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

Beam Dynamics & Control (BDC)

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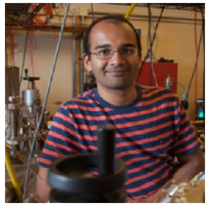
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Optimal Outcome: *Methods for* ***beam transport*** *that preserve beam quality of* ***x100 brighter beams*** *in* ***linear accelerators*** *and electron microscopes and* ***x10 brighter*** *beams in* ***storage rings****.*

BEAM DYNAMICS AND CONTROL Roadmap 2024

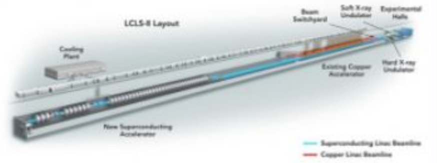
Brightness conservation of beams from extreme-low MTE linac sources subject to intense Coulomb interactions *(Conserve)*, increased brightness of beams in storage rings *(Cool)*, and advanced techniques for the optimization of many-parameter accelerators *(Control)*.

FY 22 FY 23 FY 24 FY 25 FY 26

Objectives | **Deliverables** | **Legacy**

Probe the limits of brightness conservation in the presence of collective effects in low MTE photoinjectors *(Conserve)*

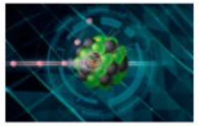
- Simulation of two injectors showing reduc emittance due to low MT ✓
- Demonstration of sub-nm emittance line at low bunch current with annual improvements thereafter ✓
- Demonstration of 100 nm emittance at 100 pC bunch charge or equivalent
- Characterization of one photocathode annually at high field or high current in support of PHC deliverables



Increased scientific reach
in
X-ray FELs

Develop methods for cooling beams

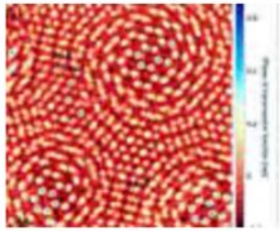
- Proof of principle demonstrations ✓



Higher
luminosity
colliders

Investigate advanced optimization schemes for phase-space control of particle accelerator systems *(Control)*

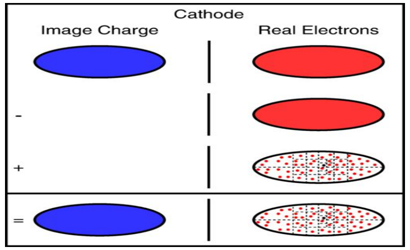
- Microscope performance comparable traditional operator tuning using ML ✓
- Higher-order EM aberration tuning, replacing intervention by company reps.
- Methods for efficiently characterizing and tuning accelerators



Active accelerator tuning and
aberration control in electron
microscopes

Key Achievements (2020-2023)

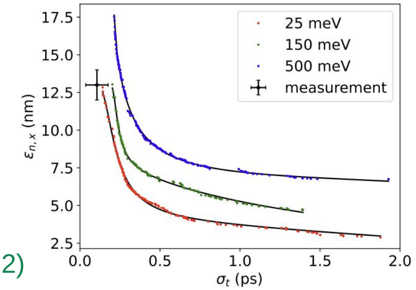
Point-to-point modeling of space-charge



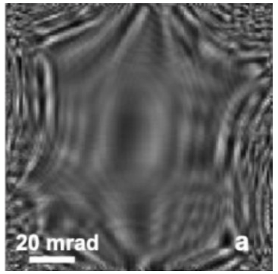
M. Gordon, et al. Phys. Rev. Accel. Beams 24, 084202 (2021)

Measurement of nanometer emittances

W. H. Li, C.J.R. Duncan, et al., Structural Dynamics 9, 024302 (2022)

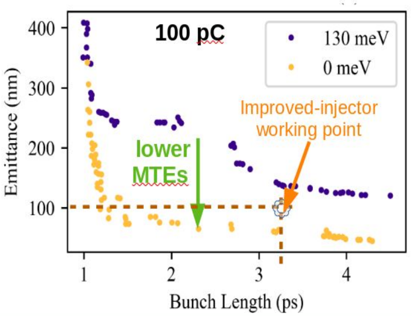


AIML-based aberration correction in TEMs



C. Zhang, et al. Microanalysis, 27(S1), 810-812 (2021)

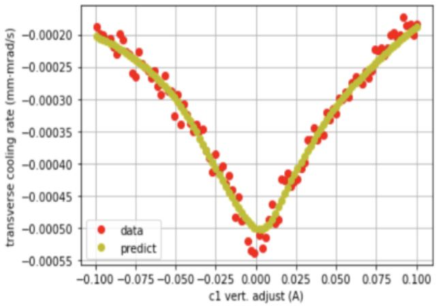
Optimization of UED beamlines & FEL injectors



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

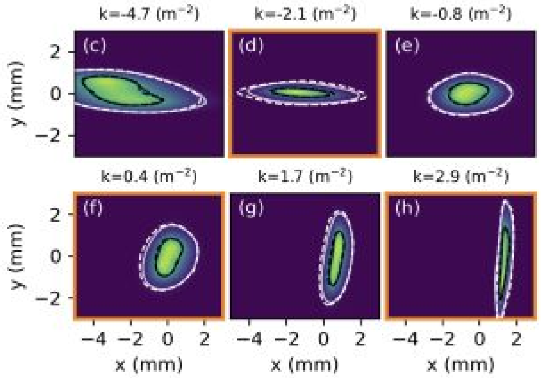
AI-ML-guided live optimization of accelerators

Y. Gao, **W. Lin**, et al., Phys. Rev. Accel. Beams 25, 014601 (2022)

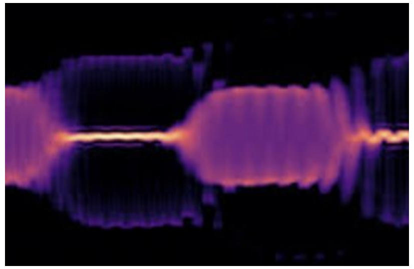


AI-ML-based 4D-phase-space Reconstruction

R. Roussel, … **J.-P. Gonzalez-Aguilera**, et al. Phys. Rev. Lett. 130, 145001 (2023).

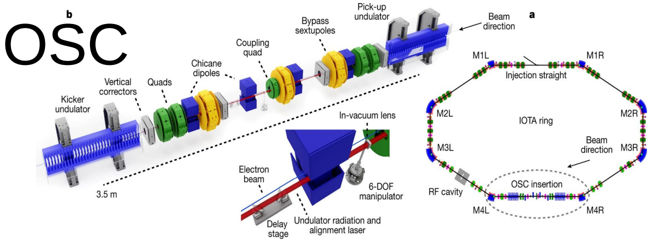


Modeling of optical stochastic cooling (OSC)



S. T. Wang, **M.B. Andorf,** et al., Phys. Rev. Accel. Beams 24, 064001 (2021);
A.J. Dick, et al. PRAB (2024)

Experimental demo of OSC @IOTA



J. D. Jarvis, et al.(**A. J. Dick**), Nature 608, 287 (2022)

NOTE: bold-face names indicates the contributing students and postdocs

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AJ Dick,
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graduated


Gevork Gevorkyan
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graduated


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Lucy Lin,
Cornell


Desheng Ma,
Cornell

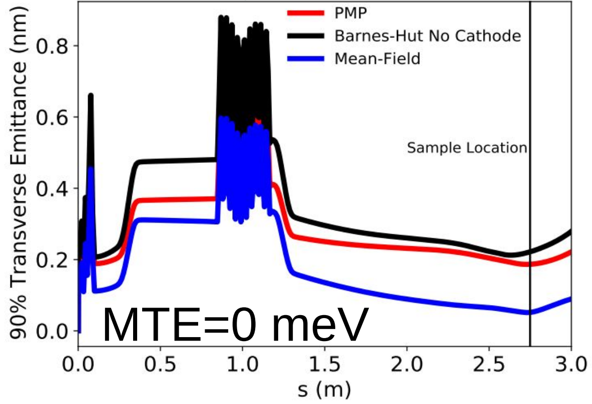
Brightness Preservation in Photoinjectors

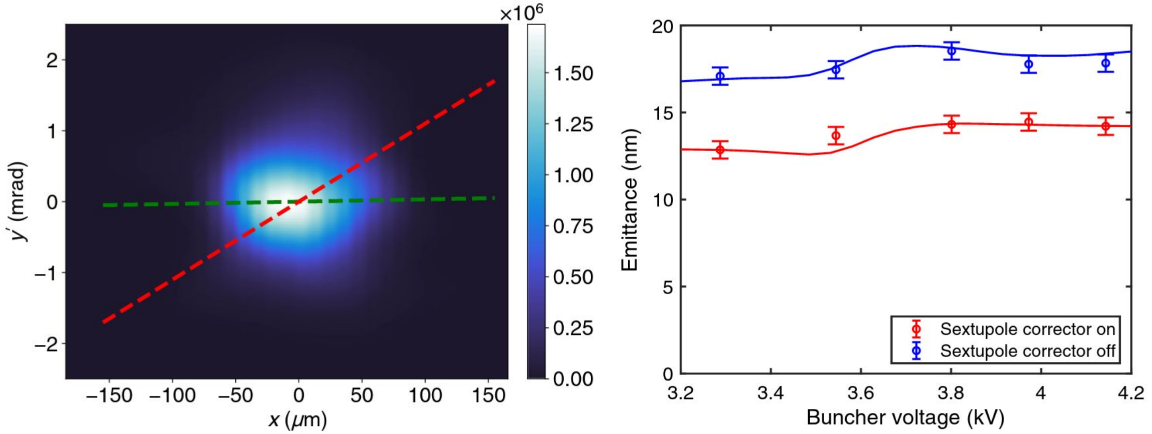
laser size

$$\varepsilon_{n(x,y)} = \sigma_{(x,y)}\sqrt{\frac{MTE}{m_e c^2}}$$

- Performances of UED/UEM and XFEL setups are ultimately limited by photoinjector brightness
- **How do we capitalize on advances in cathodes from Theme 1?**
- **Challenges:**
  - Significant emittance dilution during transport from photocathode to front-end applications
  - Brightness degradation principally occurs during acceleration to relativistic energies (i.e. to a few MeV's)
- **Methods**: emittance preservation, physics of space charge, binary collisions, beam characterization, deploy full-scale experiments at available facilities

M. Gordon, et al. Phys. Rev. Accel. Beams 24, 084202 (2021)





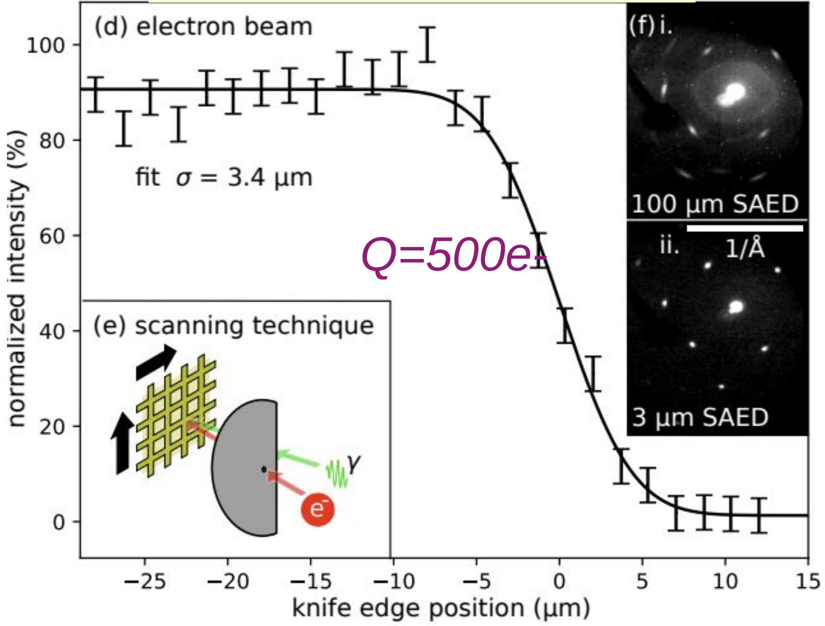
M. Gordon, W. H. Li, M. B. Andorf, A. C. Bartnik, C. J. R. Duncan, M. Kaemingk, C. A. Pennington, et al, Phys. Rev. Accel. Beams 25, 084001 (2022)

Deliverable 1.1: sub-nm transverse emittance

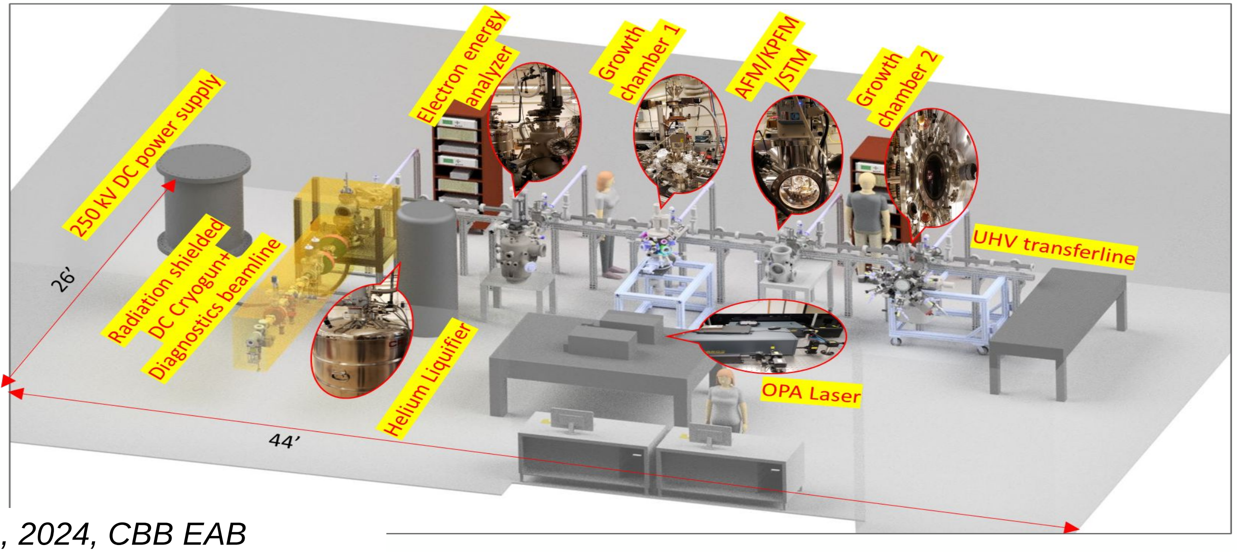
✓ Experimental demonstration of sub-nanometer emittance in at least one beamline with low bunch current with improvements thereafter [2026]

- Generated sub-nm emittances w/ 500*e*- in a DC gun (MEDUSA@Cornell) w/ 60 meV MTE [2022]
- MEDUSA performs multi-scale ultra-fast microscopy experiment [2022]
- Integration of lower MTE (<60 meV) cathodes in the MEDUSA setup [>2023]

$$\varepsilon = 0.7 \pm 0.1 \text{ nm}$$



W. H. Li, C.J.R. Duncan, et al., Structural Dynamics 9, 024302 (2022)



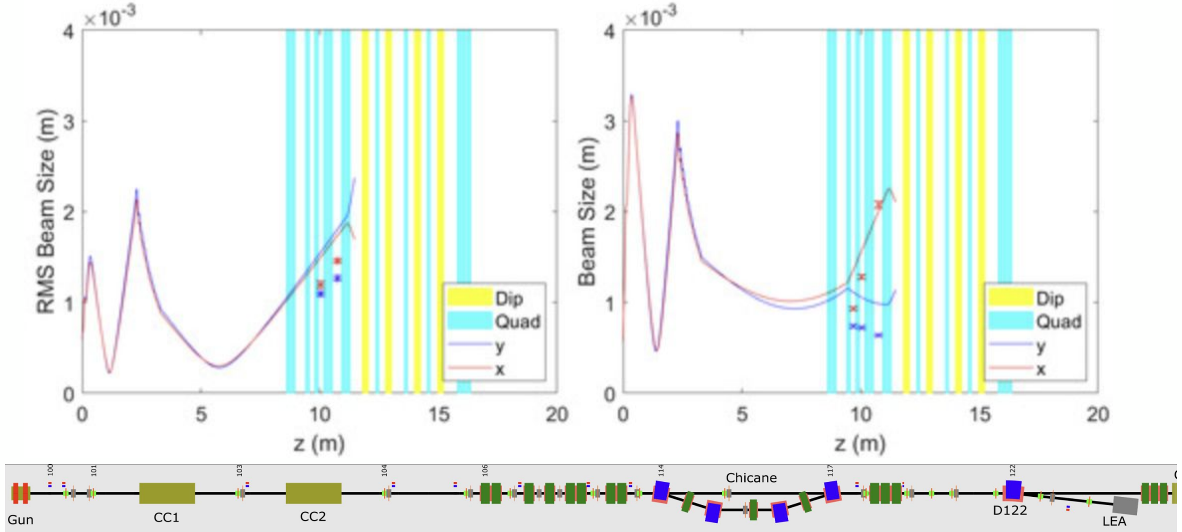
- Commissioning of the ASU DC cryogun
  - Investigation of MTE (surface roughness) have begun [>**2022**]
  - Beams from nano-sized emitters

Deliverable 1.2: low-MTE photocathodes integration in existing photoinjectors

Identification of beamlines for a potential experimental demonstration of the simultaneous generation of low-emittance and high-charge (~100 pC) bunch, using CBB low-MTE photocathodes and diagnostics, that when coupled with a bunch-compression beamline would produce beams with 5D normalized brightness $I/\varepsilon^2 > 10^{15}$ A/m^2.

- **Progress/Current Activities:**
  - Explored feasibility of integrated tests at UCLA (PEGASUS), ANL (AWA), and FNAL (FAST).
  - Investigating transverse brightness preservation during bunch compression.
  - Preparation for photocathode tests at ANL and UCLA (PEGASUS), some question regarding possible test at FNAL.

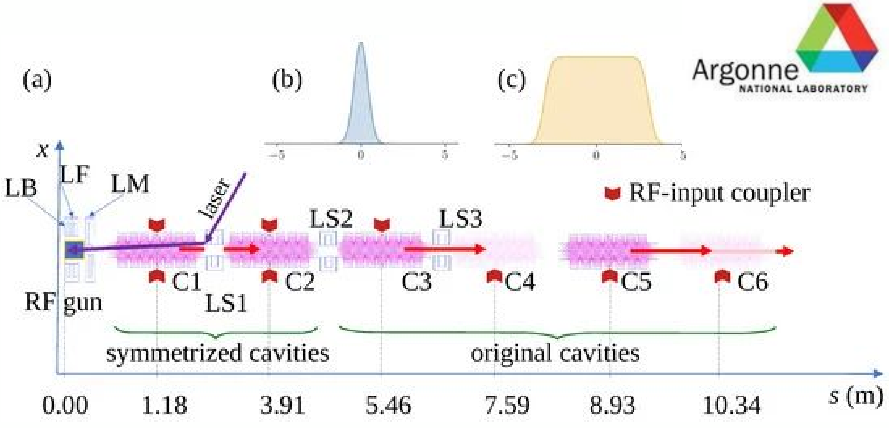
F. Cropp, et al. Instruments 2023, 7(4), 42 (2023)



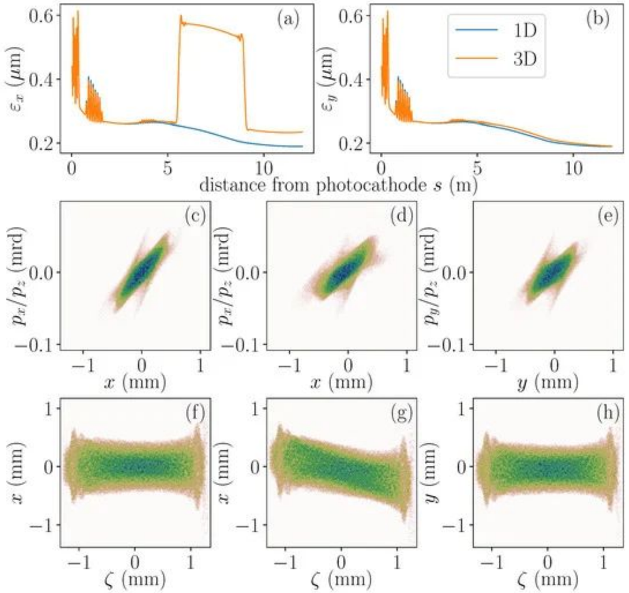
- **This deliverable is now a priority deliverable**

Deliverable 1.2: low-MTE photocathodes integration in existing photoinjectors (cnt'd)

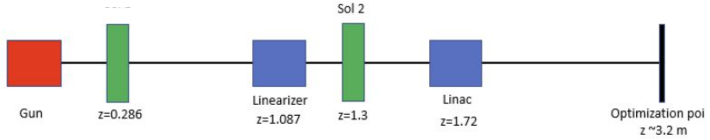
- Modeled AWA facility (w/ planned injector upgrade in August 2024)
- Support ~200 nm emittance at 60 MeV
- Tests contingent on successful cathode test on the ACT beamline (O. Chubenko)
- Possible improvement using collimation (proposed by J. Maxson; see below)



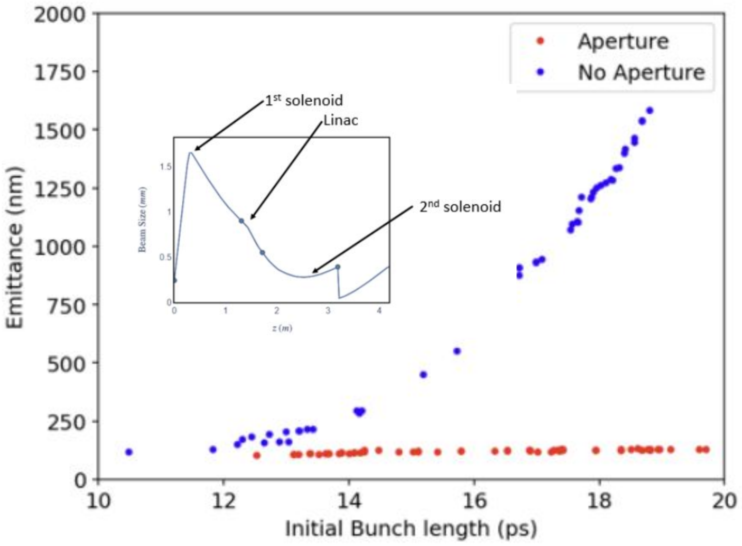
E. Frame, et al. Instruments 2023, 7(4), 48 (2023)



UCLA



J. Maxson, P Musumeci, UCLA/Cornell collaboration

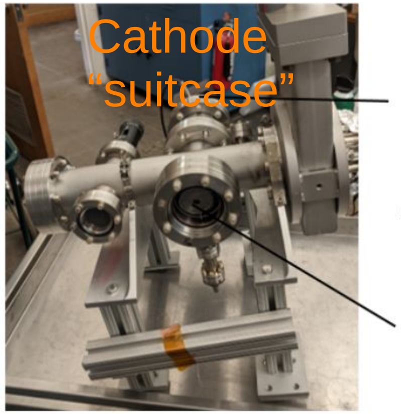


- Sacrifical collimation technique simulated at the PEGASUS beamline
- Photocathode tests at PEGASUS are ongoing
- Setup expected to produce sub 200-nm emittance at ~10 MeV

Deliverable 1.3: cathode tests

Characterization and specification of the performance of photocathodes in either high field or high current conditions as needed to complete PHC Deliverables 2.1 and 2.2 [**Annual starting 2023**].

- **Accomplishments:**
  - Two standardized cathode plugs across CBB
  - Cathode preparation, transport tests to UCLA
  - High gradients (>100 MV/m) tests at PEGASUS
  - Successful tests of low MTE cathodes at high gradients
- **Progress/Current Activities:**
  - Understanding QE degradation during transport
  - Planning tests in other RF guns (deliverable 1.2)
  - Long-term lifetime + high current (~30 mA) test in DC guns (HERACLES)

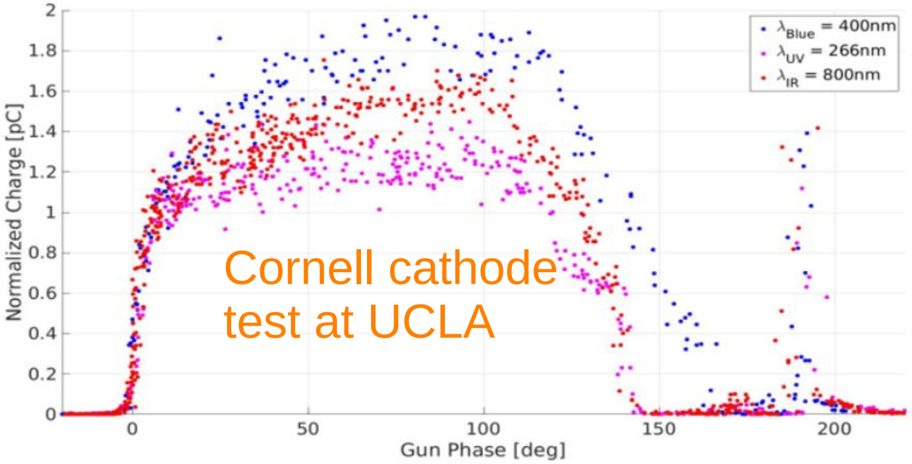

Cathode "suitcase"

NEG and ion pump achieve pressure below 1e-10 torr

NEGs allow passive pumping during suitcase shipment

Collection grid diagnostic for QE measurements

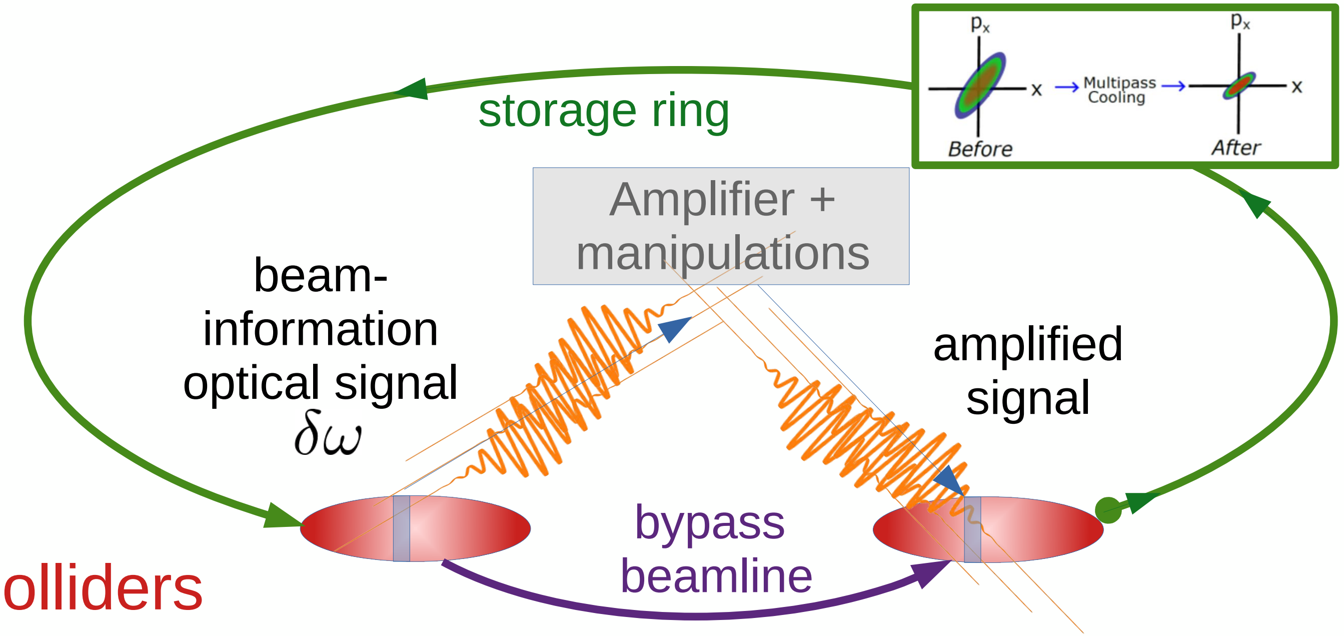
C. Pennington, et al., talk at the P3 meeting, Dec., 2021

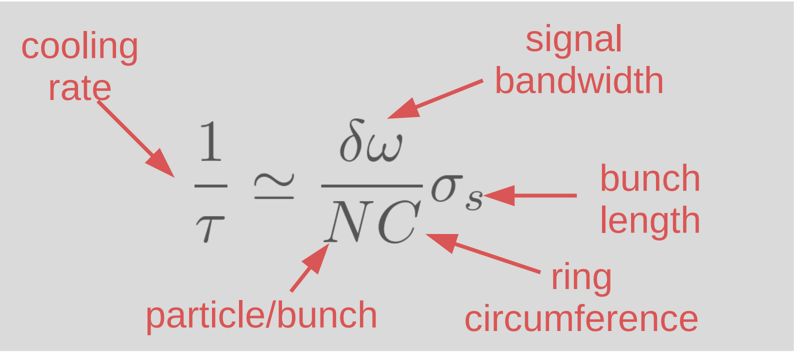


Cornell cathode test at UCLA

Objective 2: Cool – Overview

- **Objective:** Explore a novel cooling technique – optical stochastic cooling (OSC) – with ~4 orders of magnitude faster cooling times.
- **Impacts**: OSC could increase the luminosity of planned electron-ion colliders, and next-generation linear colliders it is also application to short-pulse storage-ring light sources.
- **Methods**
  - ✓ Develop high-fidelity simulations
  - ✓ Participate and contribute to on-going OSC experiment~~(s)~~
  - ~~Apply benchmarked tools to explore applications of OSC to future accelerators~~



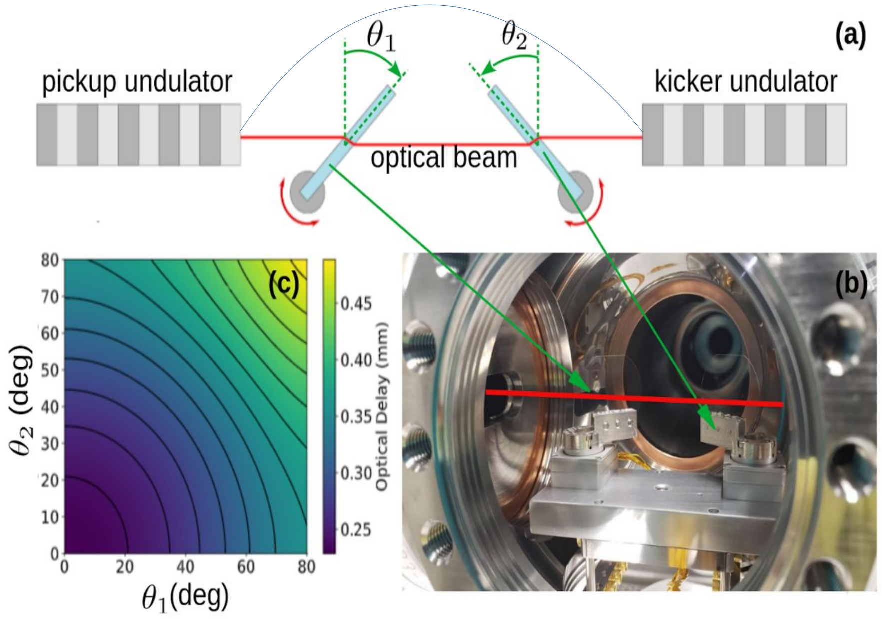


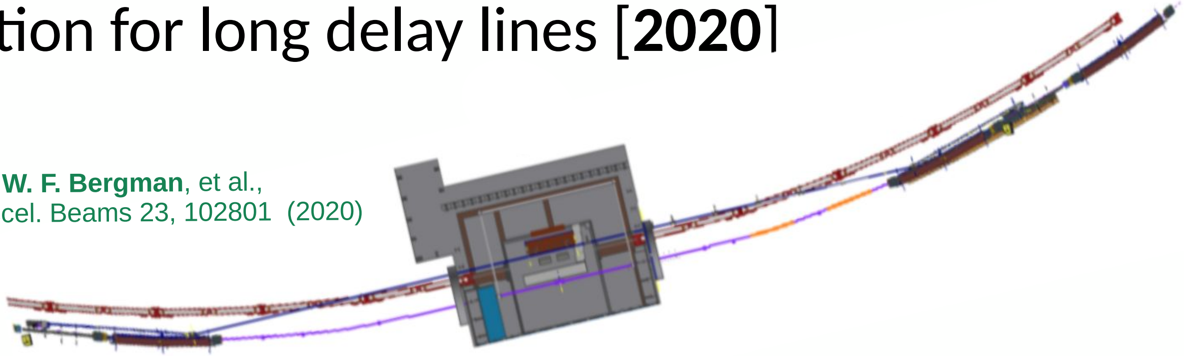
$$\frac{1}{\tau} \simeq \frac{\delta\omega}{NC}\sigma_s$$

Deliverable 2.1: experimental demo of OSC

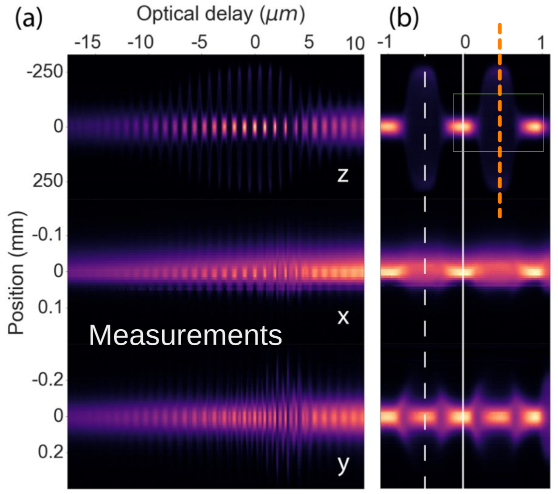
✓ Proof of principle demonstrations of key elements of optical stochastic cooling at IOTA and CESR [**by Spring 2023**].

- **Accomplishments:**
  - OSC models implemented in “popular” codes (BMAD [**2021**] and ELEGANT [**2022**])
  - Demonstration of passive OSC [**2021**]: CBB contributed the optical-delay stage
  - Development & laboratory test of active stabilization for long delay lines [**2020**]





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

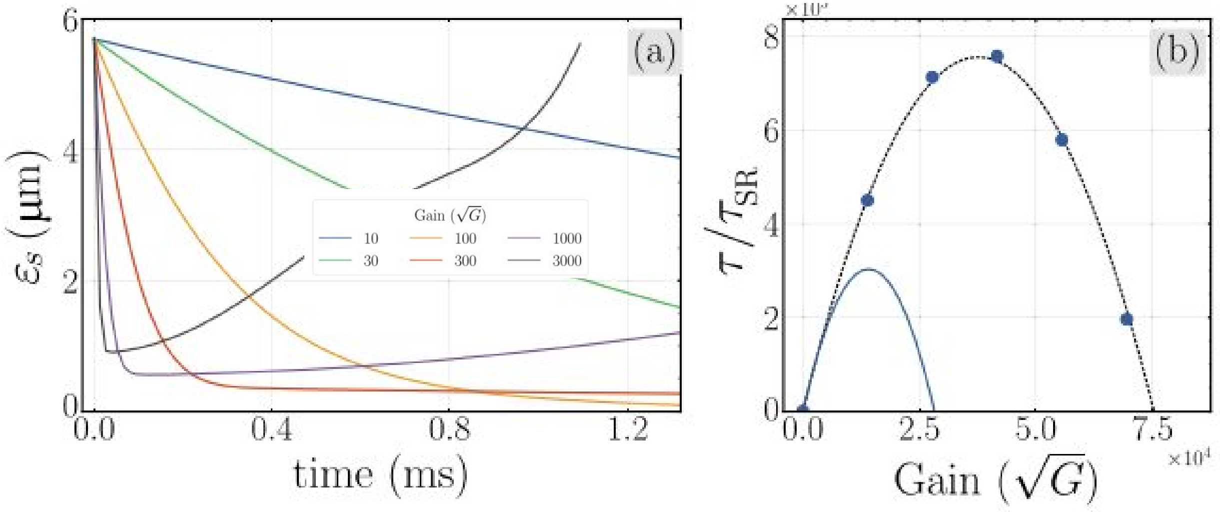


J. Jarvis, et al. (**A.J. Dick**),
Nature 608, 287 (2022)

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

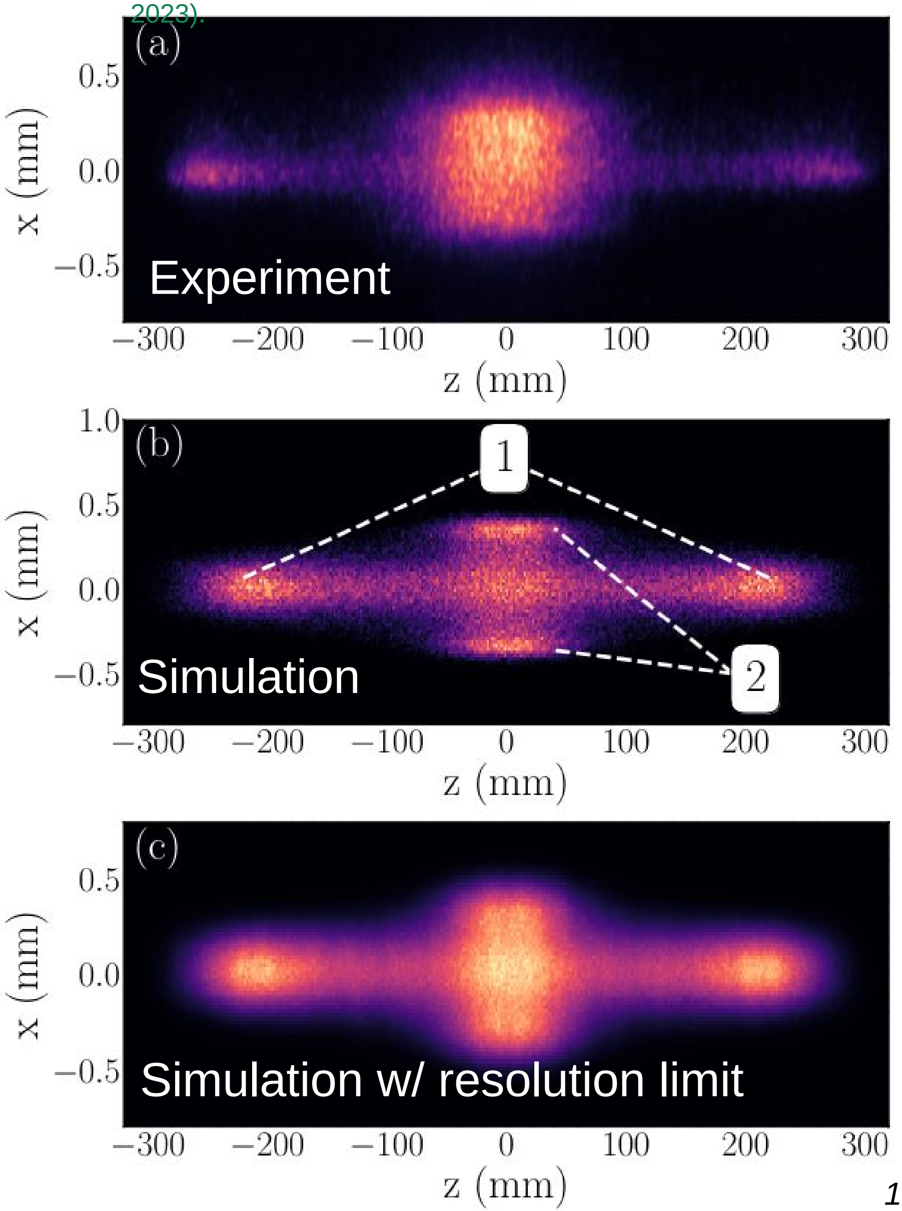
Deliverable 2.1: experimental demo of OSC

- **Last year activities:**
    - Validated ELEGANT model with IOTA data [2023]
    - Release updated algorithm in official ELEGANT version and passed all input to a FNAL
    - Investigated performance of amplified (active) OSC



- **Current status:** (unfunded) finishing simulations on OSC-based beam manipulation

A. J. Dick et al., ArXiV 2306.07898 submitted (2023), 2023).

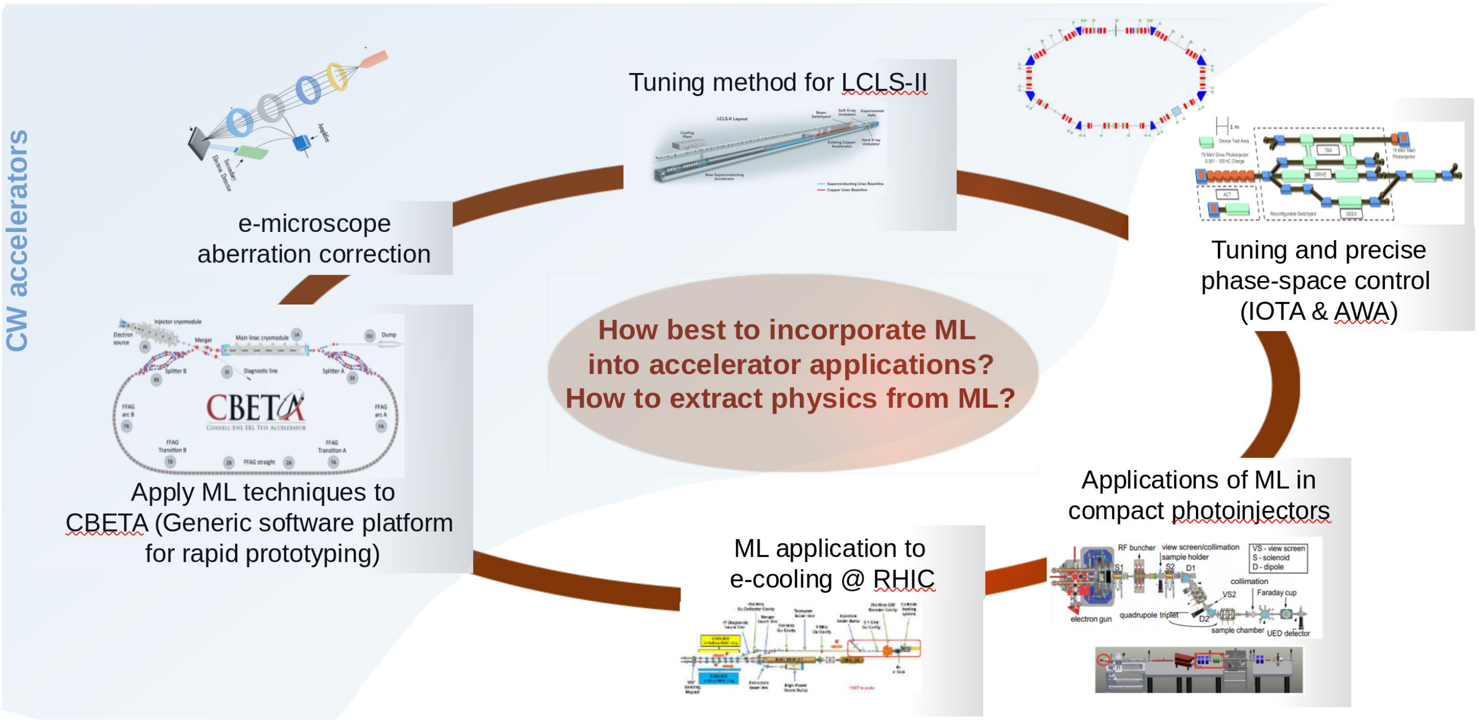


Objective 3: Control – Overview

- **Objective**: Introduce new tuning methods based on machine learning and other advanced techniques to improve the transport and storage of high-brightness beams.

- **Impacts**: Precise control over the beam distribution, partitioning of emittance, live optimization and active tuning of accelerators and electron microscopes.

- **Methods**
  - Design and test tuning & control algorithms over a wide range of accelerators accessible through CBB
  - Develop ML-based methods to control the beam's phase space distribution



CW accelerators

Tuning method for LCLS-II

e-microscope
aberration correction

Tuning and precise
phase-space control
(IOTA & AWA)

**How best to incorporate ML
into accelerator applications?
How to extract physics from ML?**

Apply ML techniques to
CBETA (Generic software platform
for rapid prototyping)

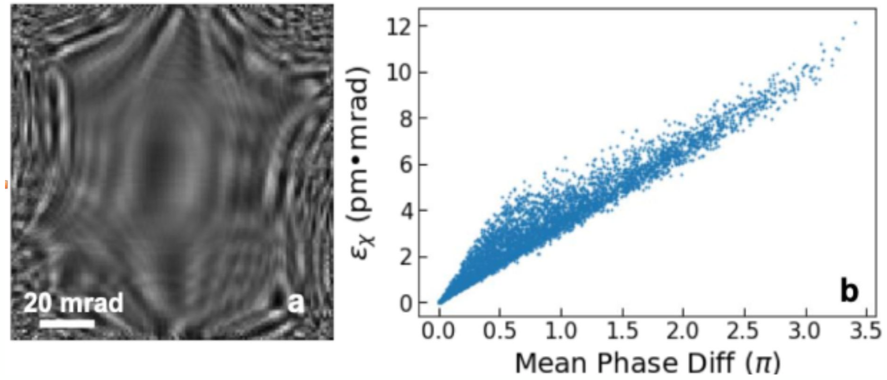
Applications of ML in
compact photoinjectors

ML application to
e-cooling @ RHIC

Deliverable 3.1: microscope “auto-tuning”

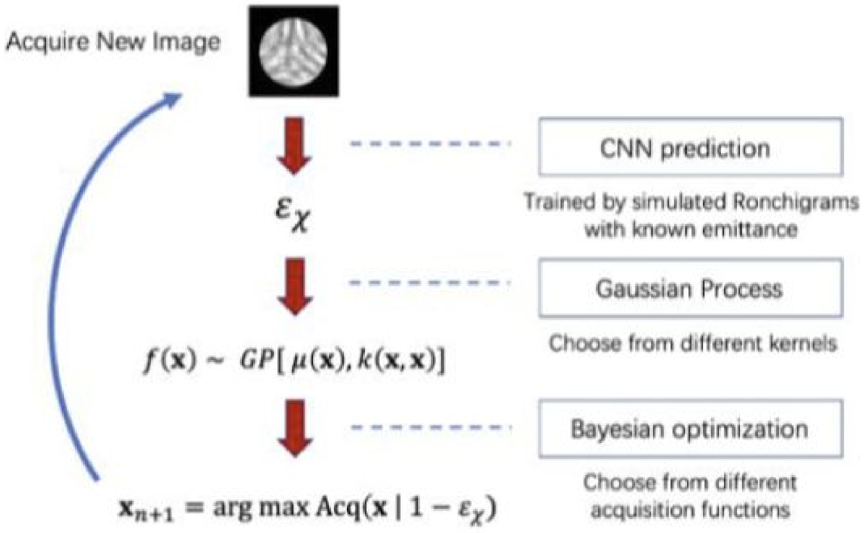
✓ Microscope performances comparable to traditional operator tuning using ML [**by Fall 2023**].

- **Accomplishments: operator-free tuning**
  - Connected emittance to aberration (Ronchigram) and developed a numerical model of a microscope [**2021**]



C. Zhang, et al., Microsc. Microanal. 27 (Suppl 1), 2021

  - Demonstrated fast (2 min) and robust Bayesian optimization (BO) to correct aberration on three different microscopes [**2022**]



Acquire New Image

CNN prediction

ε_χ

Trained by simulated Ronchigrams with known emittance

Gaussian Process

$f(\mathbf{x}) \sim GP[\,\mu(\mathbf{x}), k(\mathbf{x},\mathbf{x})]$

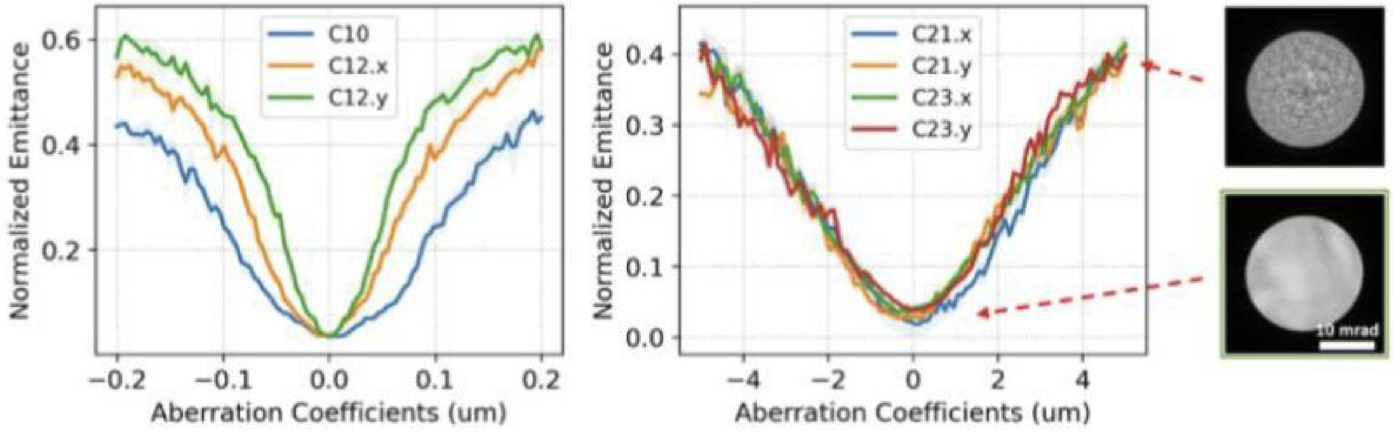
Choose from different kernels

Bayesian optimization

$\mathbf{x}_{n+1} = \arg\max \mathrm{Acq}(\mathbf{x} \mid 1 - \varepsilon_\chi)$

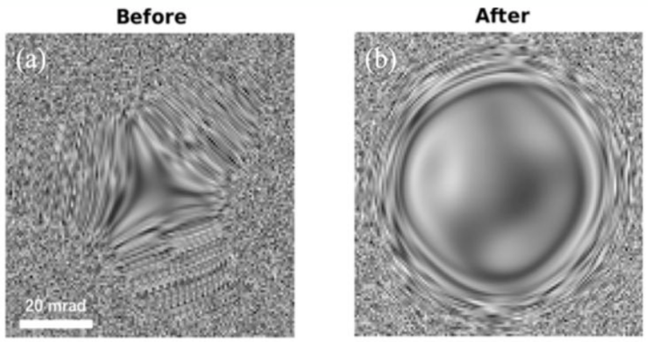
Choose from different acquisition functions

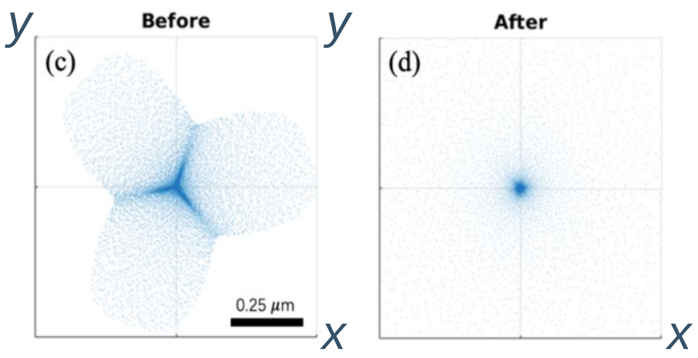
ThermoFisher Titan Cryo-S/TEM



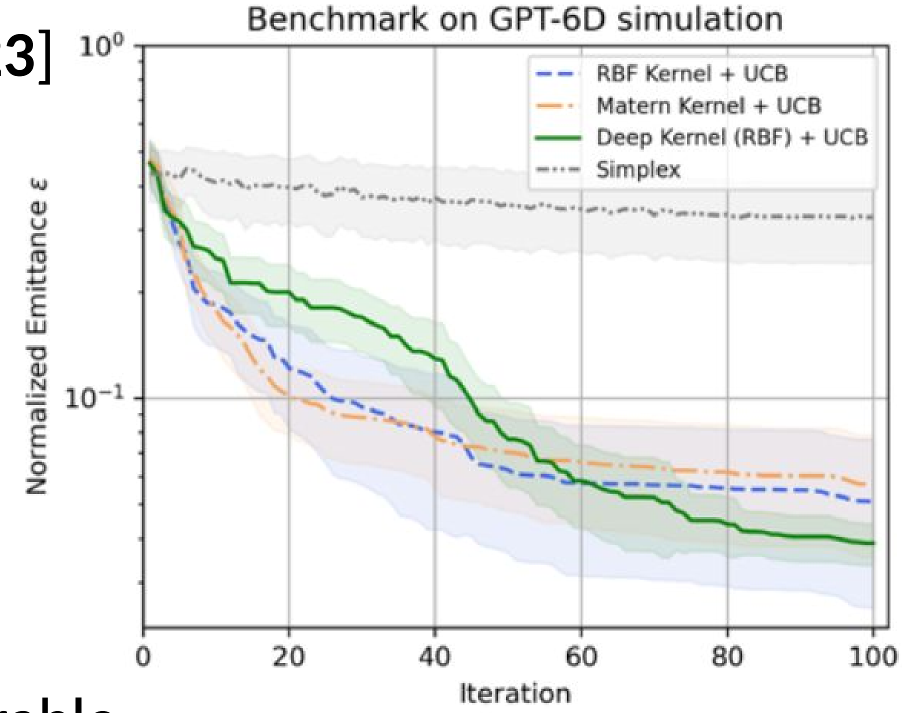
Deliverable 3.2*: microscope tuning w/o company intervention

ML-based higher-order microscope aberration tuning: replacing intervention by company reps [**by Fall 2025**].





- **Accomplishments:**
  - Demonstrated the use of BO to tune microscopes under deliverable 3.1
  - Numerical study of BO to higher-order correction [**2023**]
- **Plan:**
  - Include magnet hysteresis effects
  - Collaborate with company to deploy software on commercial system(s)
- **End users:**
  - Thermo Fisher Scientific, Corrected Electron Optical Systems. The transfer of this technology is a KT Deliverable



Deliverable 3.3: Efficient tuning of accelerators

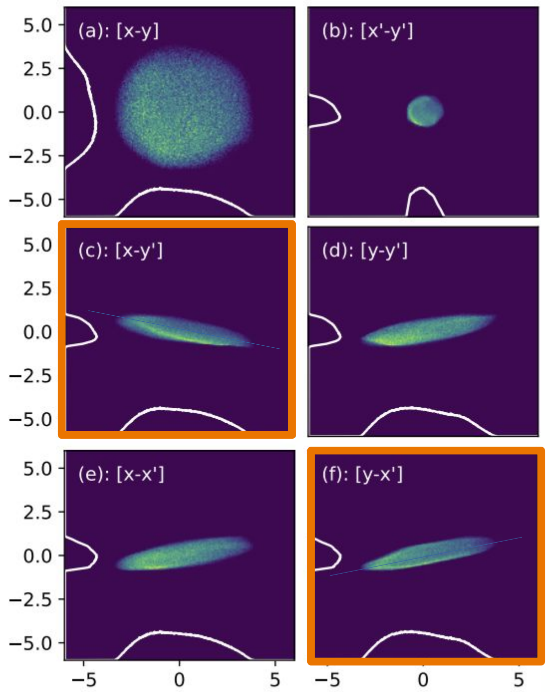
Methods for efficiently tuning an accelerator [**by Summer 2026**].

- **Accomplishments:**
  - Developed framework for rapid proto-typing of optimization algorithm [**2019**]
  - Applied ML to live tuning of accelerators (i.e. emittance and e-beam cooling [**2021**])
  - Demonstrated phase-space diagnostics [**2023**]
  - Applied virtual diagnostics to magnetized beams [**2023**]

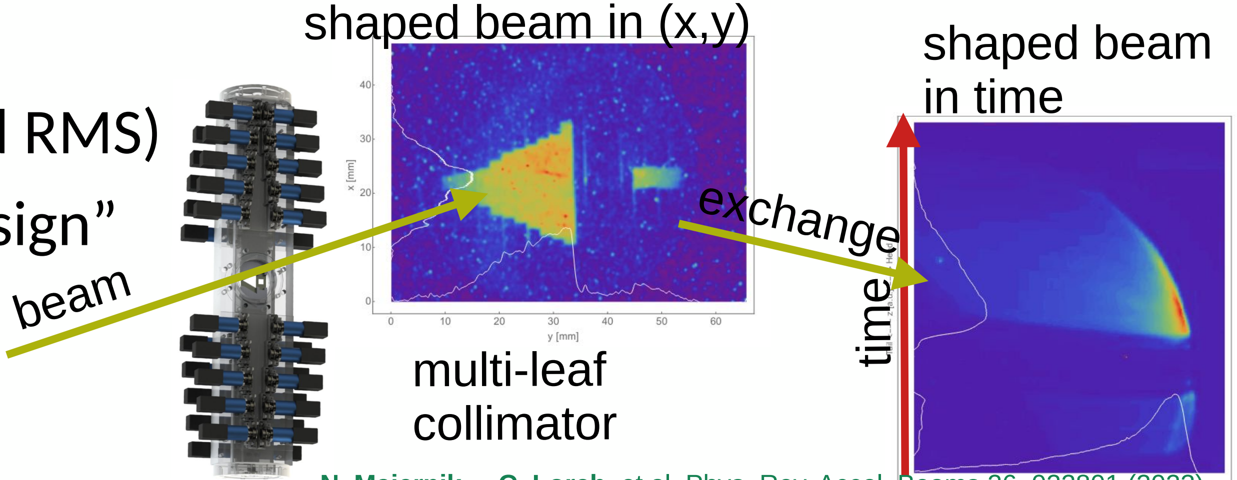
$$\Sigma = \begin{bmatrix} \epsilon_{eff}T_x & \mathcal{L}J \\ -\mathcal{L}J & \epsilon_{eff}T_y \end{bmatrix}$$

$$J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

S. Kim, .. **J.-P. Gonzalez-Aguilera**, et al.ArXiV (2024).



- **Current Activities:**
  - High-precision control of beams (beyond RMS)
  - Spatiotemporal shaping → “beam by design”
  - Extending virtual diagnostics to 6D phase space reconstruction

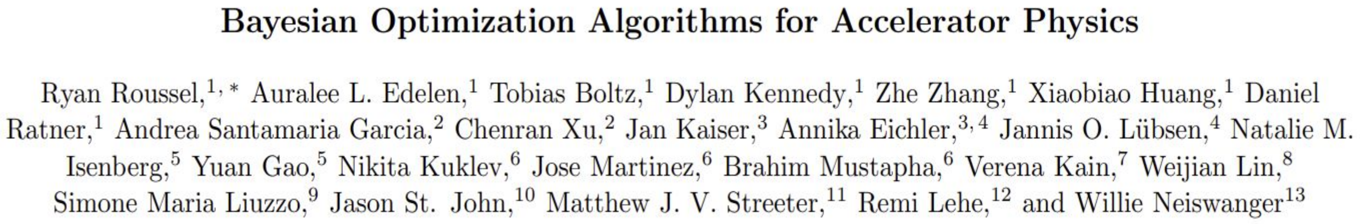


N. Majernik, .. **C. Lorch**, et al. Phys. Rev. Accel. Beams 26, 022801 (2023).

Deliverable 3.4: boundaries of applicability of ML

Summary of the boundaries of applicability of ML in accelerators with varying noise types and data availability [**by Summer 2026**].

- **Accomplishments:**
  - Demonstrated ML-assisted optimization of accelerators numerically and over a wide range of experimental conditions [**since 2019**]

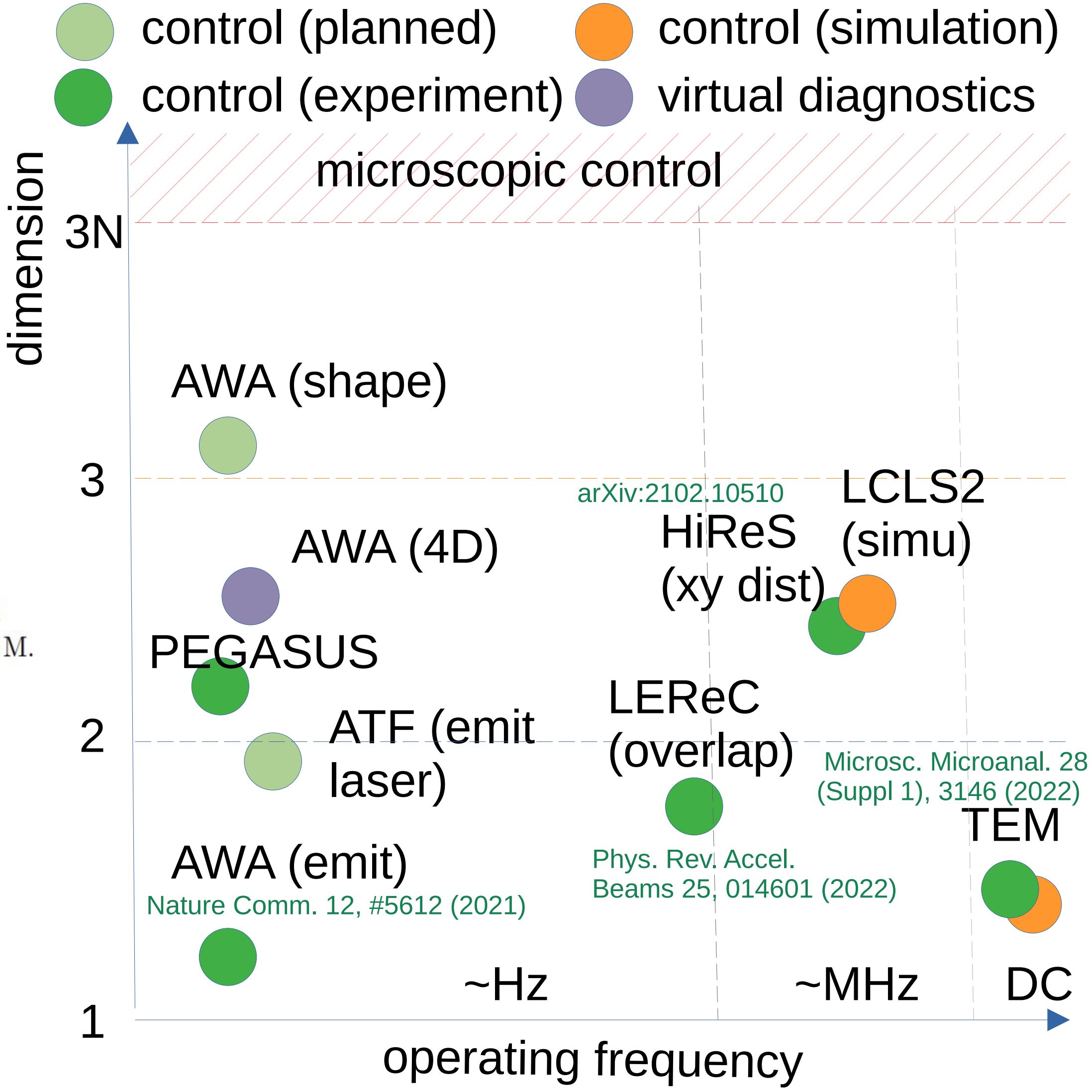


Bayesian Optimization Algorithms for Accelerator Physics

Ryan Roussel,^{1,*} Auralee L. Edelen,^{1} Tobias Boltz,^{1} Dylan Kennedy,^{1} Zhe Zhang,^{1} Xiaobiao Huang,^{1} Daniel Ratner,^{1} Andrea Santamaria Garcia,^{2} Chenran Xu,^{2} Jan Kaiser,^{3} Annika Eichler,^{3,4} Jannis O. Lübsen,^{4} Natalie M. Isenberg,^{5} Yuan Gao,^{5} Nikita Kuklev,^{6} Jose Martinez,^{6} Brahim Mustapha,^{6} Verena Kain,^{7} Weijian Lin,^{8} Simone Maria Liuzzo,^{9} Jason St. John,^{10} Matthew J. V. Streeter,^{11} Remi Lehe,^{12} and Willie Neiswanger^{13}

R, Roussel, et al. [incl 4 former or present CBB participants], arXiv:2312.05667 (2024)

- **Current Activities:**
  - Increasing complexity of phase-space control



Connections

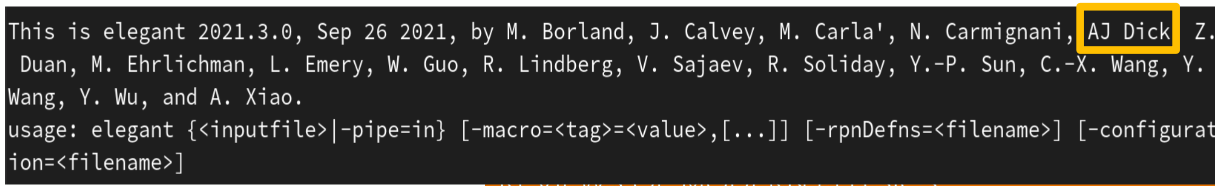
- Strong connections between Beam Production Theme (Theme 1) and Beam Dynamics and Control Theme (Theme 3)
- Access to a wide variety of accelerator test facilities
  - CESR and CBETA at Cornell
  - UCLA Pegasus normal conducting RF ultrafast beamline
  - Cornell and ASU ultrafast electron diffraction beamlines
  - LBNL HiRES relativistic electron diffraction facility
  - IOTA+FAST facility at FNAL
  - AWA at Argonne National Laboratory

National laboratories & Industrial partners are critical to student training

- Connection with industry: CBB works with microscope manufacturers Nion, CEOS, and ThermoFisher.

BDC impact on our community

- **Developed computer program openly available to the community** (space charge module for GPT, OSC in BMAD and ELEGANT)
- **CBB/BDC participates in the educational activities:**
  - USPAS classes (AIML/sources)
  - Review on beam shaping [Rev. Mod. Phys.]
- **BDC members are active participants in several community initiatives:**
  - 2021(22) Snowmass workshop (BDC participants have co-authored letters of intent on a wide range of topics including on future-collider opportunities, and proposal for education frameworks)
  - Contributing to the Accelerator & Beam Physics general accelerator R&D roadmap in preparation for the Department of Energy GARD program.
  - Contributions to *Handbook of Particle Accelerators*



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This is elegant 2021.3.0, Sep 26 2021, by M. Borland, J. Calvey, M. Carla', N. Carmignani, AJ Dick  Z.
 Duan, M. Ehrlichman, L. Emery, W. Guo, R. Lindberg, V. Sajaev, R. Soliday, Y.-P. Sun, C.-X. Wang, Y.
Wang, Y. Wu, and A. Xiao.
usage: elegant {<inputfile>|-pipe=in} [-macro=<tag>=<value>,[...]] [-rpnDefns=<filename>] [-configurat
ion=<filename>]
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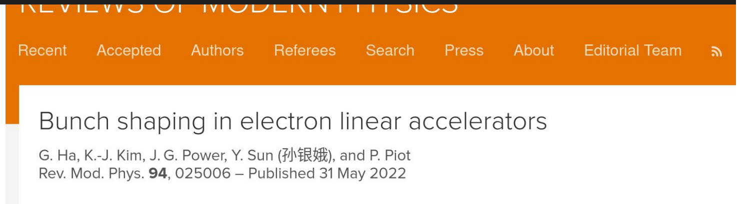
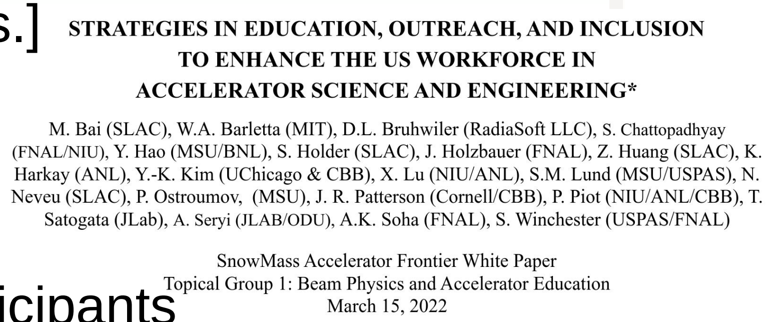


Bunch shaping in electron linear accelerators

G. Ha, K.-J. Kim, J. G. Power, Y. Sun (孙银娥), and P. Piot
Rev. Mod. Phys. **94**, 025006 – Published 31 May 2022

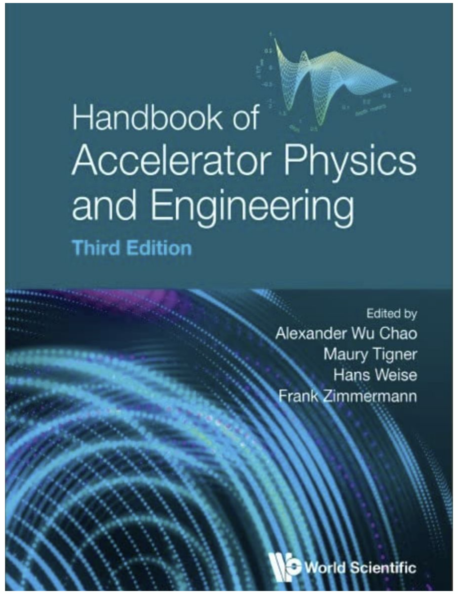
https://arxiv.org/abs/2203.08919



STRATEGIES IN EDUCATION, OUTREACH, AND INCLUSION TO ENHANCE THE US WORKFORCE IN ACCELERATOR SCIENCE AND ENGINEERING*

M. Bai (SLAC), W.A. Barletta (MIT), D.L. Bruhwiler (RadiaSoft LLC), S. Chattopadhyay (FNAL/NIU), Y. Hao (MSU/BNL), S. Holder (SLAC), J. Holzbauer (FNAL), Z. Huang (SLAC), K. Harkay (ANL), Y.-K. Kim (UChicago & CBB), X. Lu (NIU/ANL), S.M. Lund (MSU/USPAS), N. Neveu (SLAC), P. Ostroumov, (MSU), J. R. Patterson (Cornell/CBB), P. Piot (NIU/ANL/CBB), T. Satogata (JLab), A. Seryi (JLAB/ODU), A.K. Soha (FNAL), S. Winchester (USPAS/FNAL)

SnowMass Accelerator Frontier White Paper
Topical Group 1: Beam Physics and Accelerator Education
March 15, 2022



Handbook of Accelerator Physics and Engineering
Third Edition

Edited by
Alexander Wu Chao
Maury Tigner
Hans Weise
Frank Zimmermann

World Scientific

https://arxiv.org/abs/2101.04107

Accelerator and Beam Physics Research Goals and Opportunities

Working group: S. Nagaitsev (Fermilab/U.Chicago) *Chair*, Z. Huang (SLAC/Stanford), J. Power (ANL), J.-L. Vay (LBNL), P. Piot (NIU/ANL), L. Spentzouris (IIT), and J. Rosenzweig (UCLA)

Workshops conveners: Y. Cai (SLAC), S. Cousineau (ORNL/UT), M. Conde (ANL), M. Hogan (SLAC), A. Valishev (Fermilab), M. Minty (BNL), T. Zolkin (Fermilab), X. Huang (ANL), V. Shiltsev (Fermilab), J. Seeman (SLAC), J. Byrd (ANL), and Y. Hao (MSU/FRIB)

Advisors: B. Dunham (SLAC), B. Carlsten (LANL), A. Seryi (JLab), and R. Patterson (Cornell)

CBB Legacy (by 2026)

- **Convergence Science:**
  - **New regime of ultracold beams** and identifying **new physics and technical challenges** affecting beam dynamics, transport, and storage
- **Knowledge:**
  - Deeper understanding of fundamental beam brightness limits to photoinjectors and leveraging key impact parameters to advance the brightness frontier
  - New tools (computer model) and concepts available to the community
  - Dissemination of knowledge though classes and review articles
  - **By 2026: Fundamental understanding of beam brightness limits**
- **Current Activities:** Continuous training of young scientists prepared to join the workforce in areas of critical needs
- **Technology & Applications:** By 2026: improved photoinjectors, transport lines, and rings enabled by CBB advances
  - Compact and versatile light sources (from LCLS-II-HE to table-top sources)
  - Electron probes for scattering: macro-molecule single-shot UED, and atomic-sale time-resolved TEM
  - Electron-ion collider and future linear and circular colliders (EIC, future e+/e- or μ+/μ- colliders)

Growing Convergence Research
NSF Big Idea

Understanding the Rules of Life
NSF Big Idea

Quantum Leap
NSF Big Idea

Enable revolutionary instruments to study biological and quantum materials in motion and to unlock the secrets the universe