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

Beam Dynamics & Control (BDC)

Young-Kee Kim, David Muller and Philippe Piot

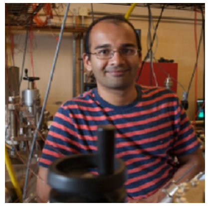
Faculty:

theme leaders


Ivan Bazarov
Cornell U.


Sandra Biedron
UNM


Georg Hofstaetter
Cornell U.


Siddharth Karkare
ASU


Jared Maxson
Cornell U.


Pietro Musumeci
UCLA


Jamie Rosenzweig
UCLA


Jim Sethna
Cornell U.


Young-Kee Kim
U. Chicago

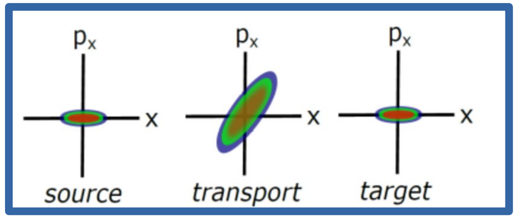

David Muller
Cornell U.


Philippe Piot
NIU/ANL

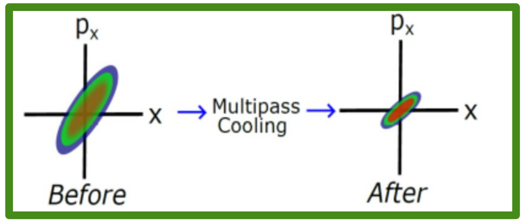
Affiliates: A. Adelman (PSI), A. Edelen (SLAC), A. Hanuka (SLAC), S. Nagaitsev (JLab), J. Power (ANL), A Scheinker (LANL), A. Valishev (FNAL)

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****.*

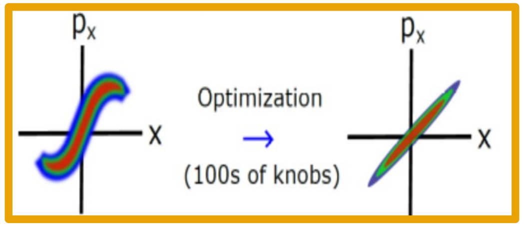
Objectives



- Objective 1 (**Conserve**): Probe the ultimate limits of **brightness conservation** in the presence of collective effects in low MTE photoinjector beamlines.



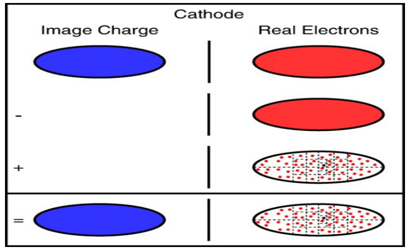
- Objective 2 (**Cool**): Develop methods for cooling beams using optical **stochastic cooling** to increase beam luminosity in next-generation colliders.



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

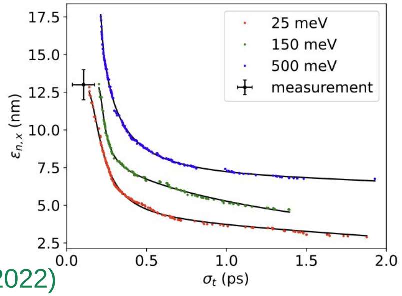
Key Achievements (2020-2022)

Point-to-point modeling of space-charge



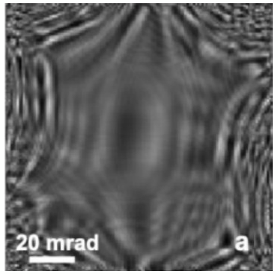
M. Gordon, et al. Phys. Rev. Accel. Beams 24, 084202 (2021)

Measurement of nanometer emittances



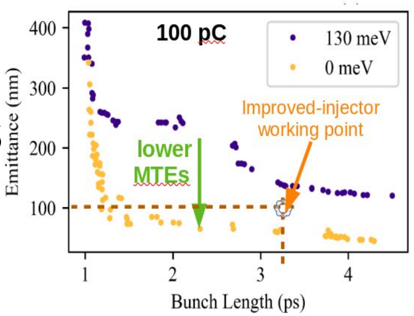
W. H. Li, C.J.R. Duncan, et al.,
Structural Dynamics 9, 024302 (2022)

AIML-based aberration correction in TEMs



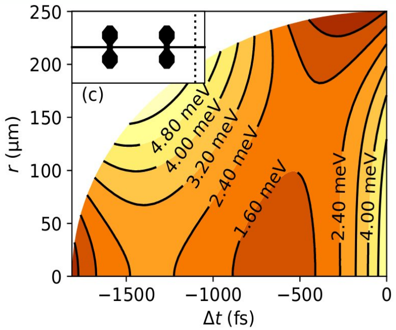
C. Zhang, et al. Microanalysis, 27(S1), 810-812 (2021)

Optimization of UED beamlines & FEL injectors



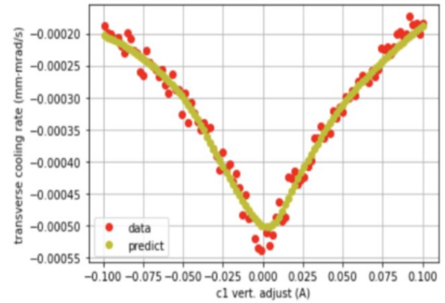
C. M. Pierce, et al. Phys. Rev. Accel. Beams 23, 070101 (2020).

10-meV ultrafast TEMs w/ lossless monochromator



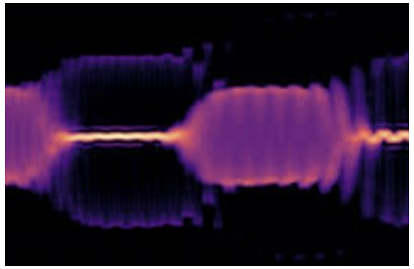
C.J.R. Duncan, et al.,
Phys. Rev. Applied 14, 014060 (2021)

AIML-based live optimization of accelerators



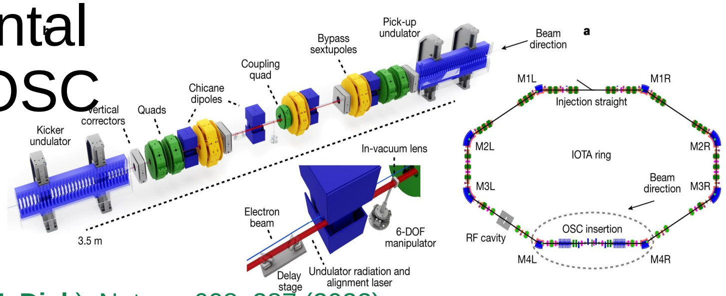
Y. Gao, **W. Lin**,et al., Phys. Rev. Accel. Beams 25, 014601 (2022)

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. doi:10.18429/JACoW-IPAC2022-WEPOMS028

Experimental demo of OSC @IOTA



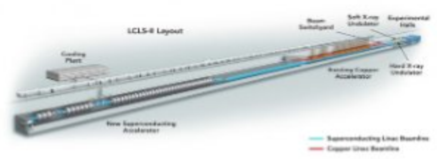
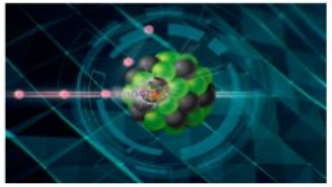
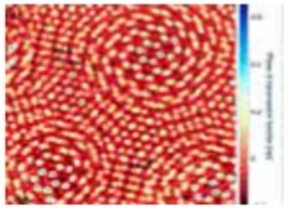
J. D. Jarvis, et al.(**A. J. Dick**), Nature 608, 287 (2022)

NOTE: bolded names indicates the contributing students and postdocs

BEAM DYNAMICS AND CONTROL Roadmap 2022

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)*	Demonstration of sub-nm emittance line at low bunch current with improvements thereafter ✓ ID of beamlines for a potential demo of low ε and high Q *(will lead to a priority deliverable)* Characterization and specification of the performance of photocathodes at high field or high current	 Increased scientific reach in X-ray FELs
Develop methods for cooling beams using optical stochastic cooling *(Cool)*	Proof-of-principle OSC demos ✓ Proof-of-principle demonstrations of *active* OSC at IOTA or CESR Configurations capable of very high cooling rates for future colliders	 Higher luminosity electron-ion collider
Investigate advanced optimization schemes for precision phase-space control of particle accelerator systems *(Control)*	EM tuning comparable to operator tuning using ML ✓ Higher-order EM aberration tuning, replacing intervention by company reps. Methods for efficiently tuning accelerators Summary of the boundaries of applicability of ML in accelerators	 Active accelerator tuning and aberration control in electron microscopes

BDC Graduate Students and Postdocs

Afnan Al Marzouk, NIU

Fabio Bosco, UCLA

postdocs

JP Gonzalez Aguilera, U Chicago

Aasma Aslan, U New Mexico

Eric Cropp, UCLA

AJ Dick, NIU

Gevork Gevorkyan, ASU

Sergei Kladov, U Chicago

Gerard Lawler, UCLA

Sam Levenson, Cornell

Lucy Lin, Cornell

Desheng Ma, Cornell

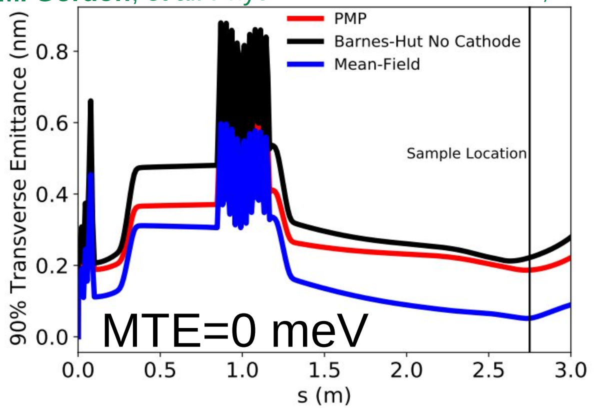
Brightness Preservation in Photoinjectors

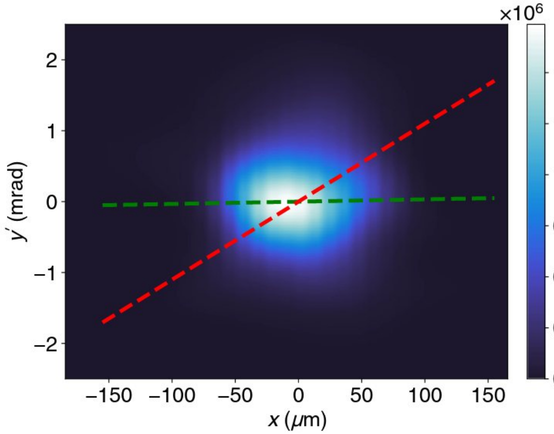
- Performances of UED/UEM and XFEL setups are ultimately limited by photoinjector brightness
- **How do we capitalize on advances in cathodes from Theme 1?**
- **Challenges:**
  - Significant emittance dilution during transport from photocathode to front-end applications
  - Brightness degradation principally 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

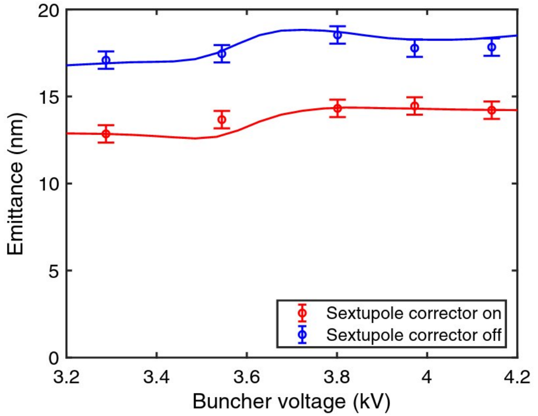
laser size

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

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







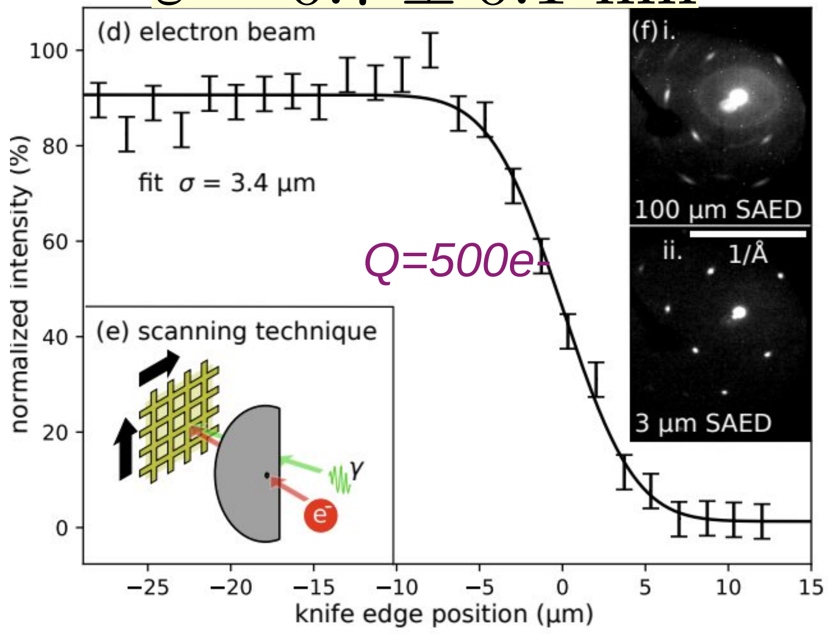
M. Gordon, W. H. Li, M. B. Andorf, A. C. Bartnik, C. J. R. Duncan, M. Kaemingk, C. A. Pennington, et al, Phys. Rev. Accel. Beams 25, 084001 (2022)

Deliverable 1.1: sub-nm transverse emittance

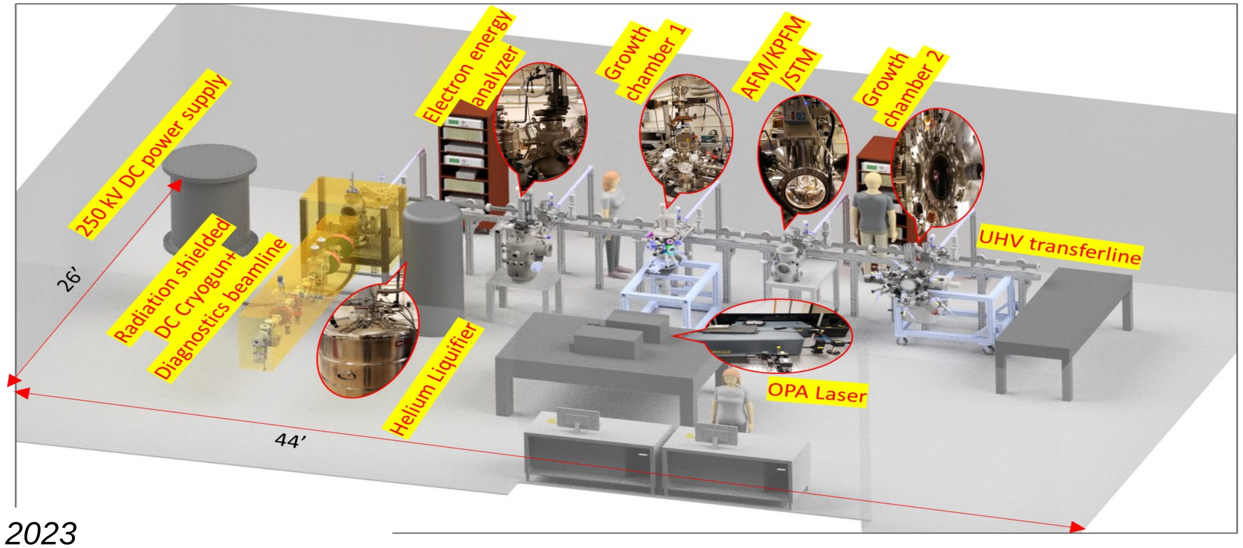
✓ Experimental demonstration of sub-nanometer emittance in at least one beamline with low bunch current with improvements thereafter [2026]

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

- 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]



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

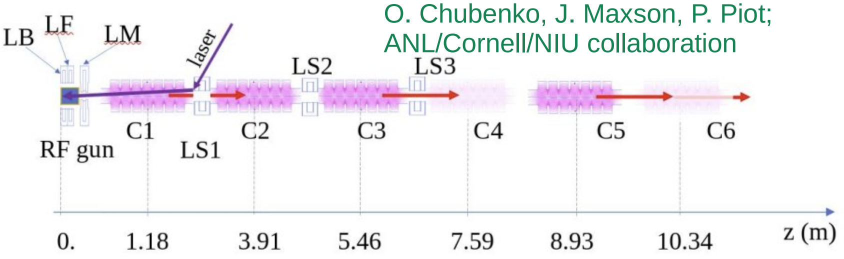
Deliverable 1.2: low-MTE photocathodes integration in existing photoinjectors

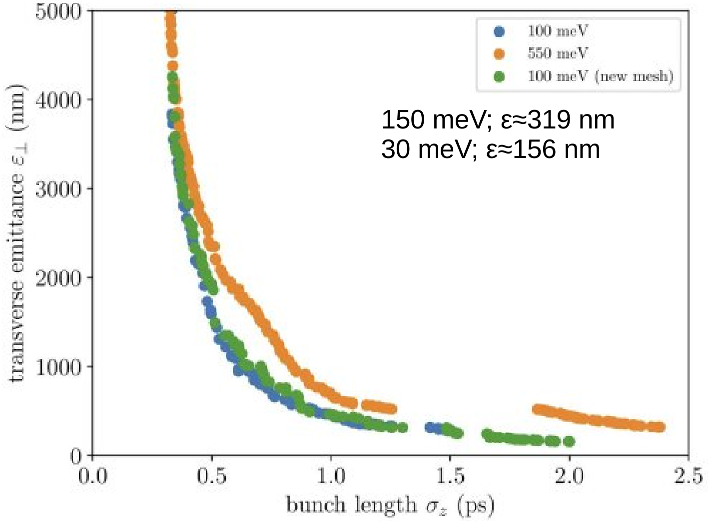
Identification of beamlines for a potential experimental demonstration of the simultaneous generation of low-emittance and high-charge (~100 pC) bunch, using CBB low-MTE photocathodes and diagnostics, that when coupled with a bunch-compression beamline would produce beams with 5D normalized brightness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

- **Progress/Current Activities:**
  - Exploring feasibility of integrated tests (at FNAL/ANL).
  - Investigating transverse brightness preservation during compression of low-emittance bunches.
  - Preparation for photocathode test at FNAL
- This deliverable will morph into a prioritized deliverable to carry relevant experiment(s) at available facilities.
- We would like to hear from EAB!

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

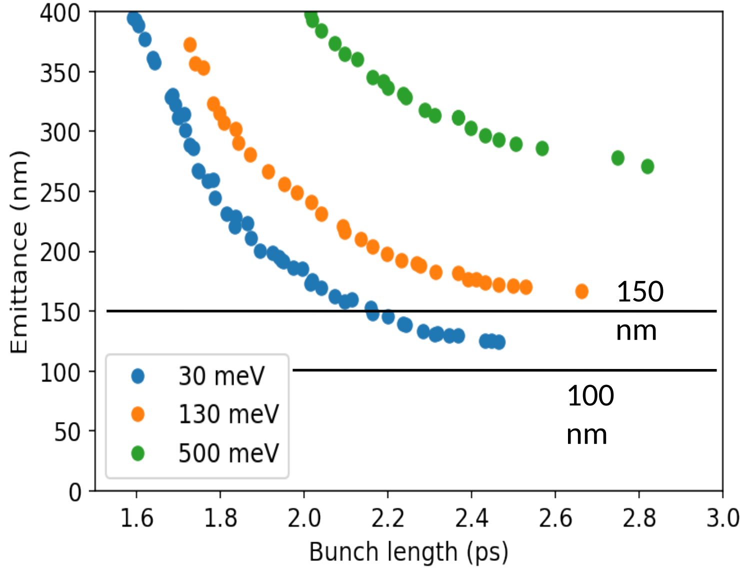
O. Chubenko, J. Maxson, P. Piot; ANL/Cornell/NIU collaboration



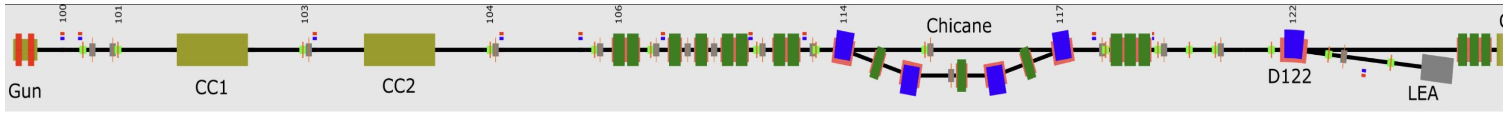


- Simulations support the goal
- Photocathode tests in AWA/ACT
- Setup could produce ε~300-nm at ~60 MeV
- Students identified

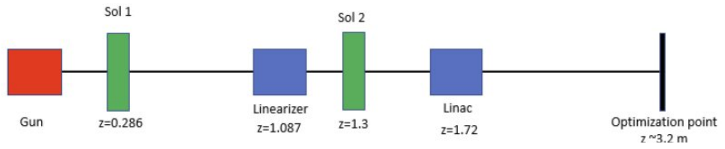
- Simulations support the goal
- Photocathode tests in FAST RF gun planned in summer 2023
- Setup could produce sub 200-nm emittance at ~40 MeV
- Students identified

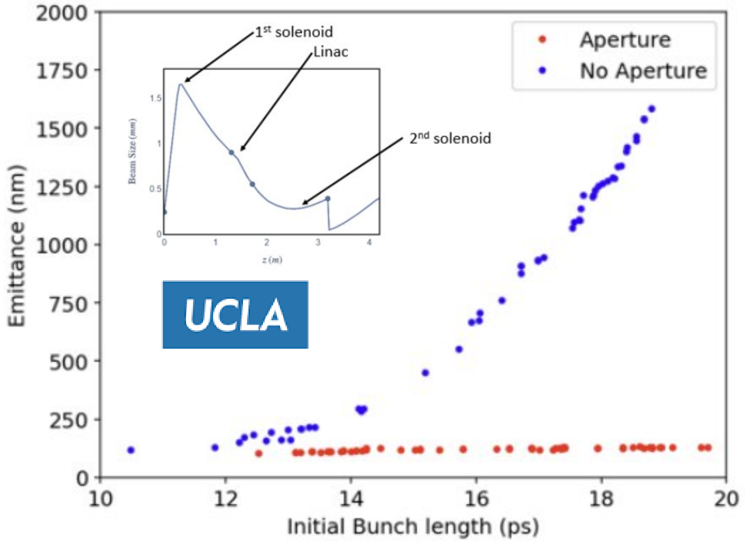


J. Maxson, P Musumeci, O. Chubenko, P. Piot; FNAL/UCLA/NIU collaboration



J. Maxson, P Musumeci, UCLA/Cornell collaboration



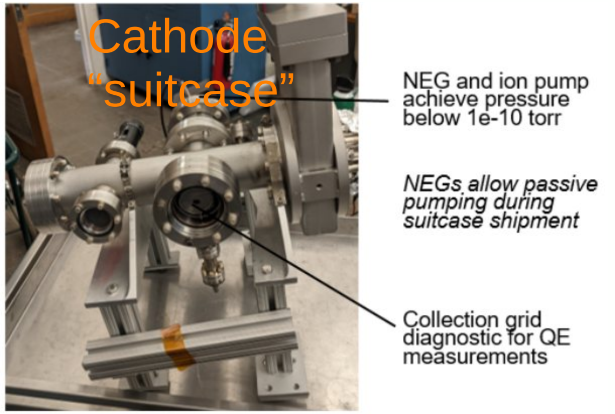


- Simulations support the goal using apertures
- Photocathode tests at PEGASUS on going
- Setup could produce sub 200-nm emittance at ~10 MeV
- Students identified

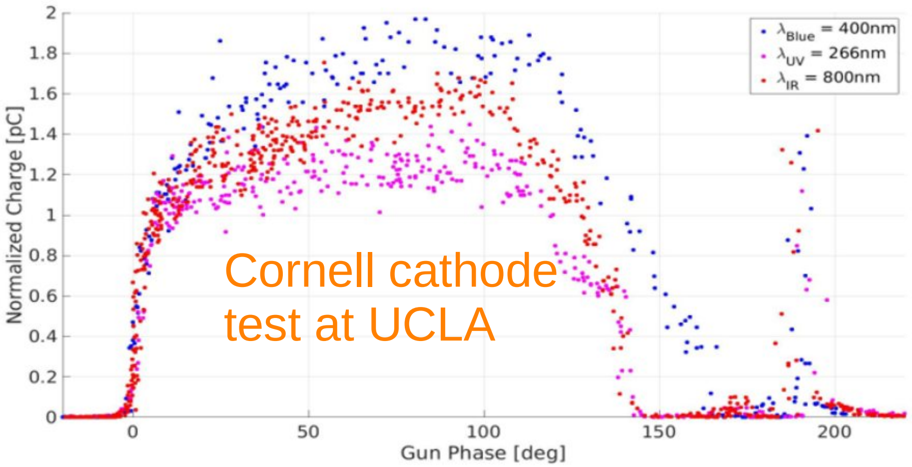
Deliverable 1.3: cathode tests

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)

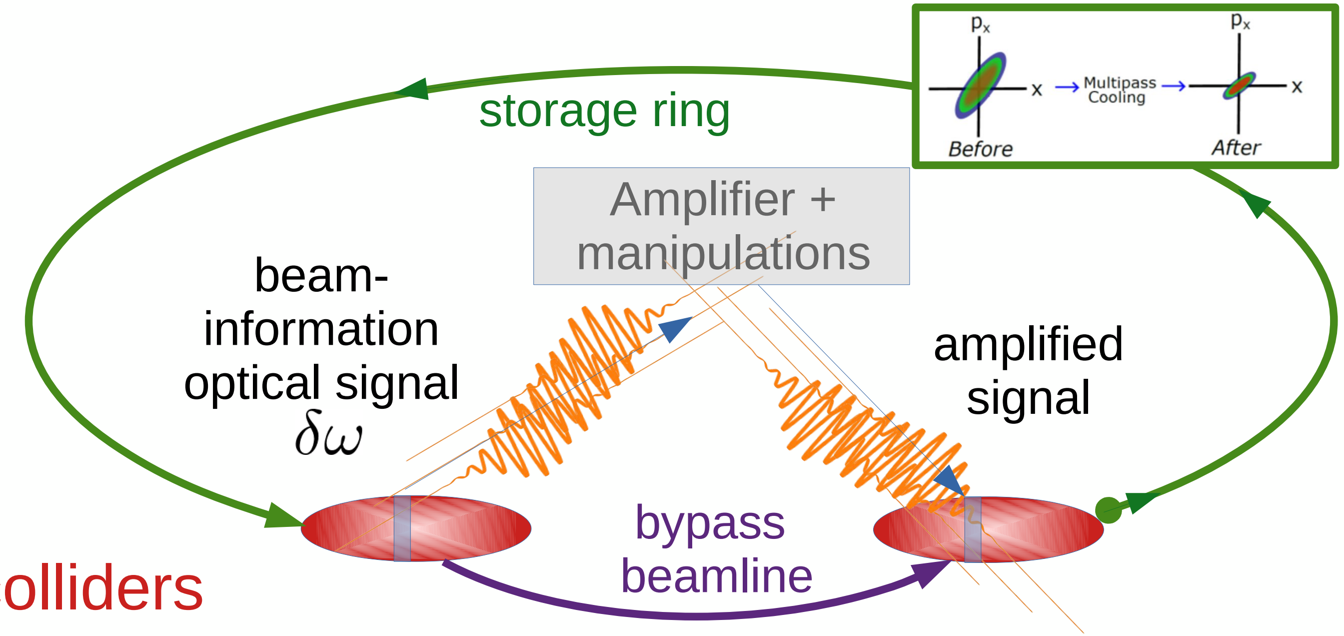


C. **Pennington**, et al., talk at the P3 meeting, Dec., 2021



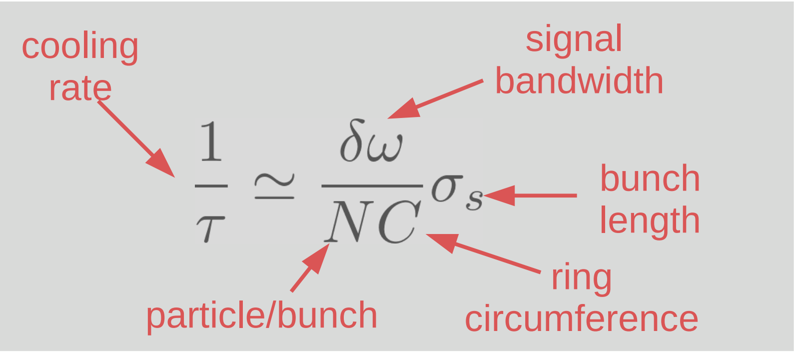
Objective 2: Cool – Overview

- **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

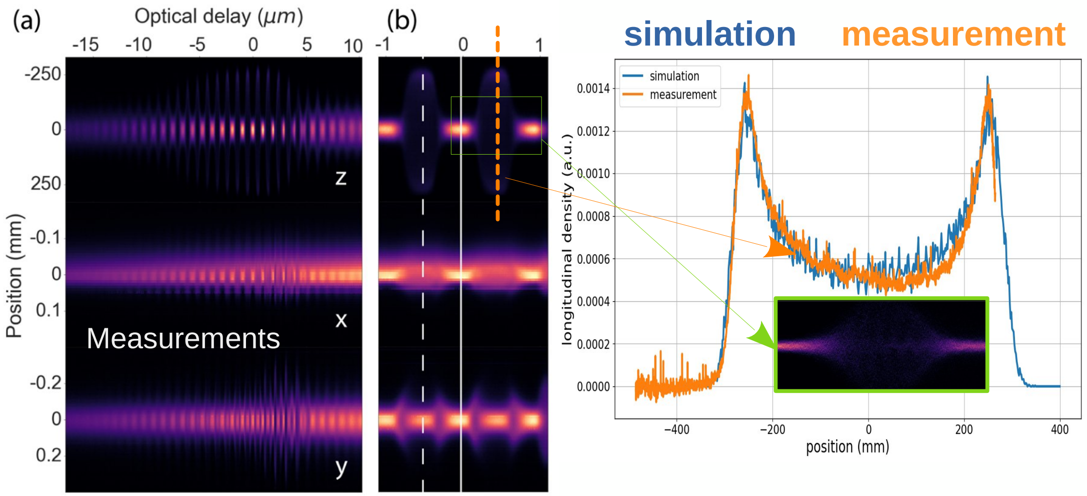


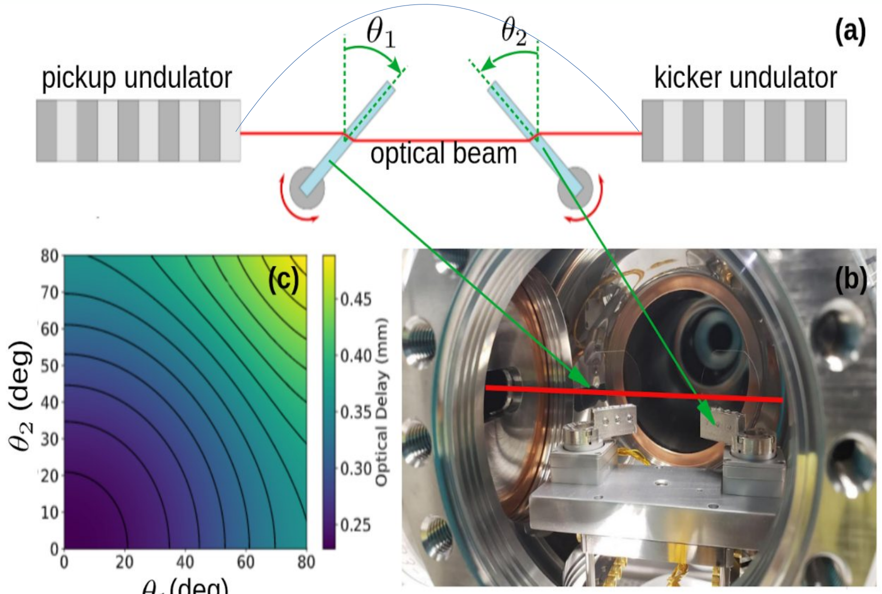
Deliverable 2.1: experimental demo of OSC

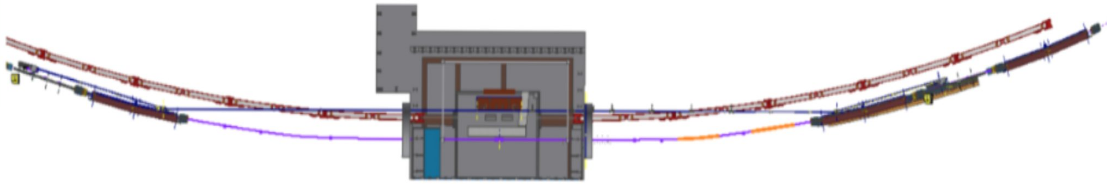
✓ Proof of principle demonstrations of key elements of optical stochastic cooling at IOTA and CESR [**by Spring 2023**].

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

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







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

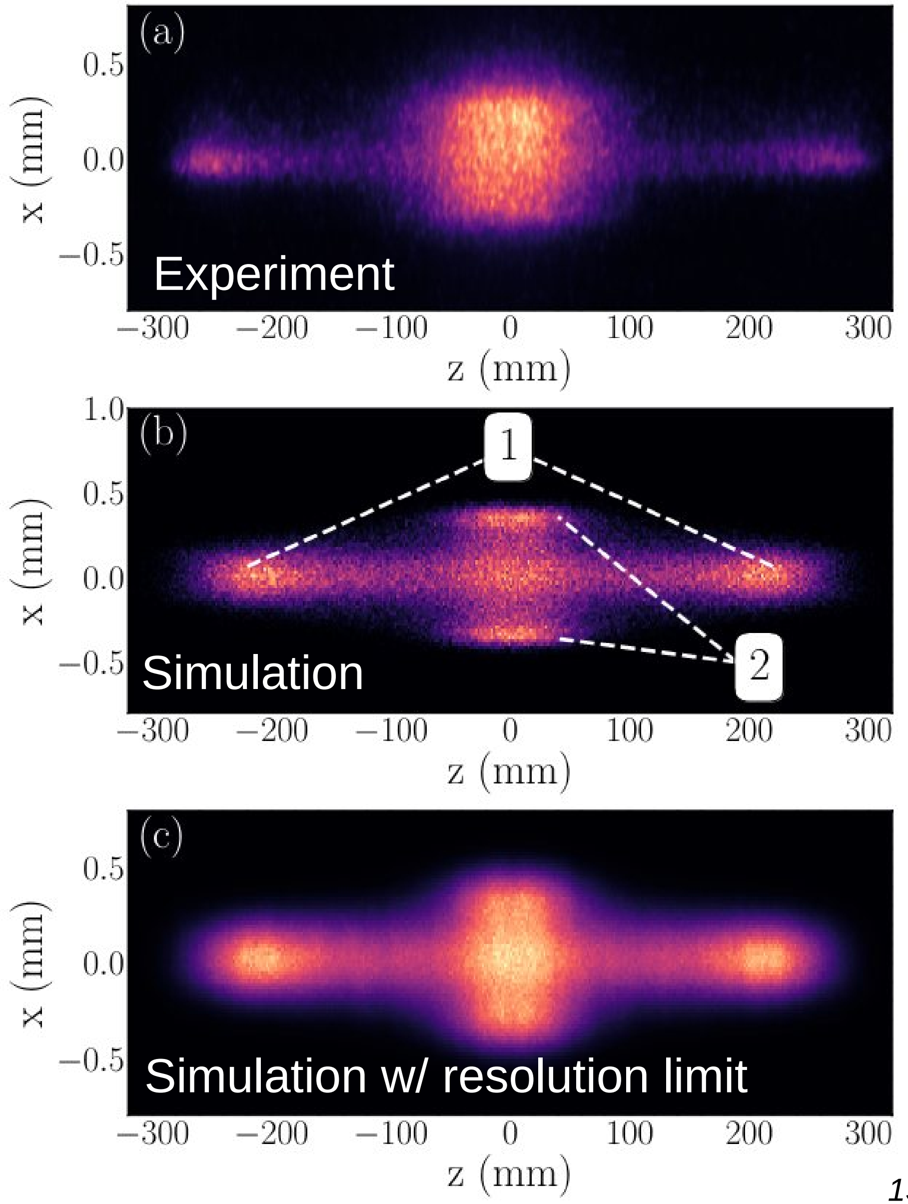
A. J. Dick et al., IPAC2021, p. WEPAB270 (2021)

Deliverable 2.2: Demo of active OSC

Proof-of-principle demonstrations of active OSC at IOTA or CESR [**by Fall 2025**].

- **Accomplishments:**
  - Preliminary design of an amplifier for IOTA [**2020**]
  - Design of scalable bypass beamline to enable high-gain active OSC [**2020**]
  - Validated ELEGANT model with IOTA data [2023]
- **Current status:**
  - Simulation of amplified OSC in the IOTA storage ring
  - Participation in high-gain amplifier design design and commissioning

A. J. Dick et al., to be submitted (June, 2023).

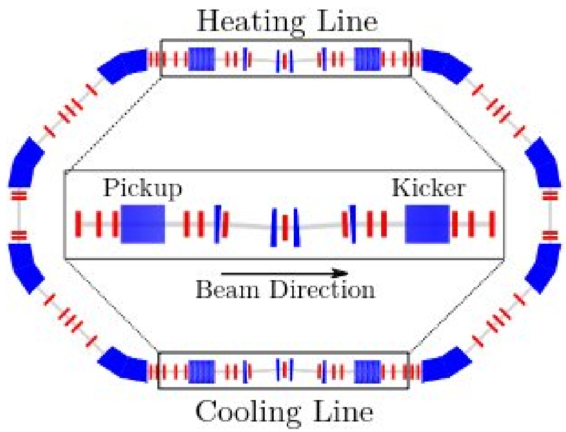


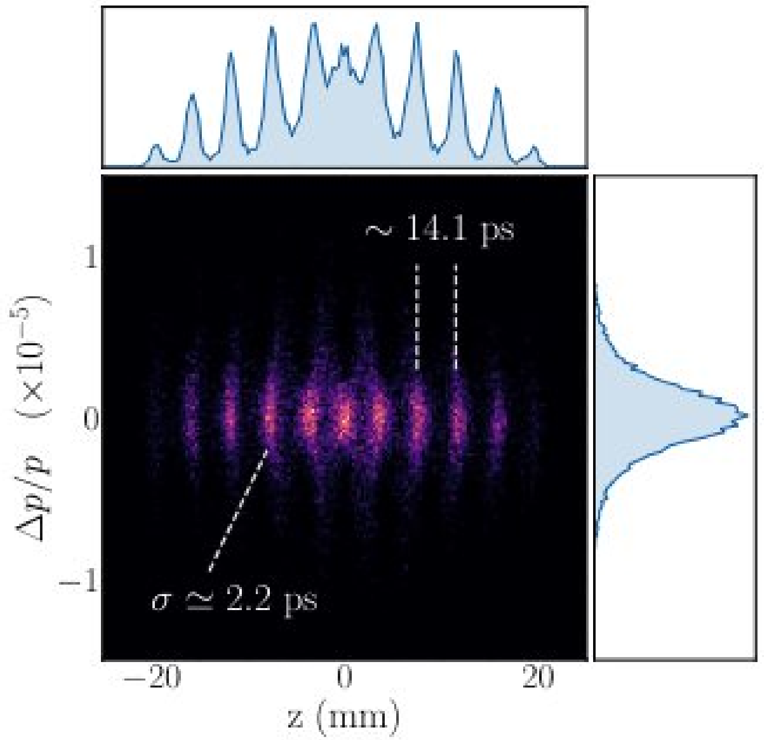
Deliverable 2.3: OSC-enabled very-high cooling

Configurations capable of very high cooling rates needed for use in future colliders or light sources [**by Fall 2026**].

- **Current Activities:**
  - Exploratory studies of turn-by-turn gain modulation of OSC amplifier for beam shaping e.g. ”ping-pong” OSC storage ring.
- **Planned Activities:**
  - Demonstrate applications of OSC to a future collider
  - Possible case studies include:
    - linear e+/e-, muons colliders, EIC,…
    - storage-ring based compact light sources.

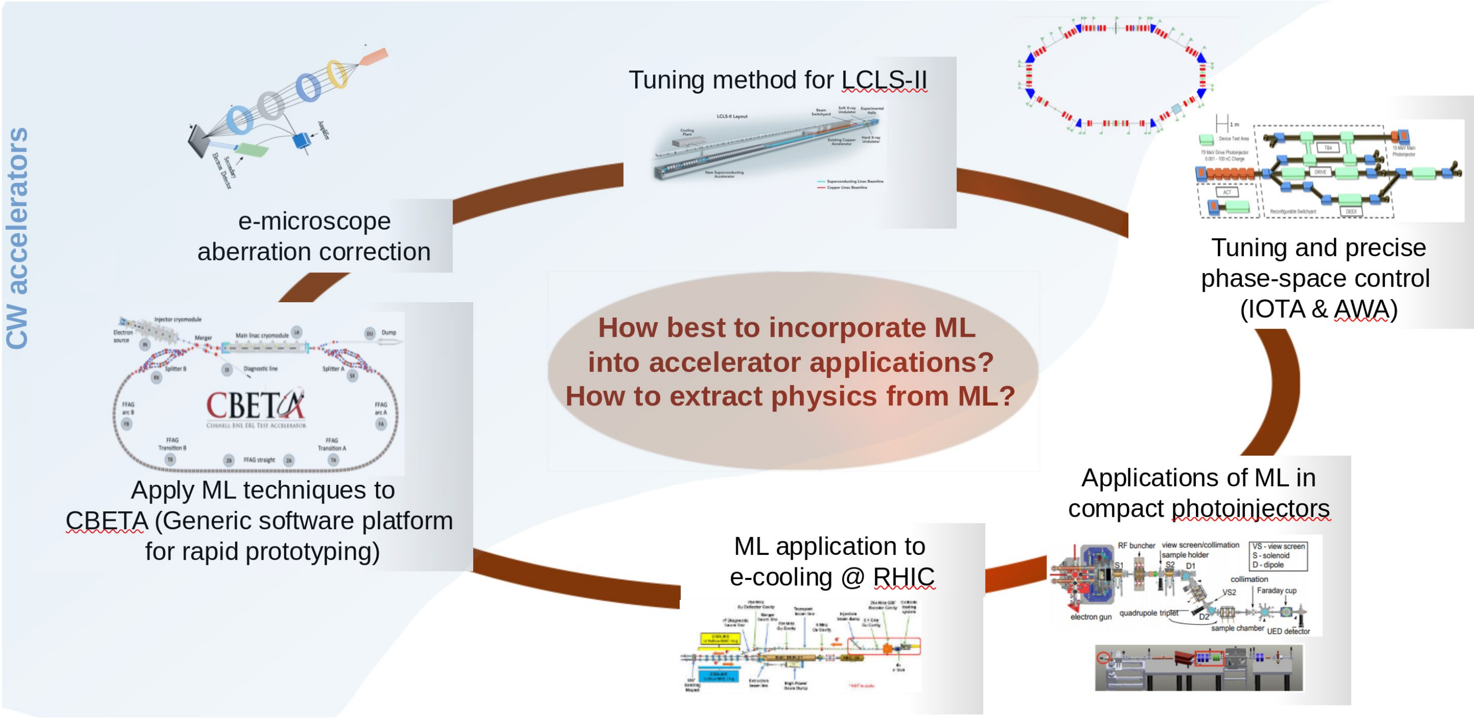
A. J. Dick et al., p. WEPA044 proc. IPAC2023 (2023).





Objective 3: Control – Overview

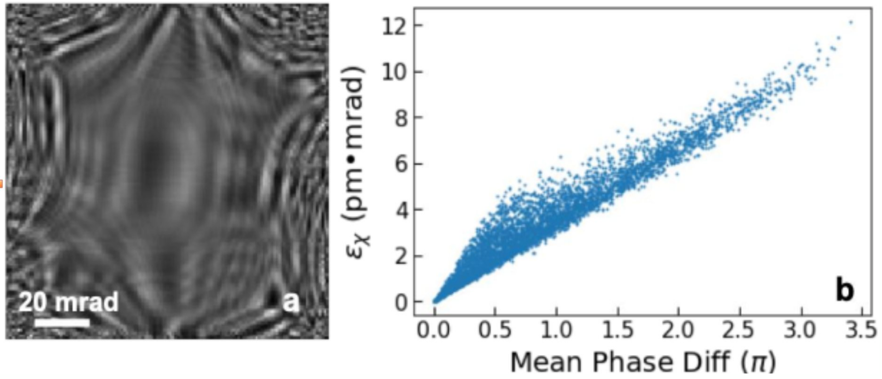
- **Objective**: Introduce new tuning methods based on machine learning and other advanced techniques to improve the transport and storage of high-brightness beams.
- **Impacts**: Precise control over the beam distribution, partitioning of emittance, live optimization and active tuning of accelerators 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



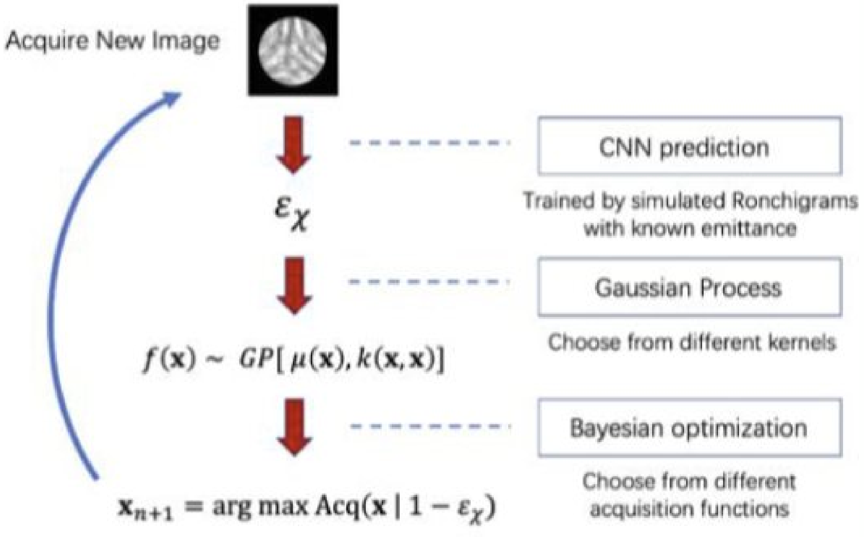
Deliverable 3.1: microscope “auto-tuning”

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

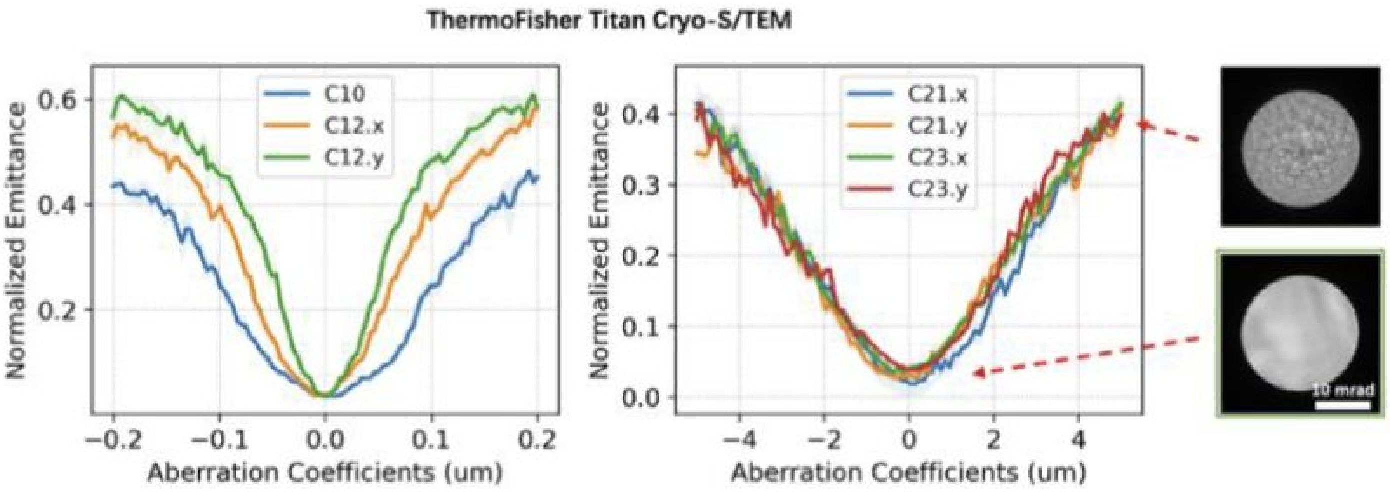
- **Accomplishments: operator-free tuning**
  - Connected emittance to aberration (Ronchigram) and developed a numerical model of a microscope [2021]



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

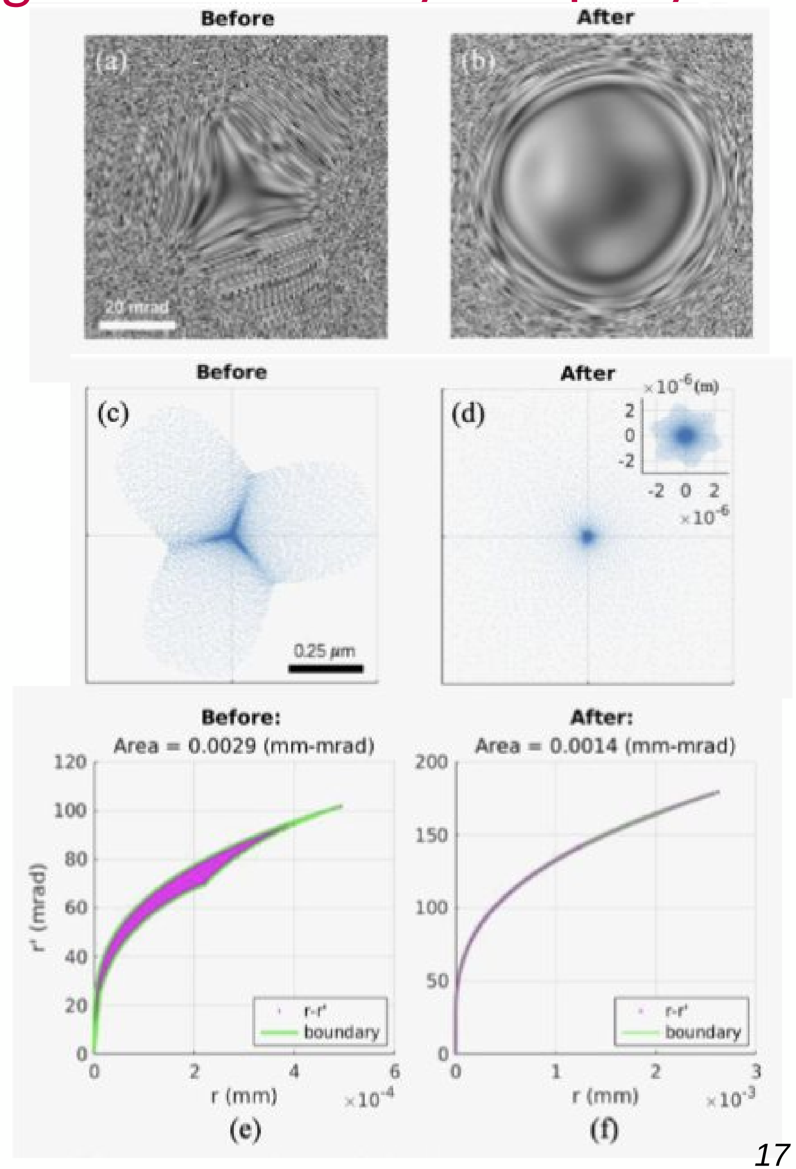


  - Demonstrated fast (2 min) and robust Bayesian optimization (BO) to correct aberration on three different microscopes [2022]



Deliverable 3.2*: microscope tuning w/o company intervention

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

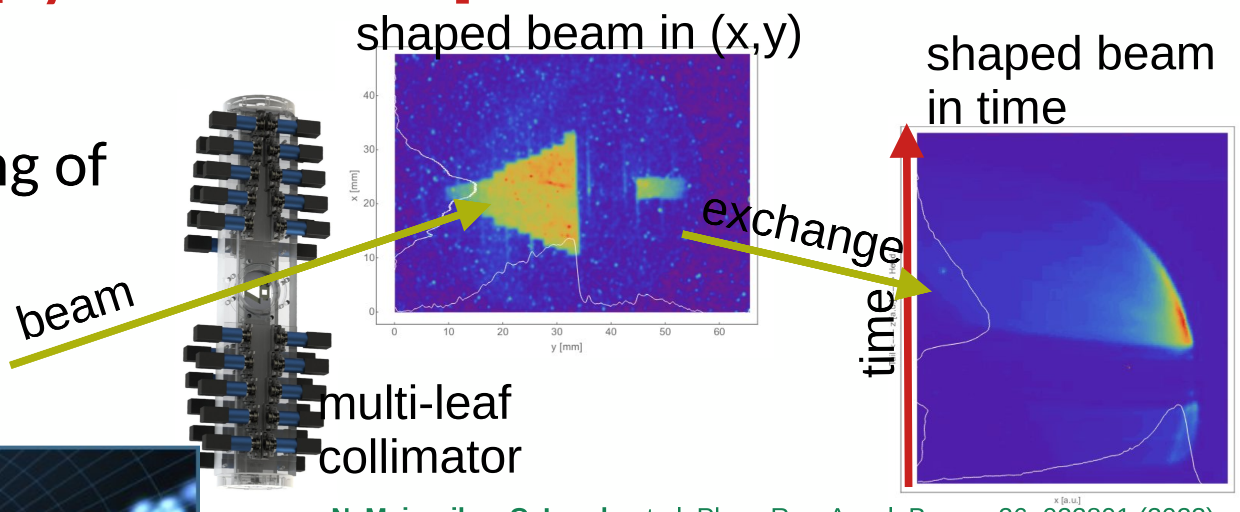


- **Accomplishments:**
  - Demonstrated the use of Bayesian optimization to tune microscope under deliverable 3.1
- **Plan:**
  - Methods developed under deliverable 3.1 will continue to be improved and tested on the Cornell Titan and Spectra aberration correctors.
- **End users:**
  - Thermo Fisher Scientific (TFS), Corrected Electron Optical Systems (CEOS). The transfer of this technology is KT Deliverable 2.6

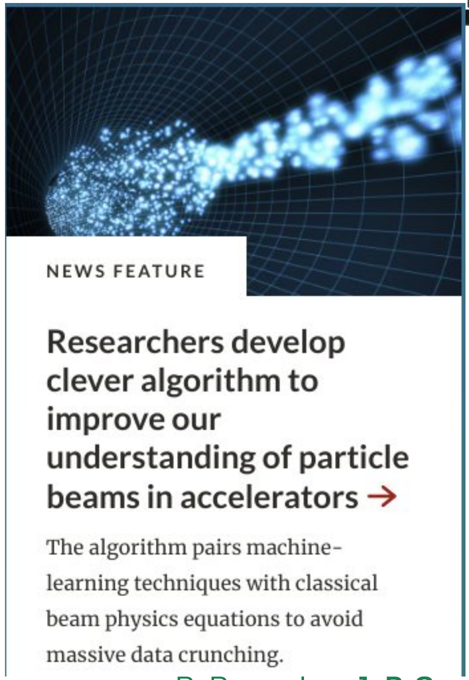
Deliverable 3.3: Efficient tuning of accelerators

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

- **Accomplishments:**
  - Developed framework for rapid prototyping of optimization algorithm [**2019**]
  - Applied live tuning of accelerators to, e.g., emittance control and e-beam cooling of hadron beams [**2021**]
  - Implemented virtual phase-space diagnostics [**2023**]
- **Current Activities:**
  - Applying ML method to higher-complexity control of beams
  - Spatiotemporal shaping → “beam by design”

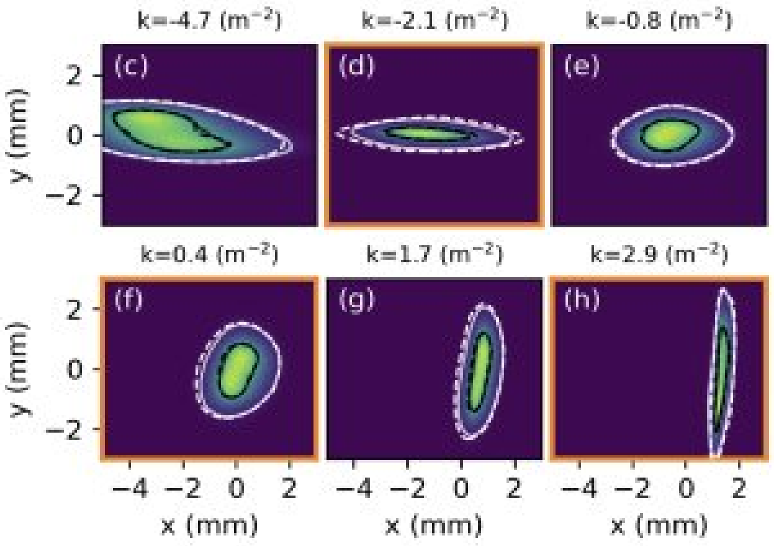


N. Majernik, .. C. Lorch, et al. Phys. Rev. Accel. Beams 26, 022801 (2023).


NEWS FEATURE

Researchers develop clever algorithm to improve our understanding of particle beams in accelerators →

The algorithm pairs machine-learning techniques with classical beam physics equations to avoid massive data crunching.

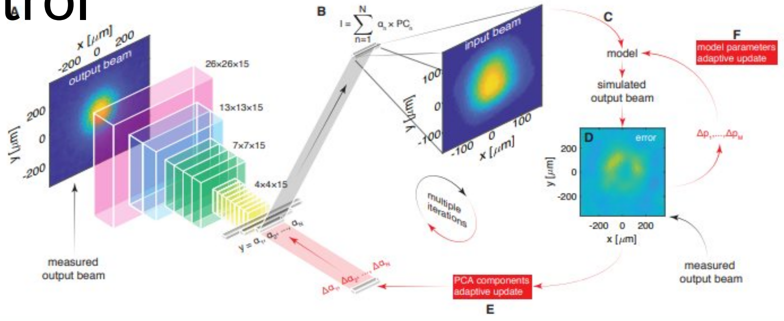


R. Roussel, … J.-P. Gonzalez-Aguilera, et al. Phys. Rev. Lett. 130, 145001 (2023).

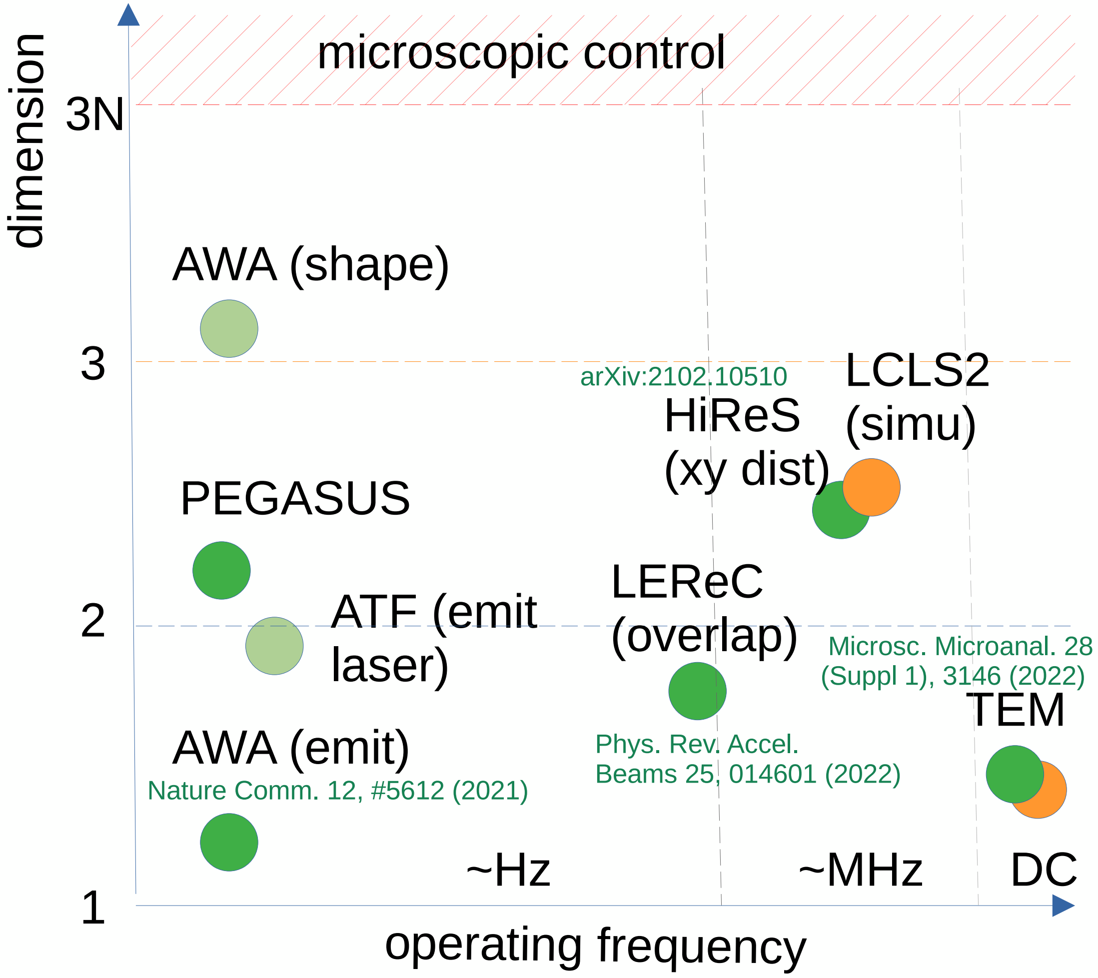
Deliverable 3.4: boundaries of applicability of ML

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**]
- **Current Activities:**
  - Applying ML methods to more complex phase-space control



A. Scheinker, **E. Cropp**, et al., Scientific Reports 11, 19187 (2021)



BDC impact on our community

- **Developed computer program openly available to the community** (space charge module for GPT, OSC in BMAD and ELEGANT)
- **Participate in the educational activities:**
  - CBB affiliates have taught USPAS classes in AIML
  - Review on beam shaping [Rev. Mod. Phys.]
- **BDC members are active participants in several community initiatives:**
  - 2021 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.

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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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REVIEWS OF MODERN PHYSICS

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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

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

https://arxiv.org/abs/2203.08919

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

Accelerator and Beam Physics Research Goals and Opportunities

https://arxiv.org/abs/2101.04107

GARD Accelerator and Beam Physics Roadmap Workshop
Sponsored by U.S. Department of Energy, Office of Science, Office of High Energy Physics
Hyatt Regency Bethesda
One Bethesda Metro Center
7400 Wisconsin Avenue
Bethesda, MD 20814
September 6-8, 2022

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)

Our Output: Highly-Trained Scientists


Matt Andorf, Research Assoc., Cornell


Stas Baturin, Faculty, ITMO University

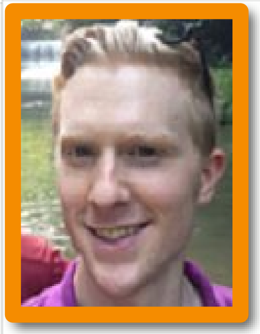

Oksana Chubenko, Faculty, NIU


Cameron Duncan, Postdoc, EPFL


Matt Gordon, Postdoc, Cornell

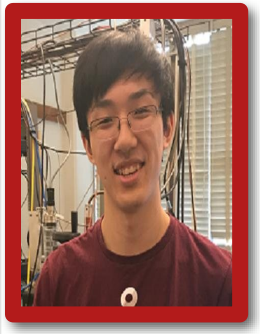

Jared Maxson, Faculty, Cornell


Alex Cahill, Engr. Physicist, Varian Medical Systems

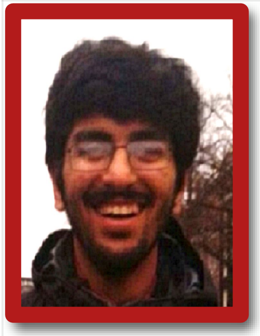

Colin Clement, Scientist, Microsoft


Lipi Gupta, Postdoc, LBNL


Nikita Kuklev, Postdoc, Argonne Nat. Lab


William Li, Postdoc, BNL


Nathan Majernik, Staff Scientist SLAC


Archishman Raju, Scientist, Nat. Centre for Biological Sciences


Ryan Roussel, Staff, SLAC


Paul Cueva, Scientist, Corning


Chenyu Zhang, Senior Engineer, ASML

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