RF cavities,” *arXiv:2201.07747 [cond-mat, physics:physics]*, Jan. 2022	LASSP LEPP
Y. Gao, W. Lin, K. A. Brown, X. Gu, G. H. Hoffstaetter, J. Morris, and S. Seletskiy, “Bayesian optimization experiment for trajectory alignment at the low energy RHIC electron cooling system,” *Phys. Rev. Accel. Beams*, vol. 25, no. 1, p. 014601, Jan. 2022	LEPP BNL
G. Ha, K.-J. Kim, P. Piot, J. G. Power, and Y. Sun, “Bunch Shaping in Electron Linear Accelerators,” *Reviews of Modern Physics*, Oct. 2021	NIU ANL
R. G. Farber, S. A. Willson, and S. J. Sibener, “Role of nanoscale surface defects on Sn adsorption and diffusion behavior on oxidized Nb(100),” *Journal of Vacuum Science & Technology A*, vol. 39, no. 6, p. 063212, Dec. 2021	Chicago
J. Lim, A. C. Hire, Y. Quan, J. S. Kim, S. R. Xie, R. S. Kumar, D. Popov, C. Park, R. J. Hemley, J. J. Hamlin, R. G. Hennig, P. J. Hirschfeld, and G. R. Stewart, “Creating superconductivity in WB2 through pressure-induced metastable planar defects,” *arXiv:2109.11521 [cond-mat]*, Sep. 2021	Florida
A. Scheinker, F. Cropp, S. Paiagua, and D. Filippetto, “An adaptive approach to machine learning for compact particle accelerators,” *Sci Rep*, vol. 11, no. 1, p. 19187, Sep. 2021	LBNL UCLA
J. T. Paul, A. Galdi, C. Parzyck, K. M. Shen, J. Maxson, and R. G. Hennig, “Computational synthesis of substrates by crystal cleavage,” *npj Comput Mater*, vol. 7, no. 1, pp. 1–6, Sep. 2021	Florida LASSP LEPP
C. Zhang, Z. Baraissov, C. Duncan, A. Hanuka, A. Edelen, J. Maxson, and D. Muller, “Aberration Corrector Tuning with Machine-Learning-Based Emittance Measurements and Bayesian Optimization,” *Microscopy and Microanalysis*, vol. 27, no. S1, pp. 810–812, Aug. 2021	LEPP AEP SLAC
D. B. Durham, C. M. Pierce, F. Riminucci, S. R. Loria, K. Kanellopulos, I. Bazarov, J. Maxson, S. Cabrini, A. M. Minor, and D. Filippetto, “Characterizing plasmon-enhanced photoemitters for bright ultrafast electron beams,” in *Plasmonics: Design, Materials, Fabrication, Characterization, and Applications XIX*, Aug. 2021	SLAC LEPP LBNL
O. Chubenko, S. Karkare, D. A. Dimitrov, J. K. Bae, L. Cultrera, I. Bazarov, and A. Afanasev, “Monte Carlo modeling of spin-polarized photoemission from p-doped bulk GaAs,” *Journal of Applied Physics*, vol. 130, no. 6, p. 063101, Aug. 2021	ASU LEPP
J. Lim, A. C. Hire, Y. Quan, J. Kim, L. Fanfarillo, S. R. Xie, R. S. Kumar, C. Park, R. J. Hemley, Y. K. Vohra, R. G. Hennig, P. J. Hirschfeld, G. R. Stewart, and J. J. Hamlin, “High-pressure study of the low-Z rich superconductor Be22Re,” *Phys. Rev. B*, vol. 104, no. 6, p. 064505, Aug. 2021	Florida
T. Y. Posos, O. Chubenko, and S. V. Baryshev, “Confirmation of Transit-Time Limited Field Emission in Advanced Carbon Materials with Fast Pattern Recognition Algorithm,” *arXiv:2108.07440 [physics]*, Aug. 2021	ASU
N. Majernik, G. Andonian, R. Roussel, S. Doran, G. Ha, J. Power, E. Wisniewski, and J. Rosenzweig, “Multileaf Collimator for Real-Time Beam Shaping using Emittance Exchange,” *arXiv:2107.00125 [physics]*, Jun. 2021	UCLA
A. Galdi, J. Balajka, W. J. I. DeBenedetti, L. Cultrera, I. V. Bazarov, M. A. Hines, and J. M. Maxson, “Reduction of surface roughness emittance of Cs3Sb photocathodes grown via codeposition on single crystal substrates,” *Appl. Phys. Lett.*, vol. 118, no. 24, p. 244101	LEPP CHEM BNL
R. Roussel, A. Hanuka, and A. Edelen, “Multiobjective Bayesian optimization for online accelerator tuning,” *Phys. Rev. Accel. Beams*, vol. 24, no. 6, p. 062801, Jun. 2021	Chicago SLAC
J. Mann and J. Rosenzweig, “Semi-Classical Cutoff Energies for Electron Emission and Scattering at Field-Enhancing Nanostructures with Large Ponderomotive Amplitudes,” *arXiv:2105.10601 [cond-mat]*, May 2021	UCLA
S. T. Wang, M. B. Andorf, I. V. Bazarov, W. F. Bergan, V. Khachatryan, J. M. Maxson, and D. L. Rubin, “Simulation of transit-time optical stochastic cooling process in Cornell Electron Storage Ring,” *Phys. Rev. Accel. Beams*, vol. 24, p. 064001, Jun. 2021	LEPP

Questions?