NSF-supported Accelerator science

J. Ritchie Patterson
Cornell University

Member of CMS
Director, Center for Bright Beams

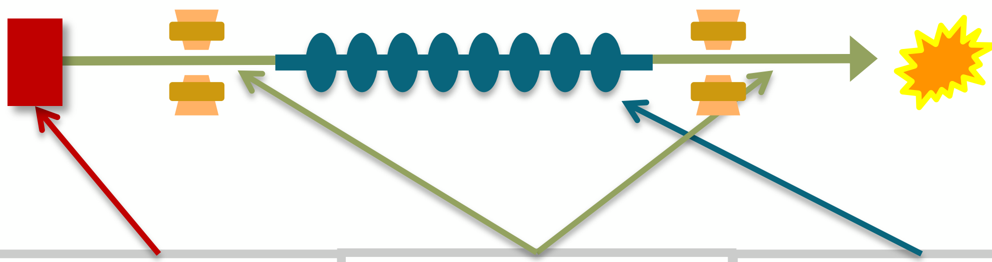
Accelerator Science at NSF

MPS Divisions

Center for Bright Beams

NSF Science & Technology Center

Gaining the fundamental understanding needed to transform the brightness of electron beams.



Beam Production	**Beam Dynamics and Control**	**Beam Acceleration**
Better photocathodes	For better beams at the IP	Better, simpler SRF cavities

CBB supports ~40 grad students and postdocs
→a pipeline for accelerator scientists

It capitalizes on accelerator infrastructure and expertise built with NSF investment over decades

Cornell · Arizona State University · The University of Chicago · BYU · Northern Illinois University · University of Florida · The University of New Mexico · UCLA

Lab Affiliates: SLAC National Accelerator Laboratory · Berkeley Lab · Fermilab

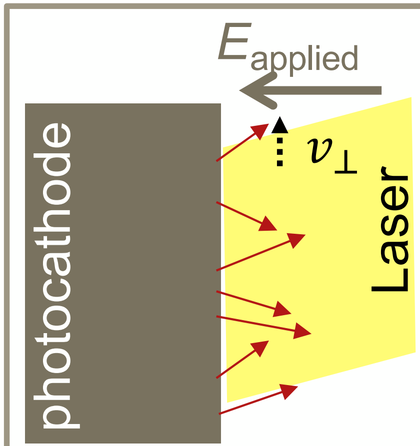
- CBB hosts almost all NSF HEP accelerator research
  Exception: advanced acceleration methods in Plasma Program
- CBB will end in 2026. **After 2026, Acc. Sci. for HEP requires *new* funding in PHY.**

Photoemission Electron Sources

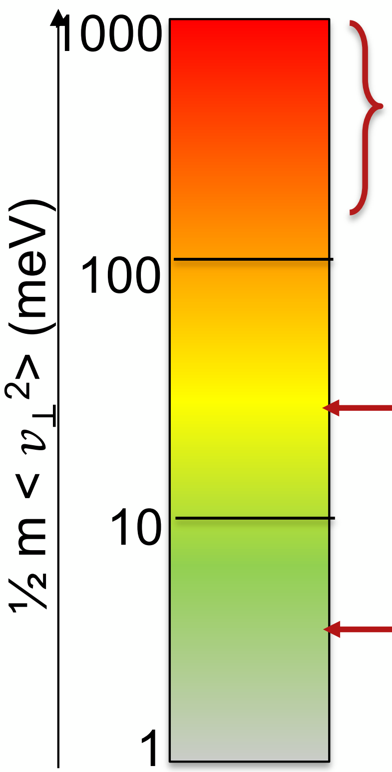
Applications

- Bright, spin-polarized bunches for e^+e^- colliders
- Cooling for FCC-hh
- Drive beam for wakefield accelerators

Cross-cuts: Electron-ion collider (NP), ultrafast electron microscopy/diffraction, x-ray FELs



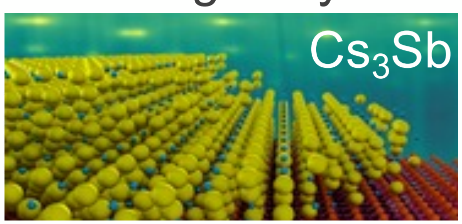
Want:
- Small $< v_\perp^2 >$
- high QE
- robustness
- high E_{app}



Typical cathodes

Coating method for **robustness**

First single crystal cathode



PRL, ***128***, *114801 (2022)*

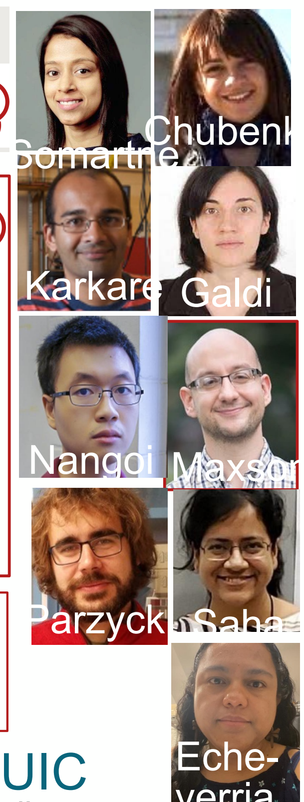
APL ***120***, *194102 (2022)*

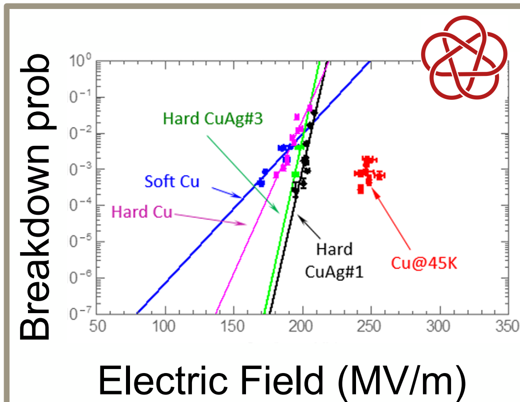
Future polarized electron source?

Cold Cu (100) (low QE)

PRL ***125***, *054801(2020)*

Cornell, ASU, BNL, LANL, LBNL, UIC

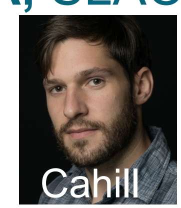




PRAB ***21***, *102002 (2018)*

Groups: **UCLA**, SLAC

This work contributed to C^3



Beam Acceleration

Superconducting RF (SRF) cavities

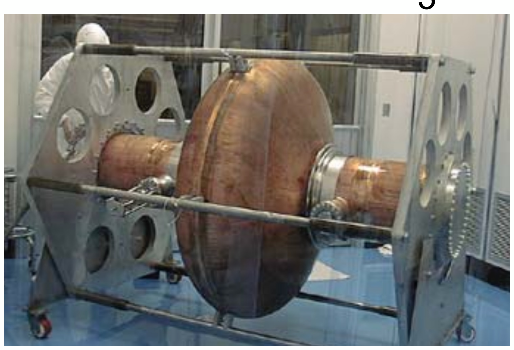
Inner surface (40 nm) drives performance

Physics is complicated and poorly understood

Niobium

Applications: FCC, μμ collider, ILC

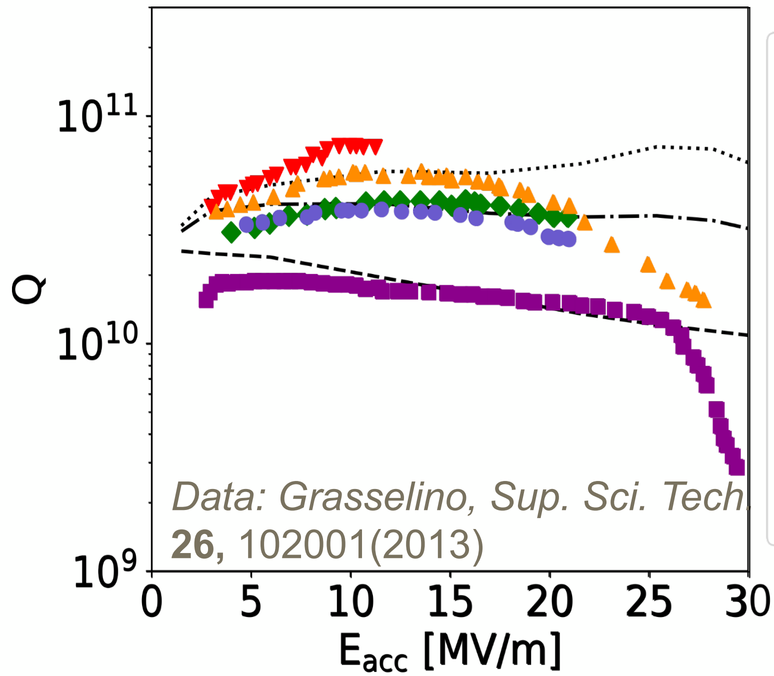
Cornell is a pioneer in SRF:
first use of an SRF cavity in a ring,
first cavity for a muon collider,
first successful Nb_3Sn.

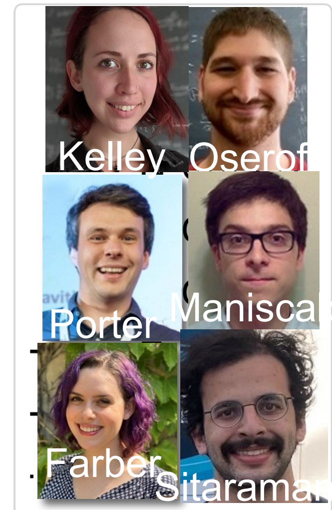


Nb/Cu cavity for a muon collider

Nitrogen Doping

"Accelerator Materials"





Successful description of N doping
A.Gurevich, PRL 113, 087001 (2014)
S. Deyo et al, PhysRevB.106.104502 (2022)

Not shown: At high field, quasiparticles are driven out of equilibrium, lowering Q
Maniscalco et al, SRF 2019, TUFUA1

Cornell, Old Dominion, U Chicago, FNAL, JLAB

Nb_3Sn Accelerating Cavities

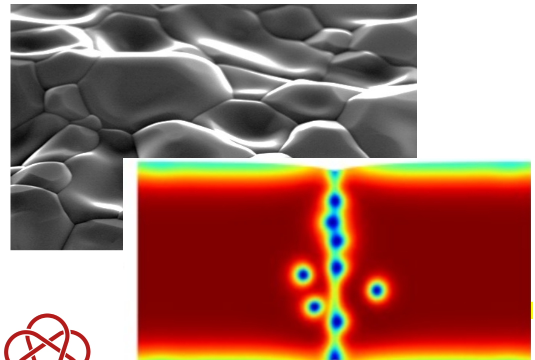
Why Nb_3Sn?

- Operation at 4K rather than 2K
  → 1/3 the cryogenic load
  Saves ~6 MW for ILC @ 250 GeV
- Potential for 2x accelerating gradient

Recent CBB advances

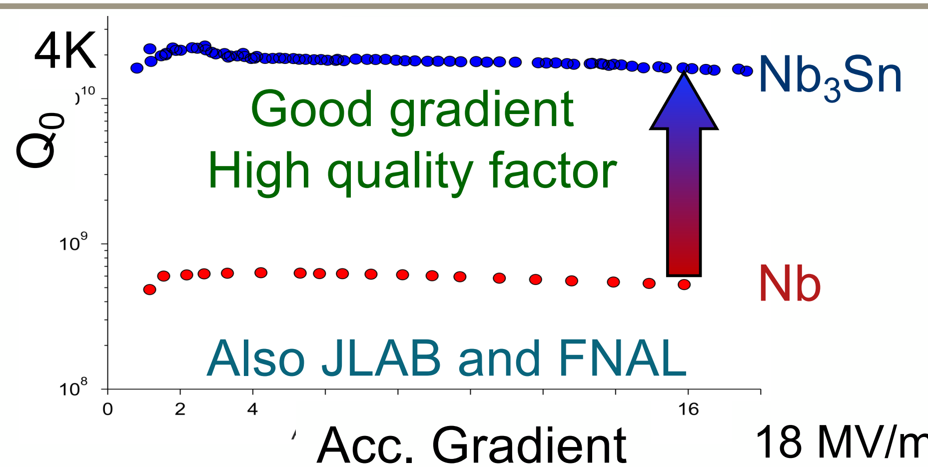
- **Growth/impurities**
  Stoichiometry *PRB **103**, 115106 (2021)*
  First Electroplating *arxiv:2302.02054*
- **Grain boundaries/vortices**
  Supercond. Sci. Technol. **34** 015015 (2021)
  *PRB **103**, 024516 (2021)*
- **Alternative materials**
  Introduced Nb-Zr
  Potential for high gradient, easy growth
  arXiv:2208.10678

Cross-cuts: Environmental applications, light sources, NP colliders, IC manuf.



*PRB **103**, 024516 (2021)*
*Supercond. Sci. Tech. **34** 015015 (2021)*
*Pathirina, Gurevich, PRB **101**, 064504 (2020)*

Groups: **Old Dominion, Cornell, Brigham Young, U Florida**



Beam Dynamics and Control

ML-assisted accelerator tuning

Crosscut: Electron microscope tuning

What are the bounds of applicability?

Hands-on training for students

CESR *W. Bergan et al.,Phys. Rev. Accel. Beams* **22**, 054601 (2019)

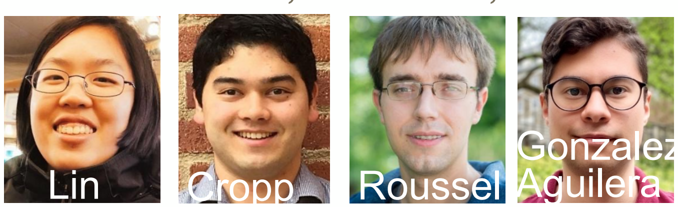
LEReC *Y. Gao et al. Phys. Rev. Accel. Beams 25, 014601 (2022)*

HiRES *A. Scheinker et al., arXiv:2102.10510 (2021); A. Scheinker et al, Nature Comm.* ***12****, 5612 (2021)*

PEGASUS *Cropp et al., NAPAC'19/frxba4*

Electron Microscope *Microsc. Microana.* ***28*** *(S1), 3146 (2022)*

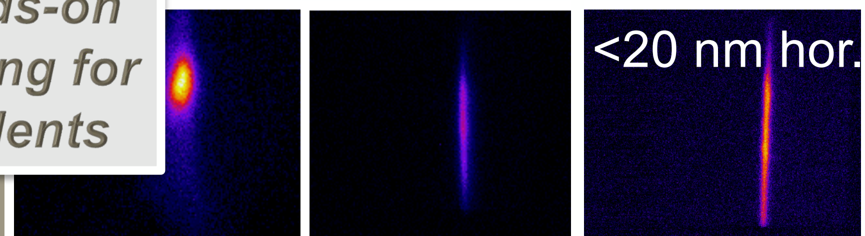
Roussel et al, PRL 130, 145001 (2023)



UCLA, NIU, U Chicago, Cornell, ANL, SLAC, BNL

Round to flat beam transform

Linear colliders and dielectric wakefield acc.



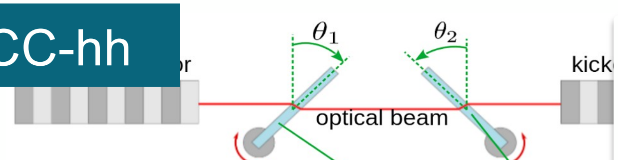
z = 9.2 cm   z = 70 cm   z = 145 cm

Cropp et al., NAPAC'19/frxba4

Groups: **UCLA**, SLAC

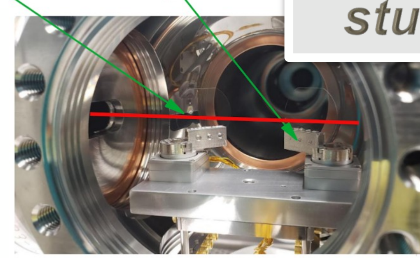
IOTA: Optical Stochastic Cooling

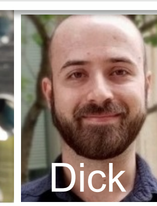
FCC-hh



Hands-on training for students

NIU provided the optical delay stage and simulation



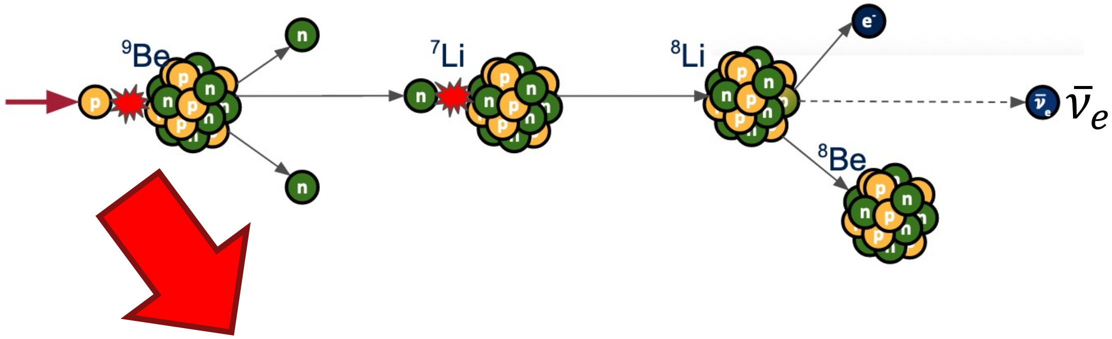


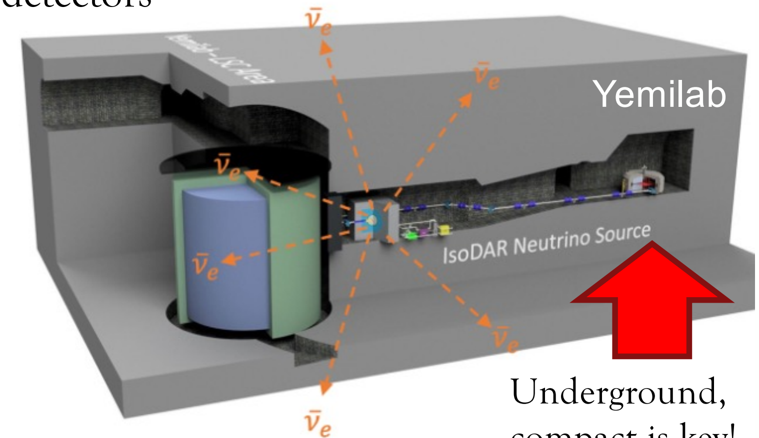
Jarvis et al., Nature 608, 287 (2022)

IsoDAR Proton Cyclotron

NSF Particle Astrophysics: Accelerators for Underground Science

New approach to new physics → high intensity sources meets ultralarge detectors





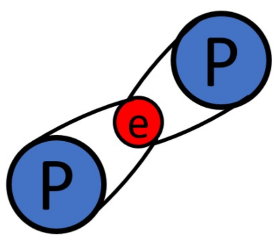
Underground, compact is key!

Required proton cyclotron:

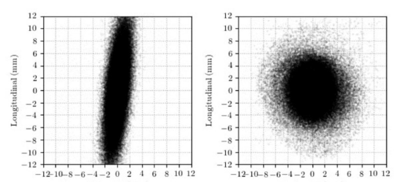
60 MeV, 10 mA (Protons are from 5 mA of H_2^+) →×10 intensity of commercial machines.

Three innovations for higher currents

Use of H_2^+

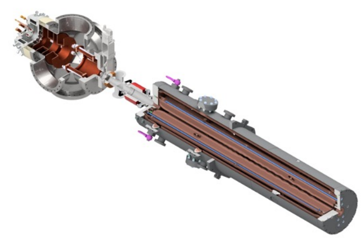


Vortex Motion



New J.Phys. 24 (2022) 2, 023038, https://arxiv.org/abs/2103.09352

RFQ Direct Injection



NSF funded: ion source | studies of PSI data | RFQ

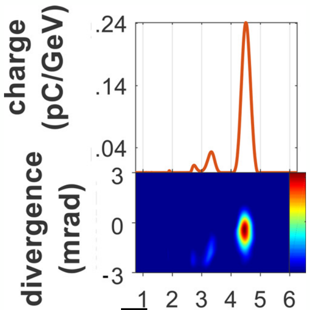
Hogil-Kim Prize

Groups: **MIT,** PSI

New J. Phys. 24, 023038 (2022)

Advanced Acceleration

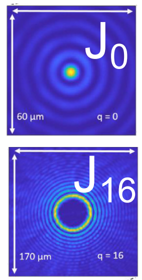
All-Optical Laser Wakefield Accelerator



Laser energy 11J, 45fs

Energy

Multi-GeV



Plasma channel

Cladding

Optically formed plasma waveguide

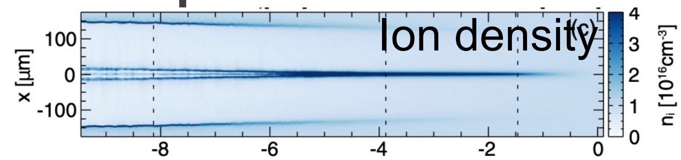
PRX 12, 031038 (2022)

*PRL **125**, 074801 (2020)*

Phys. Plasmas 29, 073101 (2022)

U. Maryland, Colorado St. and others

Stable positron acceleration



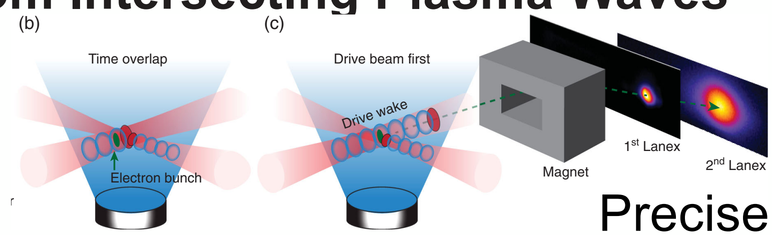
Simulation

*PRL **127**, 104801 (2021)*

Lisbon, LBNL, **UT Austin**, SLAC

UCLA established the first group on plasma-based accelerators in 1981, resulting in 4 landmark papers and the birth of the field, and it continues to be a leader.

Electron Trapping from Intersecting Plasma Waves

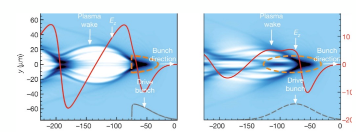


PRL 121, 104801 (2018)

U. Nebraska, SJTU

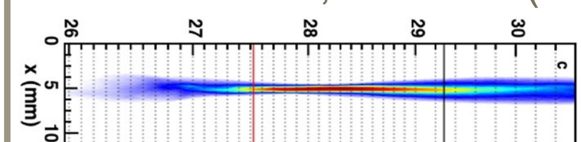
Precise timing is key…and achieved.

UCLA at FACET



Positron Acceleration

*Nature **524**, 442-445 (2015)*



9 GeV Energy Gain

*Plasma Ph. Control. Fusion **58**, 11 (2015)*

Advanced Acceleration

Acceleration strategies

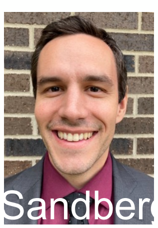
- Electron acceleration using twisted laser wavefronts *Plasma Phys. Control. Fusion* **63** 125032 (2021) USTC, **UCSD**
- Transition Radiation in Photonic Topological Crystals: Quasiresonant Excitation of Robust Edge States by a Moving Charge *PRL 123, 057402 (2019)* **Cornell, UT Austin**, ANL

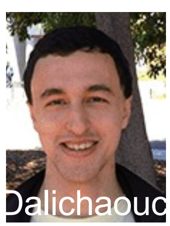
Positrons

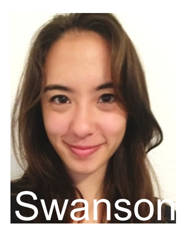
- Stable positron acceleration in a warm, narrow hollow channel, *PRL **127**, 104801 (2021)* Lisbon, LBNL, **UT Austin**, SLAC

Rep rate

- Laser-Accelerated, Low-Divergence 15-MeV Quasi-monoenergetic Electron Bunches at 1 kHz, *PRX **11**, 021055 (2021)*, **U Maryland**, U Arizona







Injection schemes

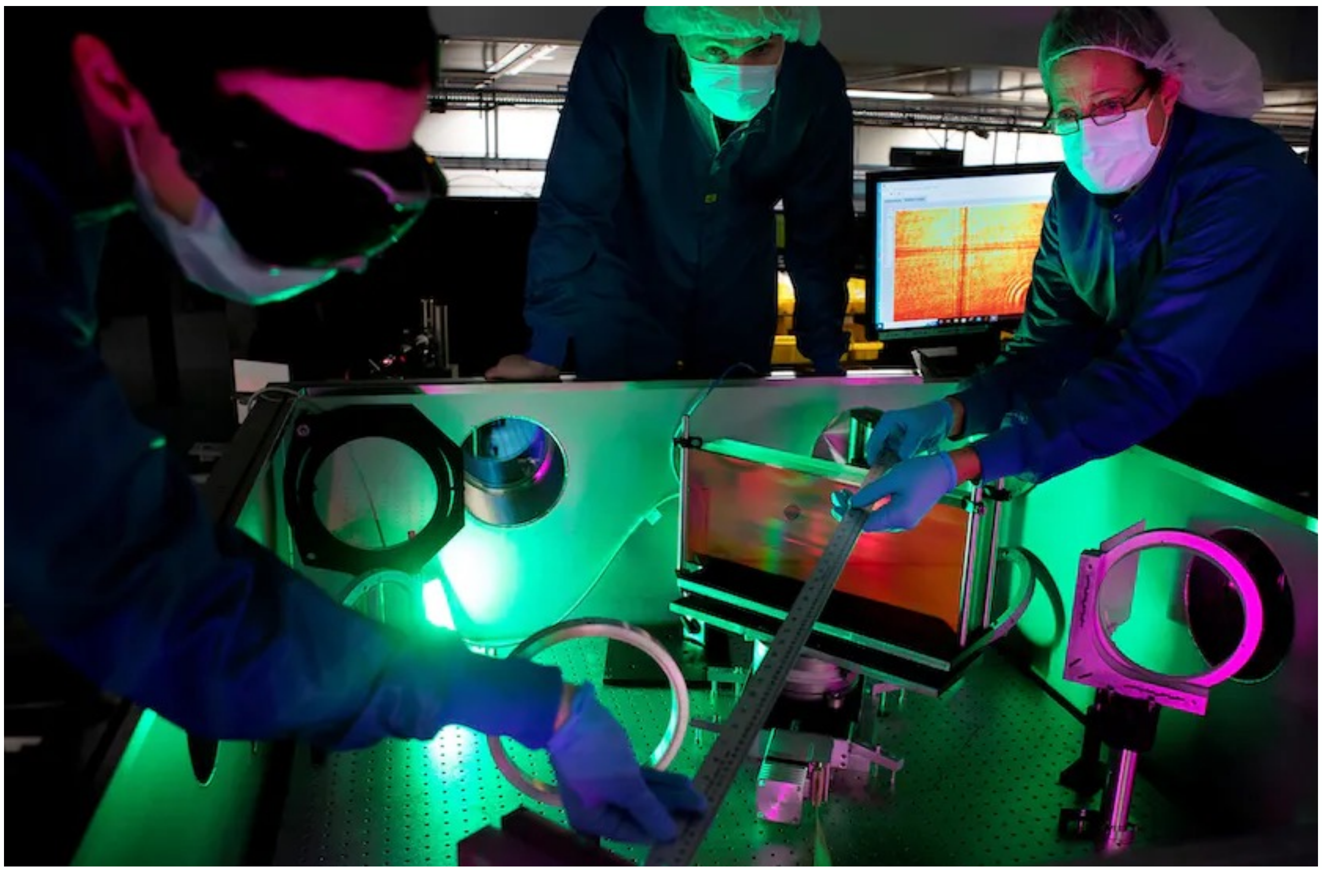
- Transient, Relativistic Plasma Grating for Tailoring High-Power Laser Fields, Wakefield Plasma Waves, and Electron Injection *PRL **128**, 164801 (2022)* **U. Nebraska ELL**, Cz. Acad Sci, Cz. Tech U, Chalmers, Ecole Poly.
- Highly spin-polarized multi-GeV electron beams generated by single-species plasma photocathodes, *PR Res. **4**, 033015 (2022)*, **UCLA**, MPI, Beijing Norm. U
- Evolution of the self-injection process in long wavelength infrared laser driven LWFA *Physics of Plasmas* 28, 013102 (2021) **Stony Brook U.**, BNL, **UT Austin**
- High-throughput injection–acceleration of electron bunches from a linear accelerator to a laser wakefield accelerator *Nature Physics* **17**, 801–806 (2021) Tsinghua, **UCLA**

Extreme Light Lab
UNIVERSITY OF Nebraska

U Maryland Laser upgrade to 100 TW

Looking forward

ZEUS ZETTAWATT-EQUIVALENT ULTRASHORT PULSE LASER SYSTEM
UNIVERSITY OF MICHIGAN



LWFA of > 10 GeV electron beams using a 3 PW driver

500 TW,
5 Hz burst mode

Initial 24-week operating cycle in 2023-24.

High Field Magnets

Applications: FCC-hh (16 T dipoles) and μμ collider (30-50T solenoids)

Cross-cuts: 20 T at 20K for commercial Tokamak-style fusion reactors, MRI

NATIONAL HIGH MAGNETIC FIELD LABORATORY

NSF DMR

World's highest field solenoid 45.5 T

Hahn et al., Nature ***570****, 496 (2019)*

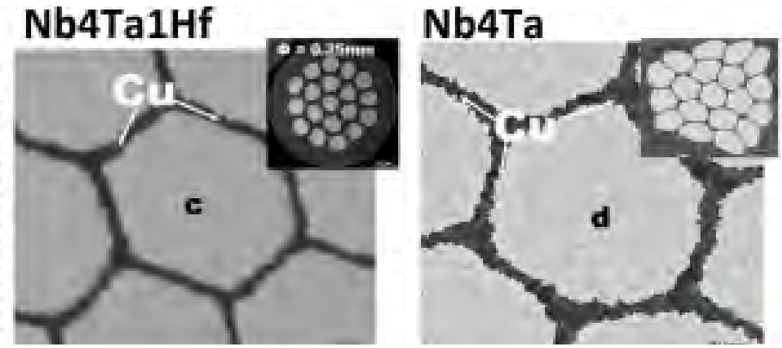
Leader in REBCO and Bi-2212 tech.

"Accelerator Materials"

US Magnet Development Program

Florida State U/MagLab, LBNL, FNAL, BNL

Nb_3Sn doping



Halfnium doped Undoped

Hardens Nb_3Sn and reduces grain size

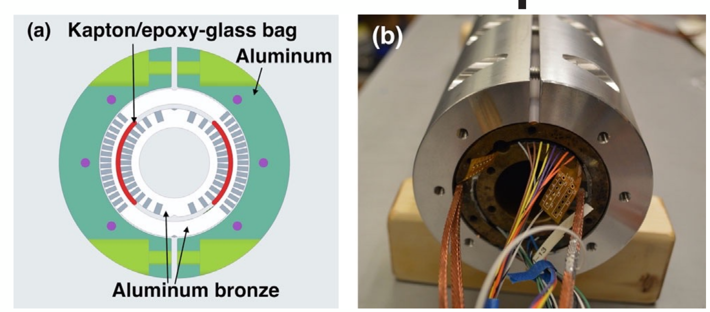
→ likely higher critical field

→ better vortex pinning

Supercond. Sci. Technol. 32, 044006 (2019)

Sci. Rep. 11, 17845 (2021)

Bi-2212 accelerator dipole magnet



Phys. Rev. Accel. Beams ***25****, 122401 (2022)*

Groups: LBNL, **MagLab**

Broadening Participation

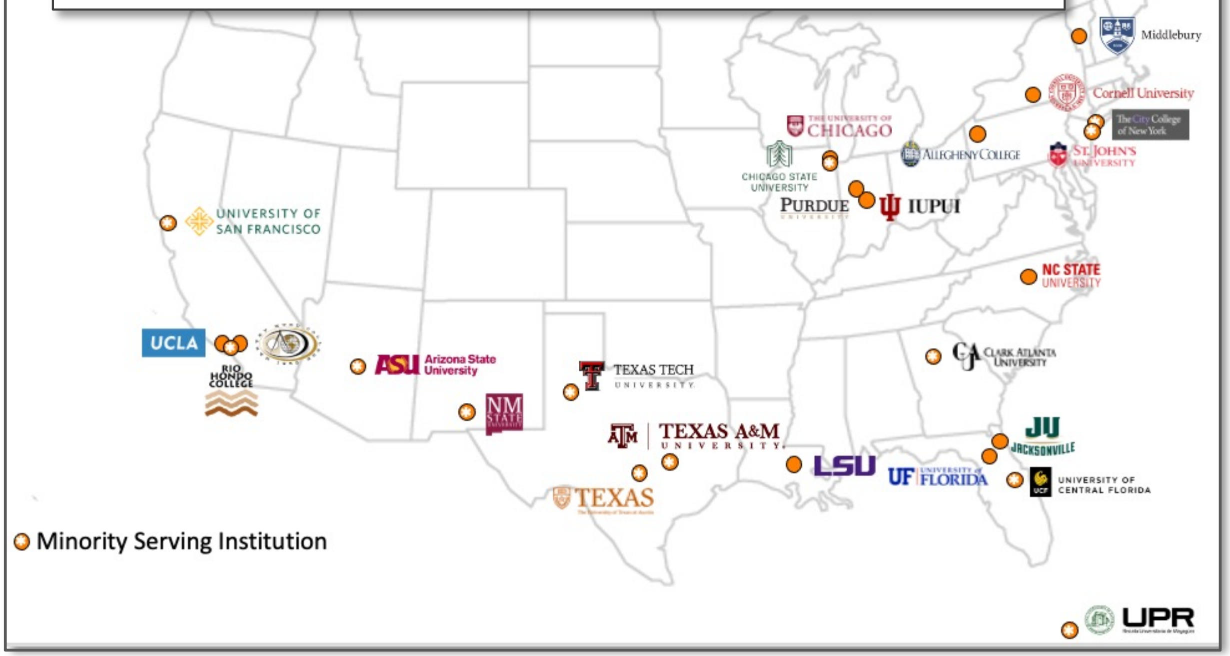
Research Experience for Undergraduates (NSF REU) brings in undergrads from across the country

REU recruiting at URM conferences such as SACNAS and NSBP

Participants in the virtual 2020 REU

Grace Mattingly, REU 2019

Institutions of undergrads participating in Center for Bright Beams research



Zeinab Ismail, REU 2021

Conclusions

Universities do excellent accelerator science. And they educate students.

NSF expects both

Accelerator science has become a distinct discipline suitable for the academy.

To flourish, universities need

- On-campus research with university-scale facilities, and access to facilities at national labs
- Funding stability

On-campus labs enable strong research and attract students

A strong program includes both DOE and NSF

- NSF PHY needs a new initiative in Acc. Sci. for HEP. This could provide continuity for some of CBB's 40 grad students and postdocs after 2026.
- NSF has strong campus education, such as REU
- NSF can support research not specifically aligned with DOE roadmaps

PHY supports only AAC and IsoDAR.