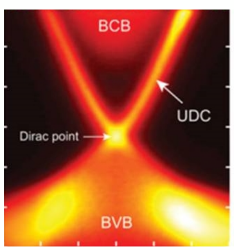
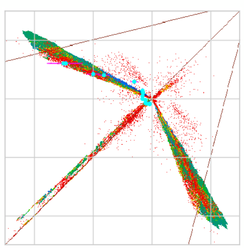
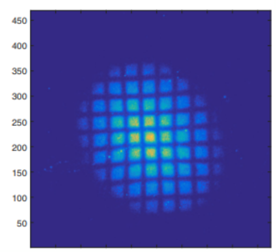
The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

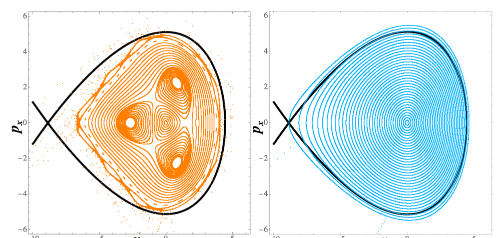
Center for Bright Beams (CBB)

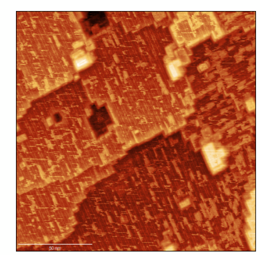
J. Ritchie Patterson
Center Director

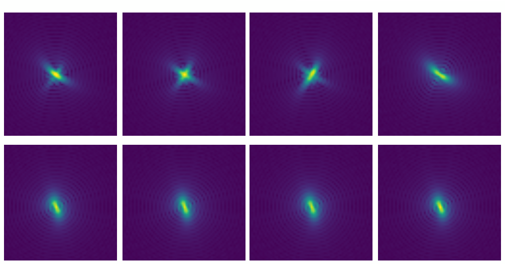


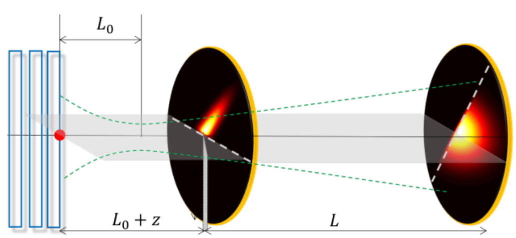


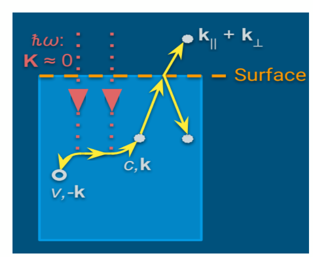


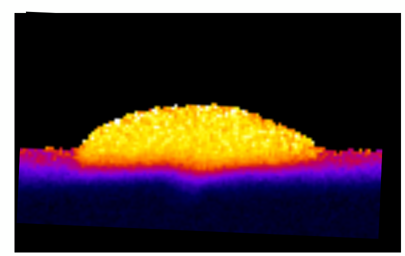








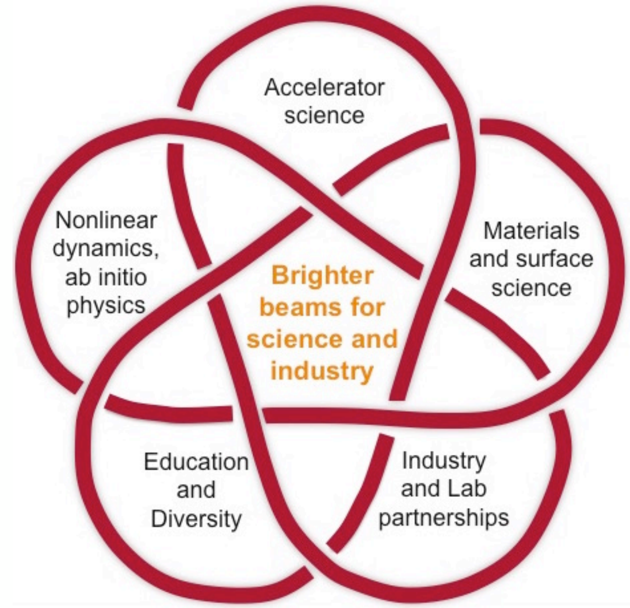




Center for Bright Beams - CBB

An NSF Science and Technology Center

Launched in 2016, 9 institutions led by Cornell
~$23M spread over 5 years



Center Vision:

Gain the fundamental understanding needed to revolutionize the brightness of electron beams for science, medicine and industry.

Center Mission:

Transform the reach of electron beams with **methods** that increase brightness x100 and reducing cost and size

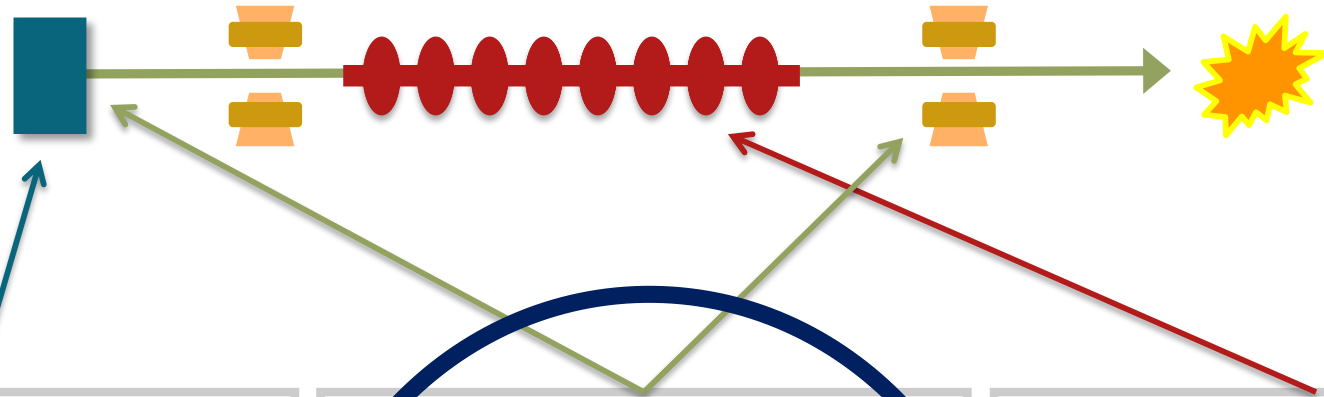
Transfer these methods
to national labs and industry.

Workforce development

Note: Most CBB funding goes to student and postdoc support, so institutions rely on additional accelerator awards.

ASU Arizona State University
BYU Brigham Young University, Provo, Utah
The University of Chicago
Cornell
UF University of Florida
NIU Northern Illinois University
UCLA
Fermilab
Berkeley Lab

CBB Research Themes



Beam Production
Methods for better photocathodes

GARD: particle sources and targets

Beam Dynamics and Control
Methods to conserve, cool and control beams

GARD: Accelerator and Beam Physics

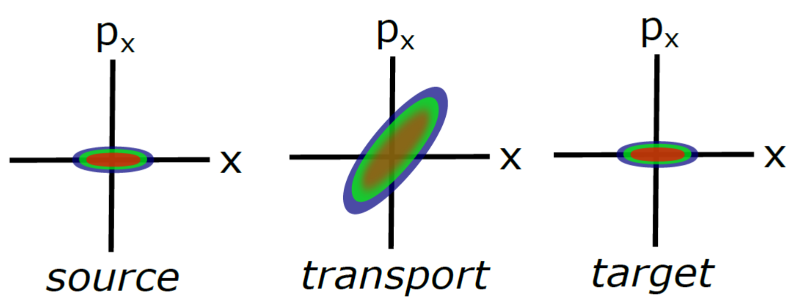
Beam Acceleration
Methods for high performance superconducting RF accelerating cavities

GARD: RF Acceleration

Gaining the fundamental understanding needed to transform the brightness of electron beams available to science, medicine and industry.

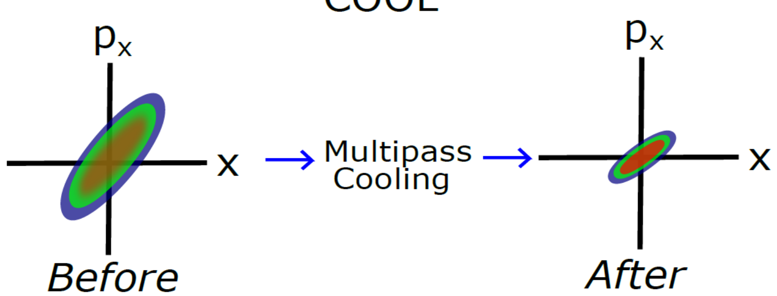
Beam Dynamics and Control

CONSERVE



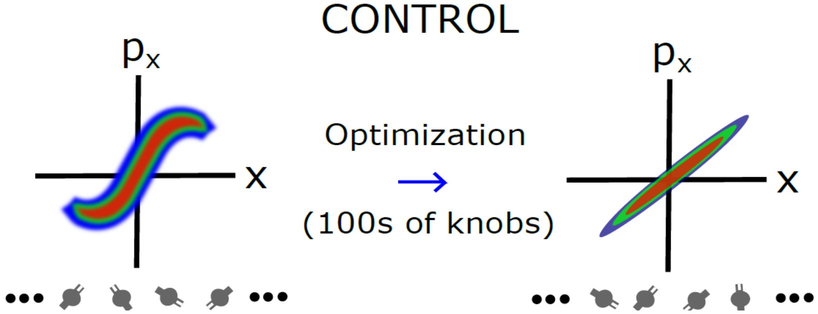
Conserve: Conserve the brightness of extreme-low MTE linac sources throughout transport in the presence of *space charge*.

COOL



Cool: Increase the brightness of beams in storage rings

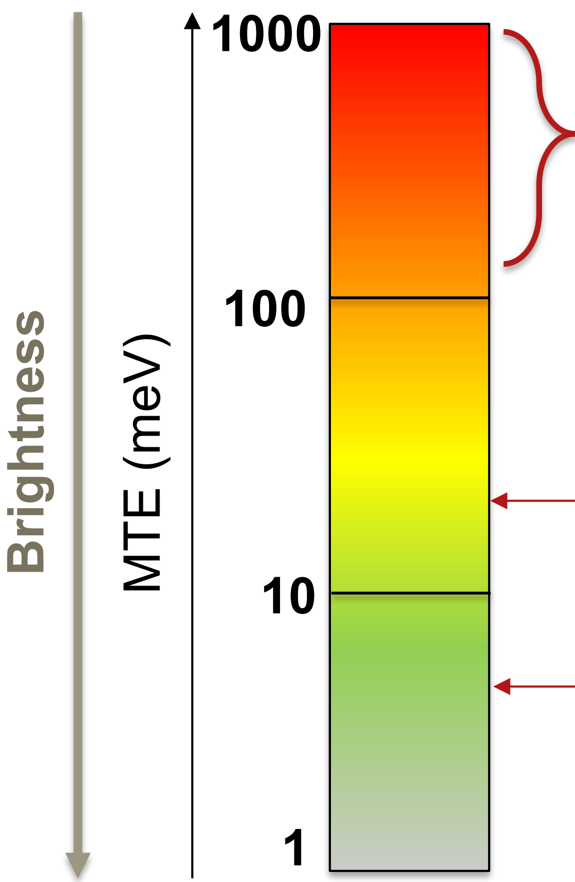
CONTROL



Control: Use advanced techniques to optimize and control transport in storage rings and linacs

These map onto the ABP Grand Challenges

New photocathodes → potential for brighter injectors



Typical cathodes

$$\varepsilon_n = A_x \sqrt{\frac{\mathrm{MTE}}{m_e c^2}}$$

Laser spot size

Mean Transverse Energy

$$\mathrm{MTE} = \frac{1}{2} m < v_\perp^2 >$$

Future: epitaxially grown semiconductors with capping for robustness (high current density)

CBB cathode, tested at LBNL with cold copper (100) surface (low current density)
Karkare et al., arXiv:2002.11579

Sources of MTE
Surface roughness, band structure, many body scattering, non-linear photoemission, photon energy

Groups: CBB, BNL, LBNL, UIC

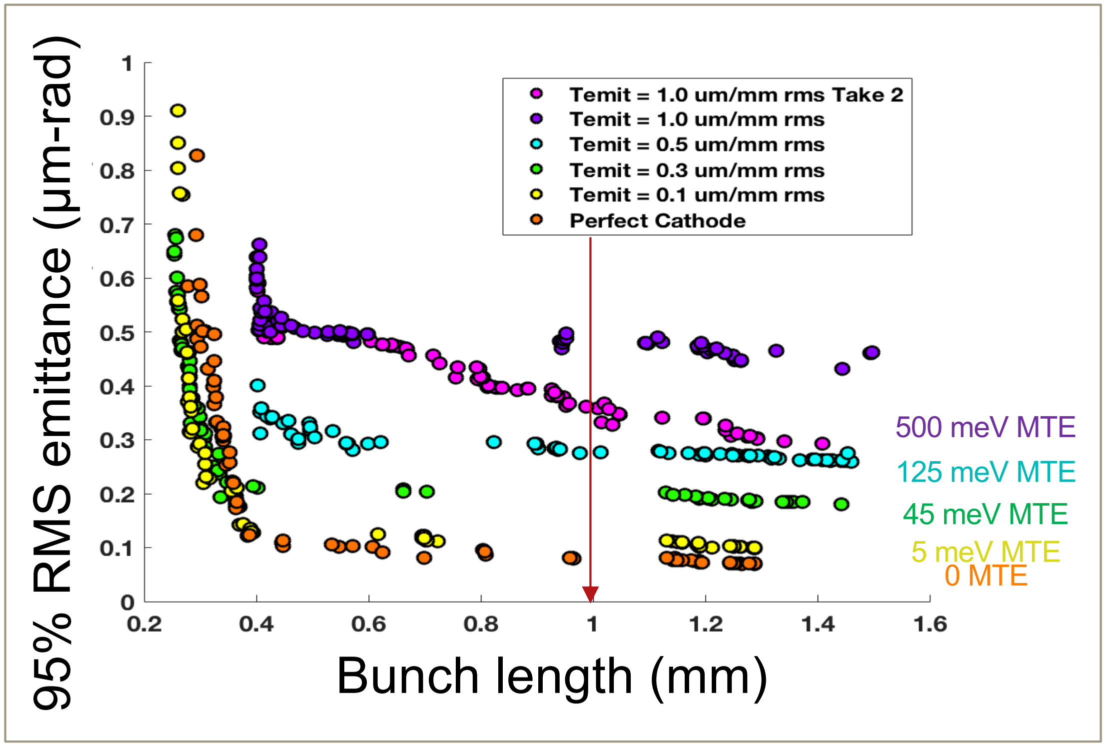
I. Bazarov *et al.*, Phys. Rev. Lett. **102**, 104801 (2009)

Photoinjector optimization

Can photoinjectors benefit from high-performance photocathodes? **(ABP Challenges #1 and #2).**

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., arXiv:2004.08034

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

Cooling

Can you reduce the phase space occupied by the beam?
(ABP Challenges #2 and #3).

Application: FCC-hh
Cross-cut: Electron-ion collider (NP); future storage ring X-ray sources (BES)

- Needed for luminosity at high energy colliders with hadrons

- Many ideas (see talk by Thomas Roser and EIC Hadron Cooling Workshop), two categories:
  - Stochastic cooling
  - Scattering with a cold electron beam

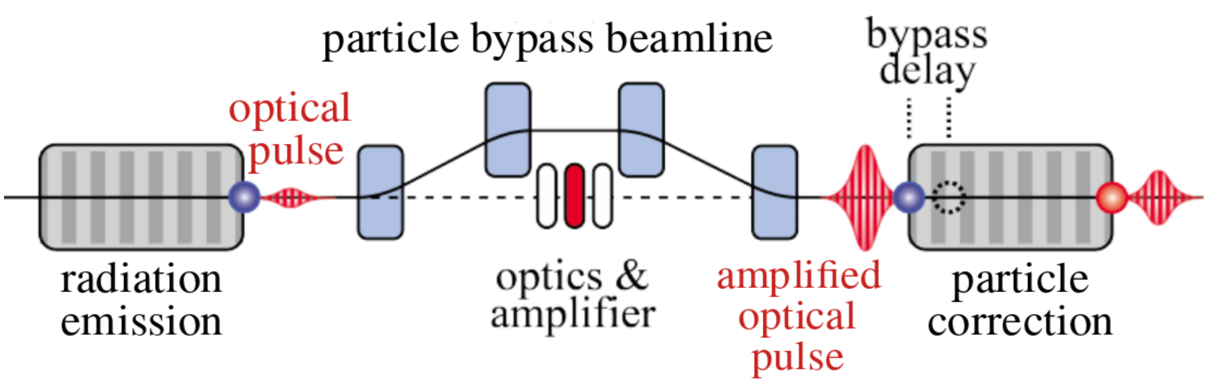
- CBB: Optical Stochastic Cooling
  Invented by Mikhailichenko & Zolotorev (1993), but not yet realized.

  Like microwave stochastic cooling, but at optical wavelengths for 10^4 faster cooling (in principle!)

EIC Hadron Cooling Workshop
October 2019

Optical Stochastic Cooling

The circulating beam interacts with its own synchrotron radiation over multiple passes



Hands-on training for students

IOTA will use a low-charge, 150-MeV electron beam and focus on the physics of OSC using a low-gain amplifier

CESR will use high-energy, high-charge bunches with undulators and a high-gain amplifier *CBB supports the initial bypass tests.*

Groups: CBB, FNAL, ANL

For CESR:
Novel scalable-delay bypass beamline provides fast cooling, large acceptance and properly corrected nonlinearities.
Bergan et al, IPAC2019/mopgw100

For IOTA:
Design of a Cr:ZnSe single-pass amplifier Compact, high gain,with wavelength tuned for IOTA, tested at APS.
Andorf et al, arXiv:2004.13223

Energy Recovery Linacs

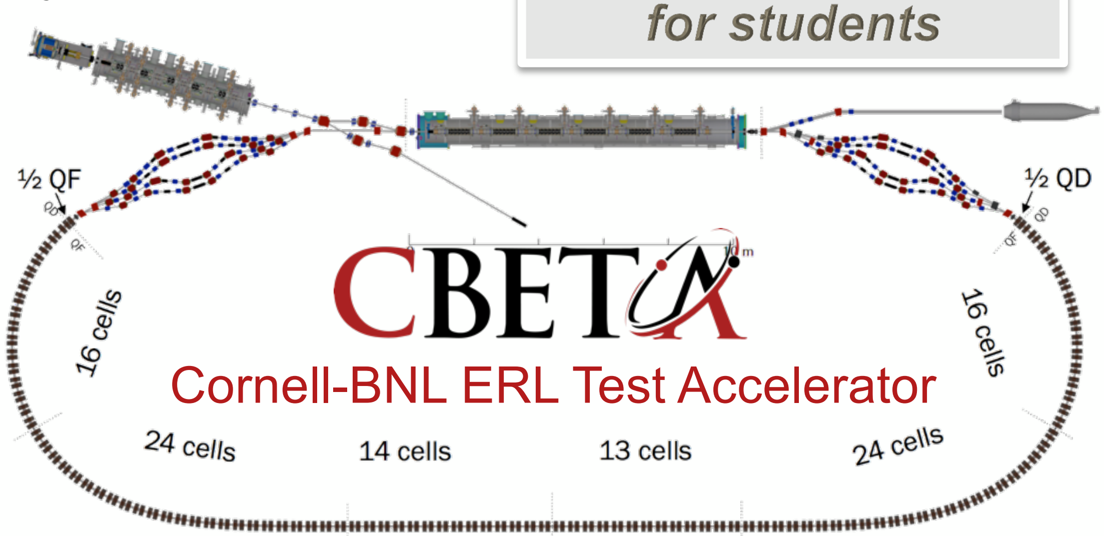
Many cooling schemes require high current electron beams
→Energy Recovery Linacs (100-1000mA, 100-150MeV)

Application:
FCC-hh cooling
Cross-cut:
Electron-ion collider (NP) (cooling or electro source)

A conclusion of EIC Hadron Cooling Workshop:

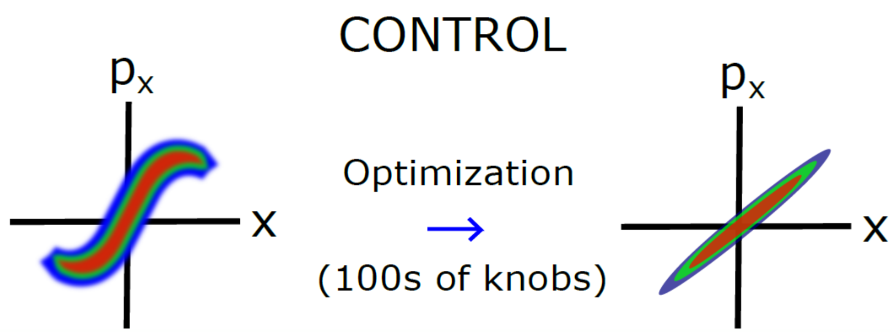
- High current tests of ERL injectors are needed
- Still much design work to do (CSR in arcs e.g.)
- Prototyping is ongoing.
- Definitely need ERL testbed facility for high currents:
    - Halo
    - Beam loading
    - Beam breakup instability
    - Transients

Hands-on training for students



This work is outside the CBB scope, but is synergistic.

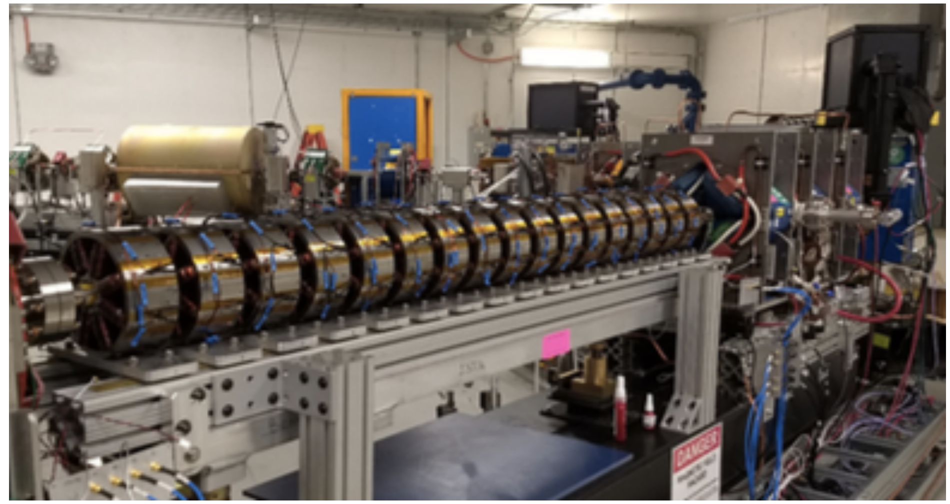
December 2019: CBETA demonstrated 4-turn energy recovery.



Control: Use advanced techniques to optimize and control transport in storage rings and linacs

Control: IOTA octupole insertion

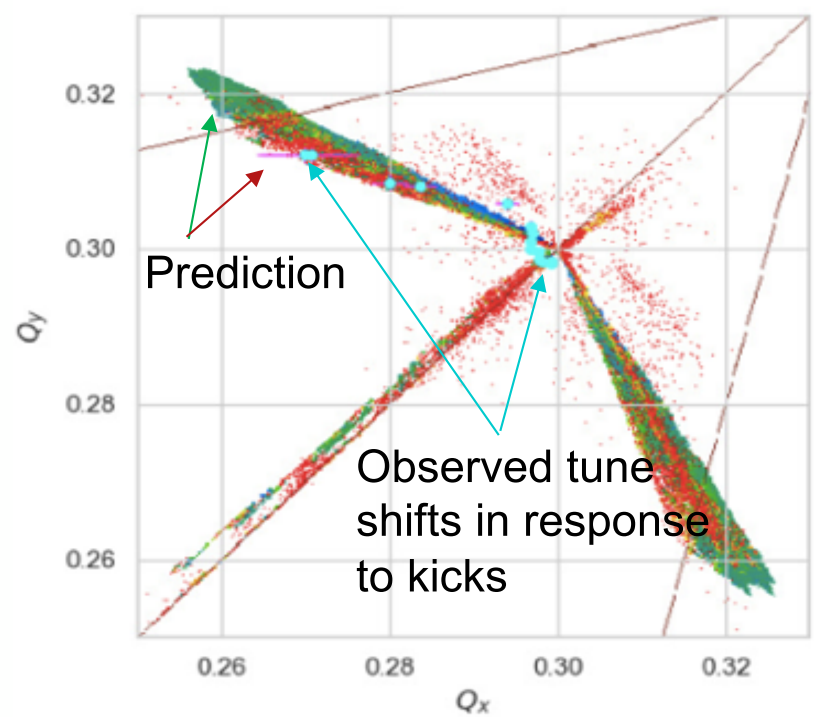
Nonlinear integrable optics at IOTA
Sextupole magnets are necessary for storage rings to correct chromatic aberration, but introduce nonlinearities that can lead to beam loss. Nonlinear integrable optics could offer stable, long-lifetime, high-amplitude orbits.



17 octupole Henon-Heiles quasi-integrable magnet insertion in the IOTA ring at FNAL

- Initial run promising, achieving up to 70% of ideal-case performance
- Recent second run, with improvements.

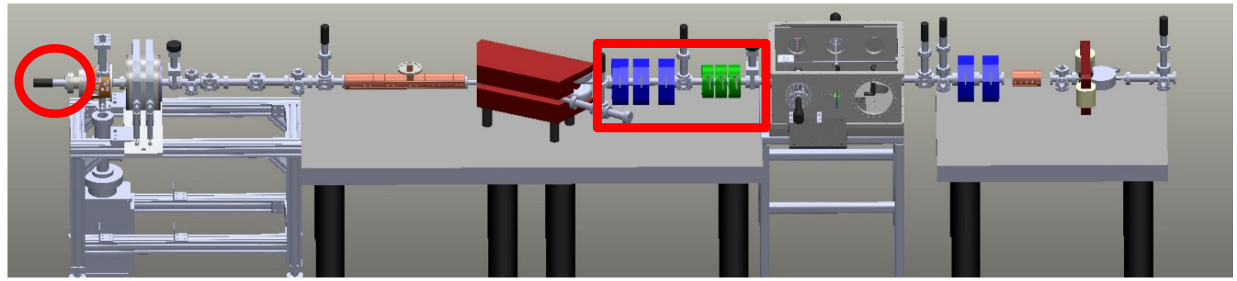
Kuklev et al, IPAC2019/MOPGW113



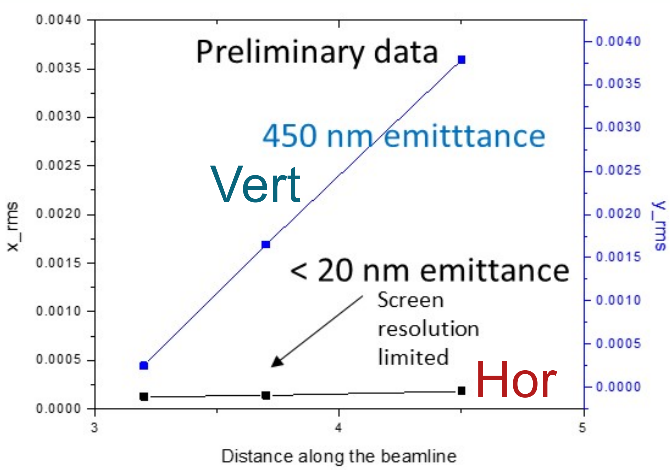
Groups: CBB, FNAL (Valishev)

Control: Round → Flat transform

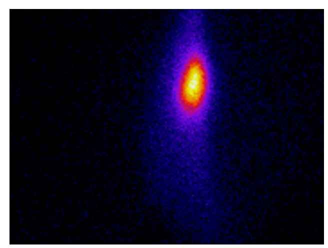
Application: Linear colliders and dielectric wakefield and laser accelerators with slab geometry



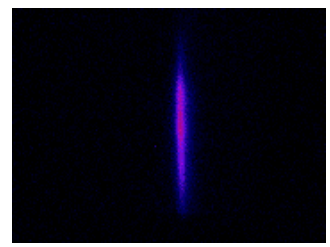
Pegasus at UCLA. Quad triplet removes beam angular momentum from magnetized gun needed to couple x and y phase space.



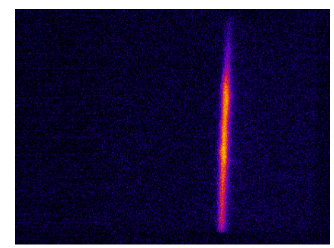
Spot size vs distance



Screen 9.2cm fro third skew quad



Screen 70.2cm fro third skew quad



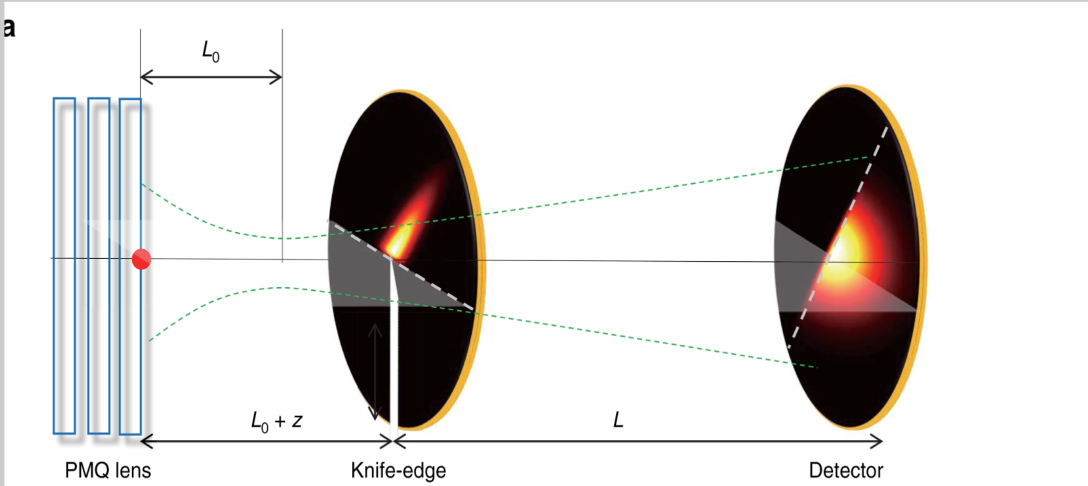
Screen 144.6cm from third skew quad

Cropp et al., NAPAC'19/frxba4

Hands-on training for students

Low emittance diagnostics

Very low emittances require new instrumentation



Knife-edge measures 4D emittance down to 0.0144 (nm-rad)^2 and beam sizes as small as 90nm.

Developed at Hi-RES at LBNL

Groups: LBNL, CBB

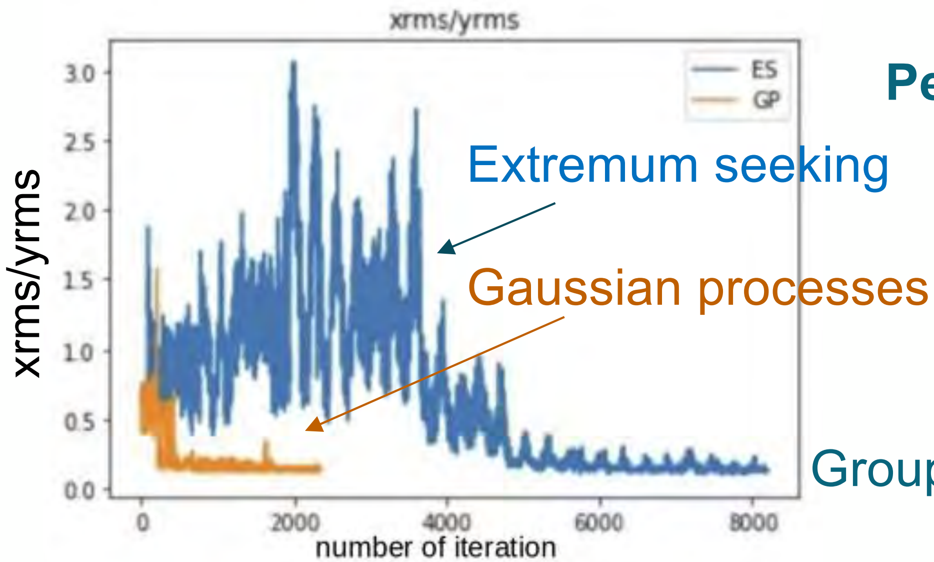
cf Talk by Jared Maxson at Workshop #1

Connection: WS #2: Advanced instrumentation and controls

Ji et al., PRAB ***22***, 082801 (2019)

Now implemented at Pegasus and in the Cornell cryo source

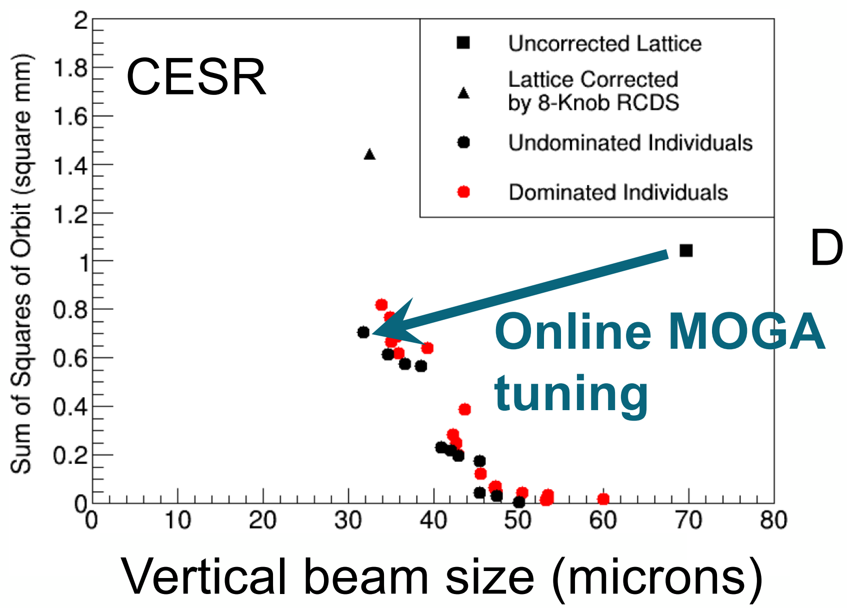
Smart Tuning: initial forays



Pegasus – pulsed beam

Groups: CBB, SLAC (Edelen)

Hands-on training for students



CESR – continuous wave

Dimension reduction (81→8 knobs)
+
Machine learning

Online tuning?

Bergan et al., PRAB ***22****, 054601 (2019)*

Phase-space tuning

Broader Questions:

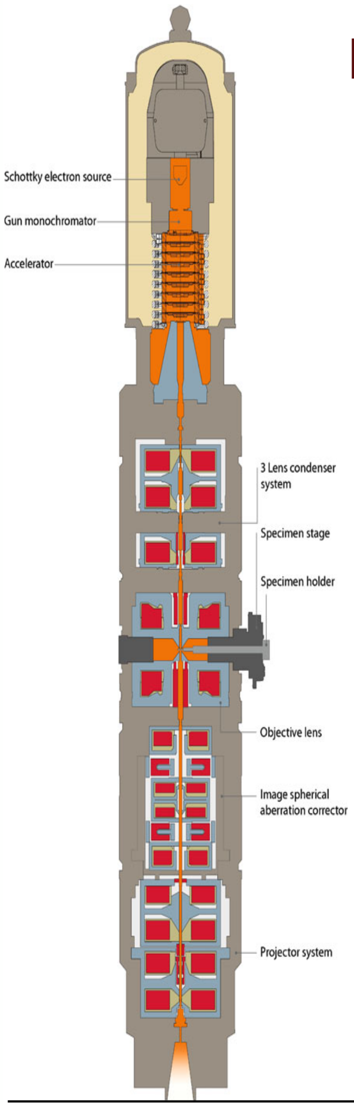
What are the boundaries of applicability of ML in accelerators with varying noise types, pulse structure, and data availability?

Can ML "teach" us about the physical state of the accelerator without precise beam characterization?

ABP Challenges #2 and #3

Applications: HEP accelerators
Cross-cut: X-ray synchrotron sources and xFELs. UED/UEM, Electron microscopy

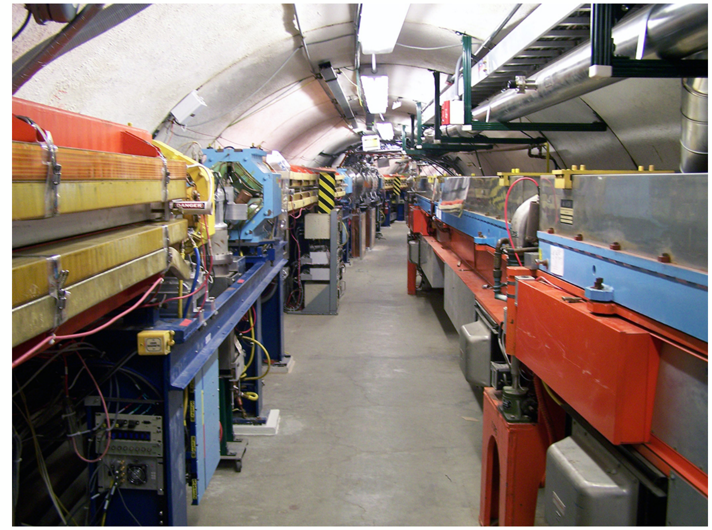
Electron Microscopes



[1]Images from Kirkland

Electron microscope

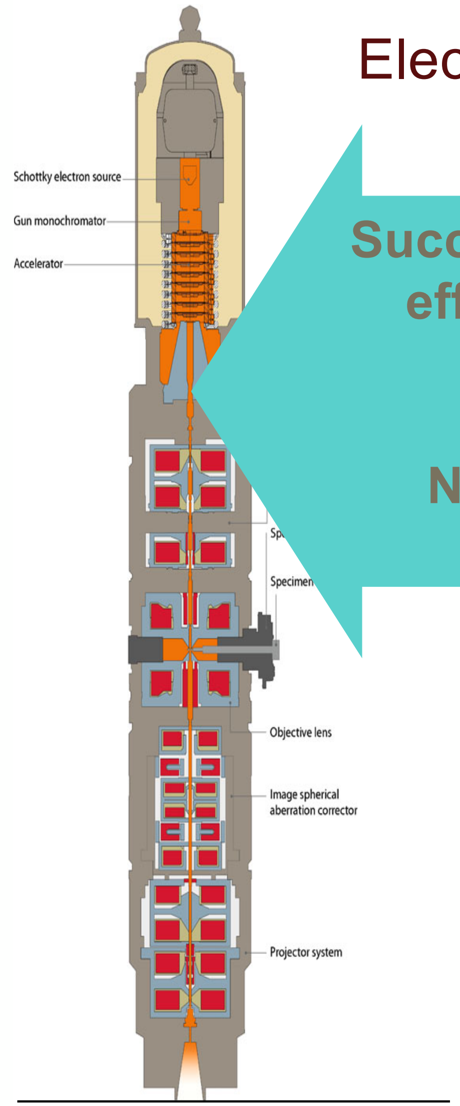
Cornell Electron Storage Ring



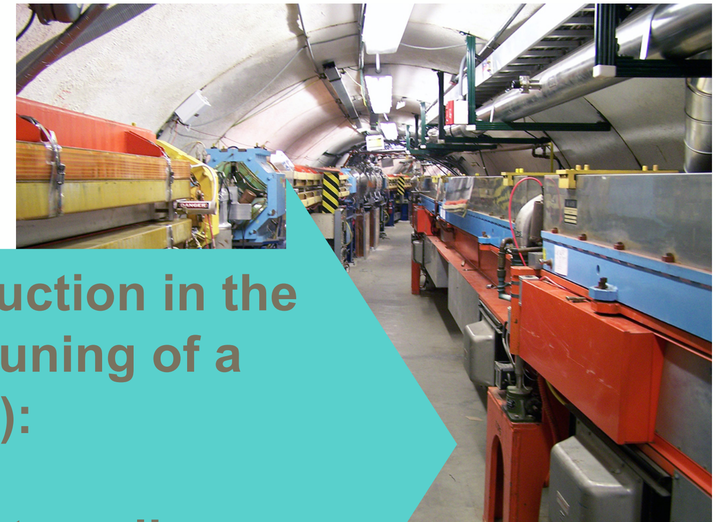
	Microscope	Particle accelerator
~100 tuning knobs		
Chromatic aberrations + multi-pole correctors		
Emittance optimization is essential for performance		

Groups: CBB, Nion, CEOS, and Thermo Fisher

Electron Microscopes



Electron microscope



Successful demonstration of X10 reduction in the effective number of knobs for live tuning of a particle accelerator (CESR):

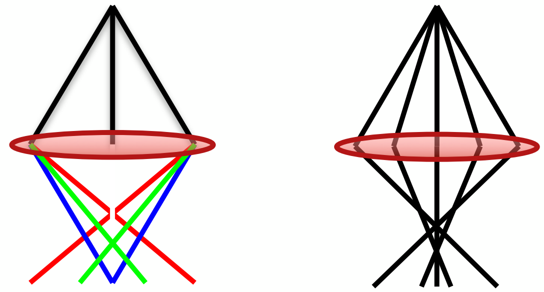
Now applying the same technique to online correction of electron microscopes.

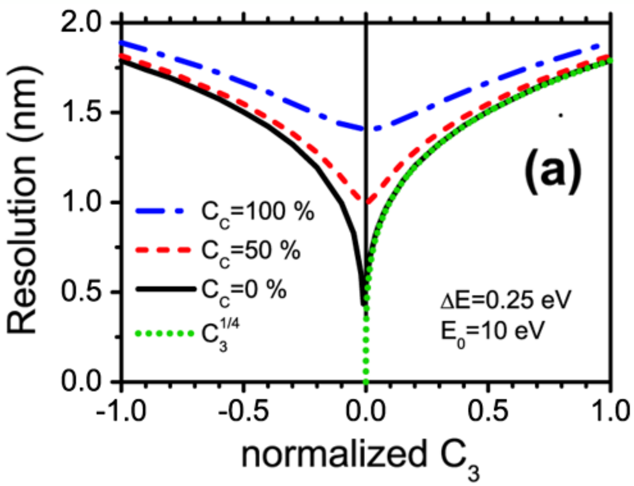
[illegible]	**Particle accelerator**
~100 tuning knobs	
Chromatic aberrations + multi-pole correctors	
Emittance optimization is essential for performance*	

[1]Images from Kirkland

Aberration measurement

Geometric & chromatic aberrations

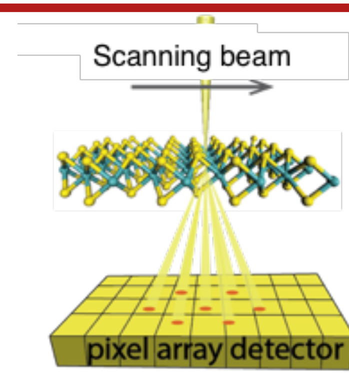




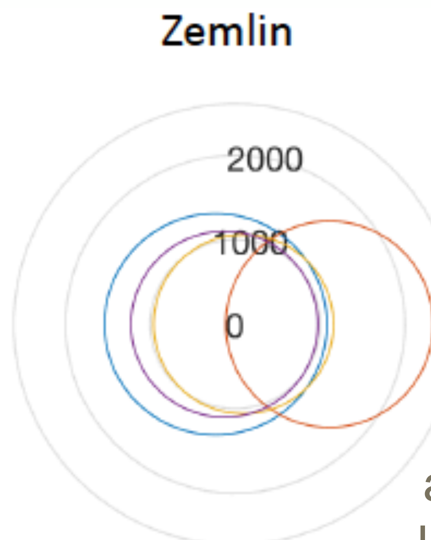
TEM requires chromatic aberration correction (C_3) stability of 1/10,000 or better

Schramm et al, PRL 109 (2012) 163901

→ Constant tuning

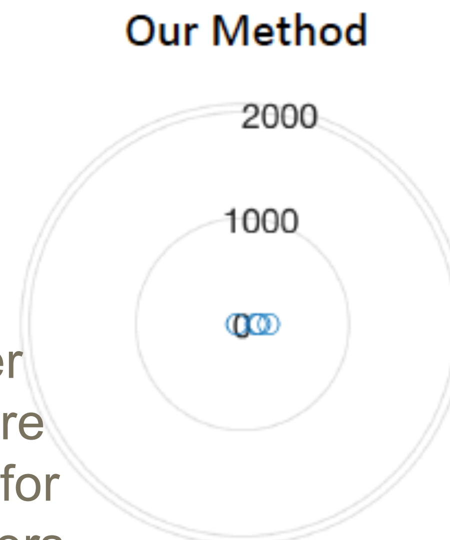


4D-STEM to characterize aberrations based on full (p_x,p_y) map at each (x, y)



C_{30}

6x faster
100x more accurate for lower orders



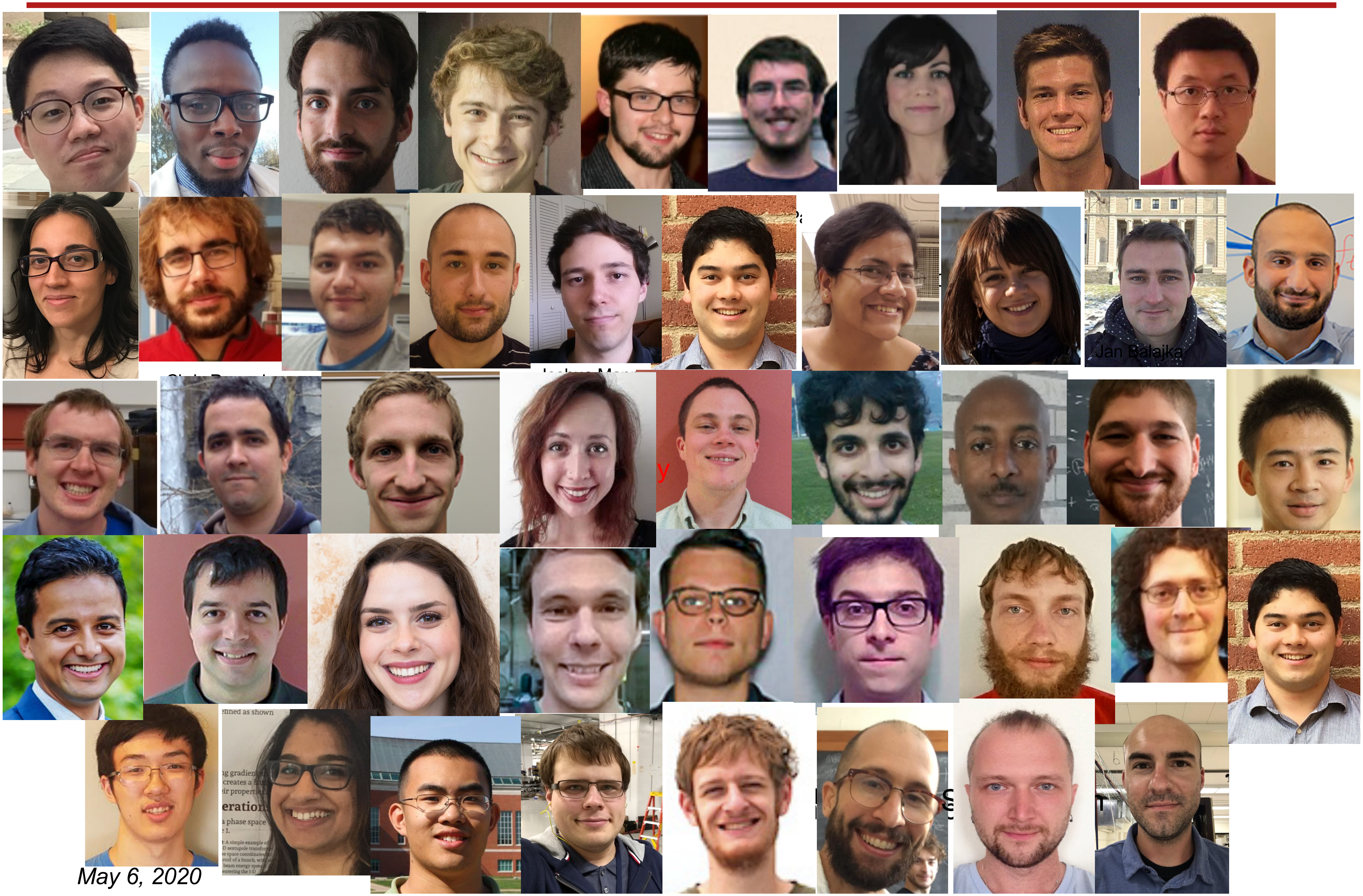
Also: Related the aberration function to emittance

Next: Apply accelerator techniques for tuning

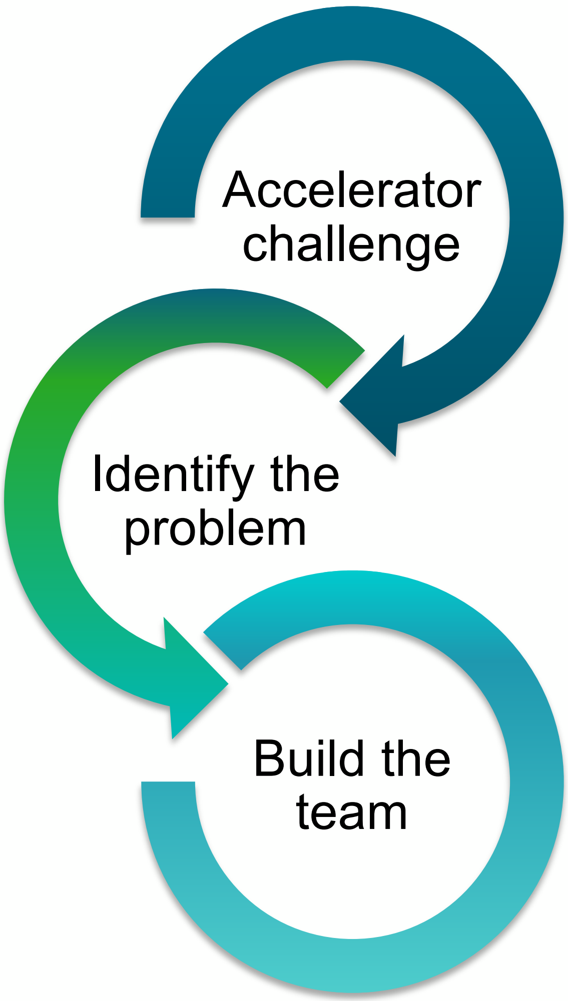
Goal: real time tuning

Groups: CBB, Nion, CEOS, and Thermo Fisher

Grad students and post-docs



CBB Team

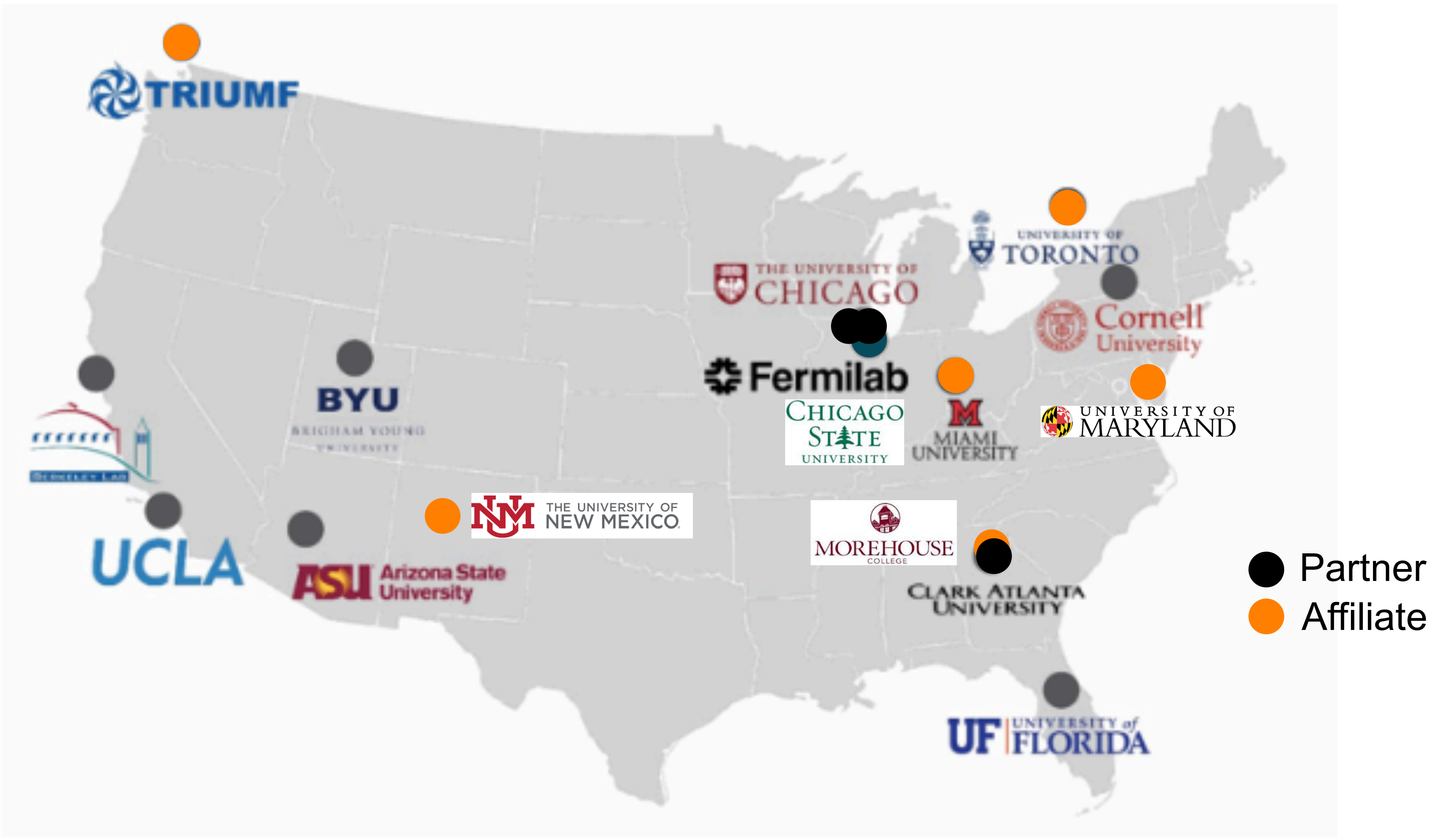


- Accelerator science
- Surface chemistry
- Nonlinear dynamics
- Condensed matter physics
- Materials science
- Ultrafast electron microscopy
- Computational physics

Growing Convergence Research
NSF Big Idea

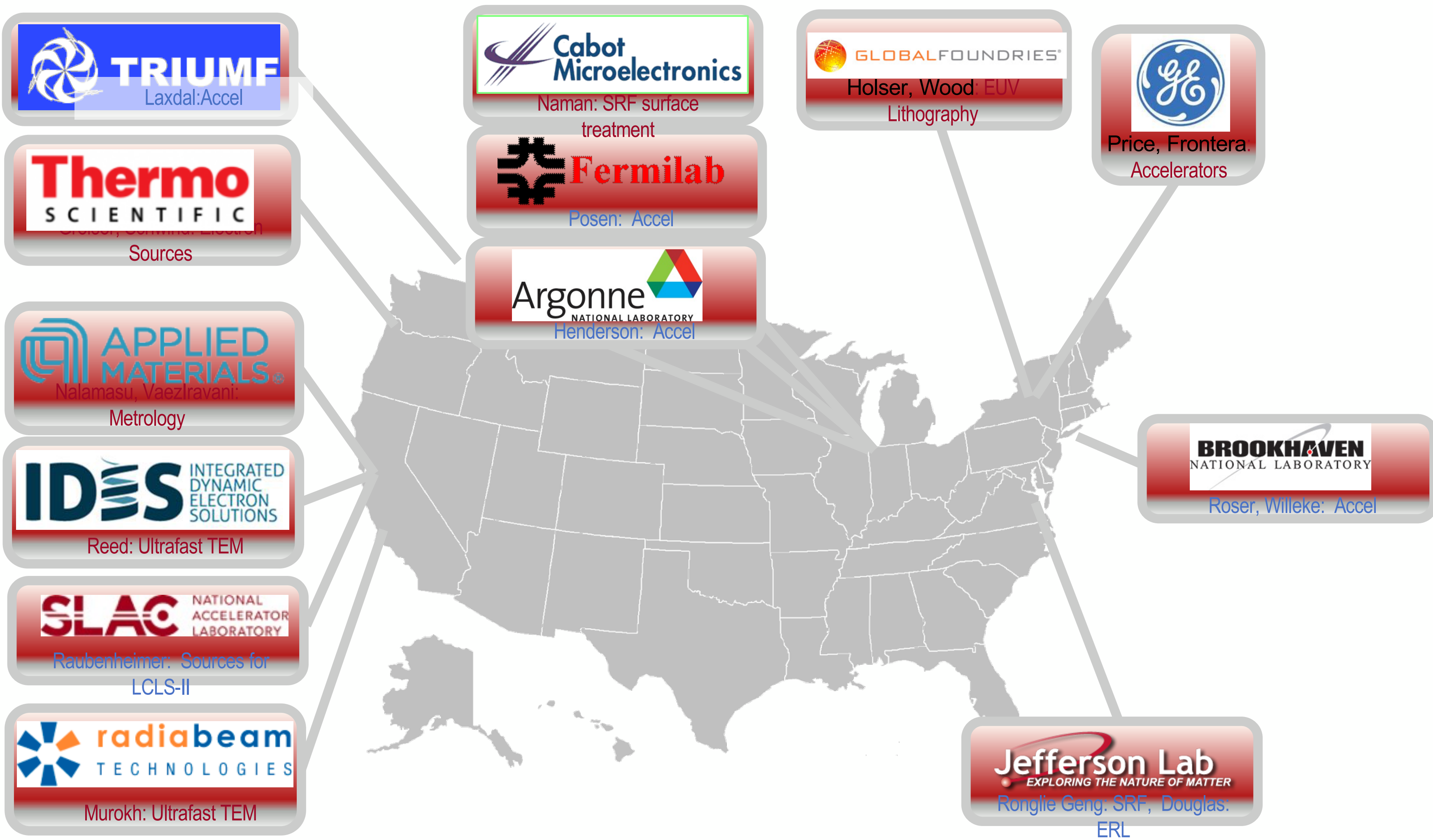
Interdisciplinary teamwork is key to CBB success

CBB groups



Teamwork is essential

Some of CBB’s Partners



Summary

NSF Center for Bright Beams

Gaining the fundamental understanding needed to transform the brightness of electron beams available to science, medicine and industry.

Focus areas: Photoemission sources, SRF cavities, Beam Dynamics & Control

This talk

CBB is eager for close collaboration with labs

- For better, faster progress
- So that useful CBB methods can be integrated into future accelerators

CBB trains students and postdocs in accelerator science, including hands-on experience.

Thank you.