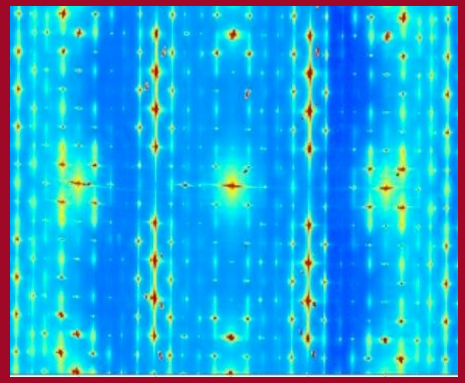
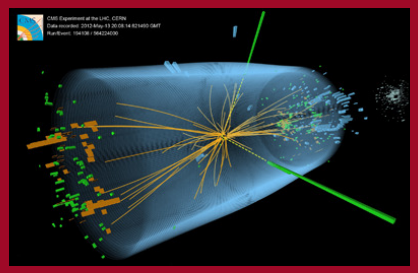
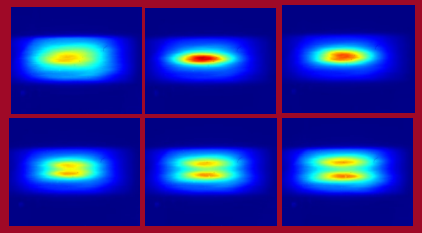
Accelerator Science at Cornell

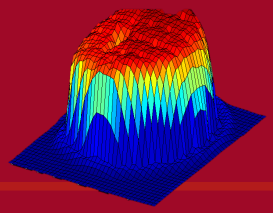
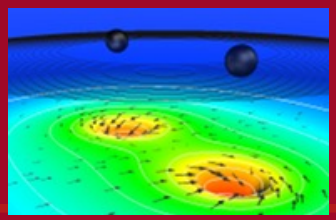
Ritchie Patterson, with Ivan Bazarov, Don Hartill, Georg Hoffstaetter, Matthias Liepe, Nigel Lockyer, Jared Maxson,

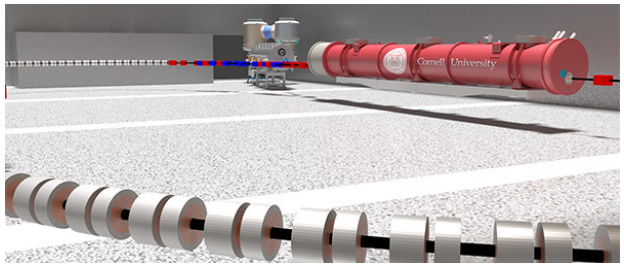
October 11, 2023

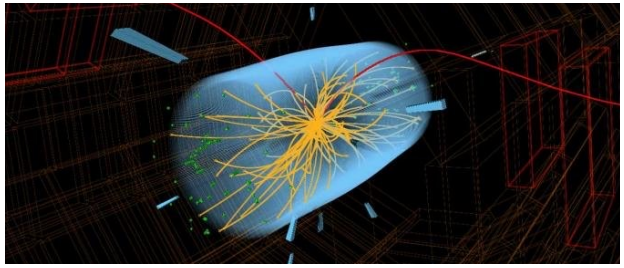












Cornell Laboratory for Accelerator-based Sciences and Education

CLASSE

Accelerator physics

Innovation in high quality electron beams

Particle and astrophysics

CMS (NSF upgrade lead), muon g-2, cosmology, theory

CHESS

X-ray user facility used by 1300 scientists annually from around the world

World renowned research and leadership in large-scale projects

High impact accelerator research

- Superconducting acceleration
- Energy Recovery Linacs
- Stored beam phenomena
- Bright electron sources

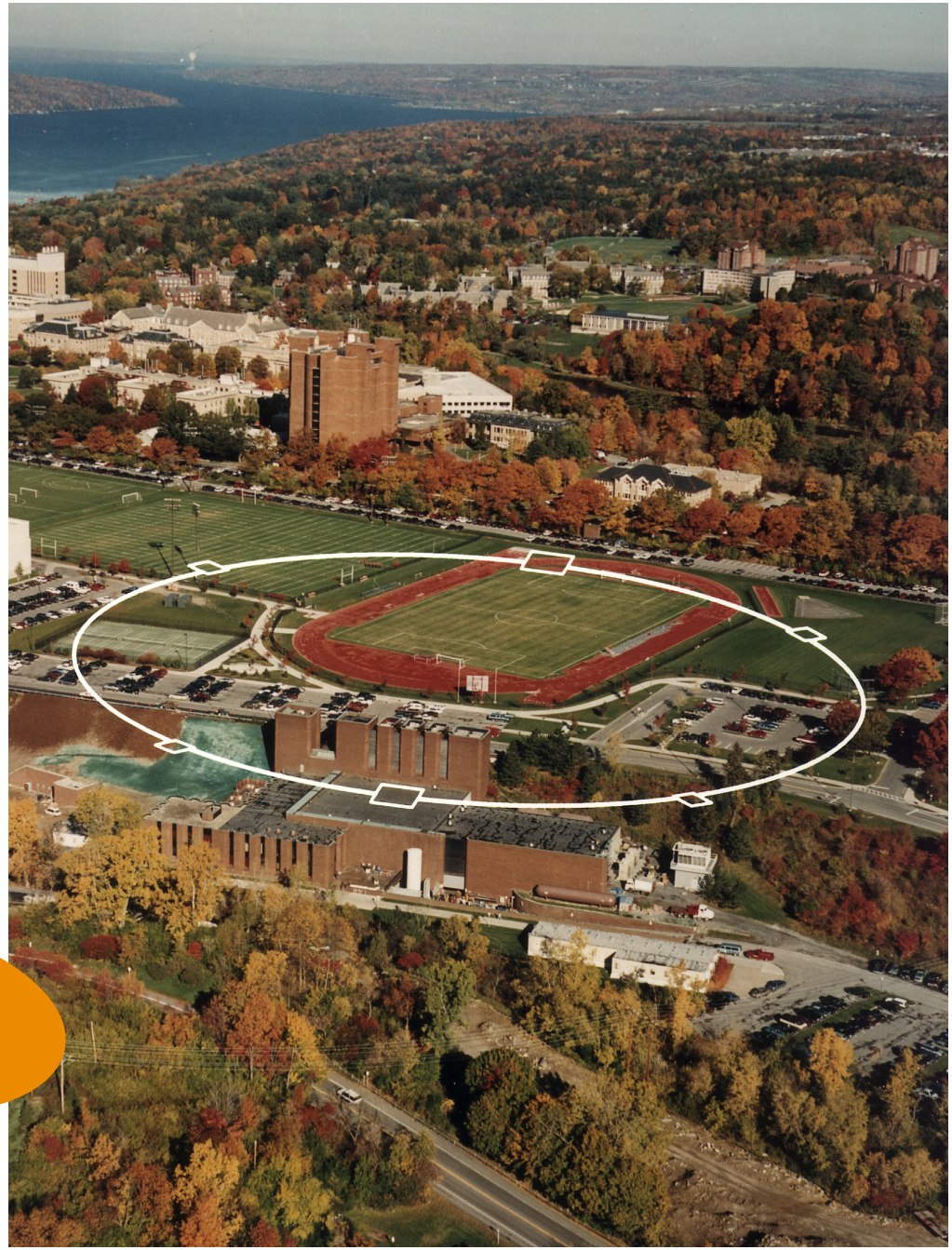
Strong academic program in accelerator science

~20% of US PhD's

15 current grad students

Student and post-doc alums:
SLAC and FNAL SRF heads,
FNAL Chief Tech. Officer,
FNAL Interim Assoc. Lab. Dir.
ANL APS Acc. Div. Dir.,
SLAC Acc. Div. Head (former),
JLAB Director
etc.

Hands-on training



Cornell-trained accelerator physicists

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

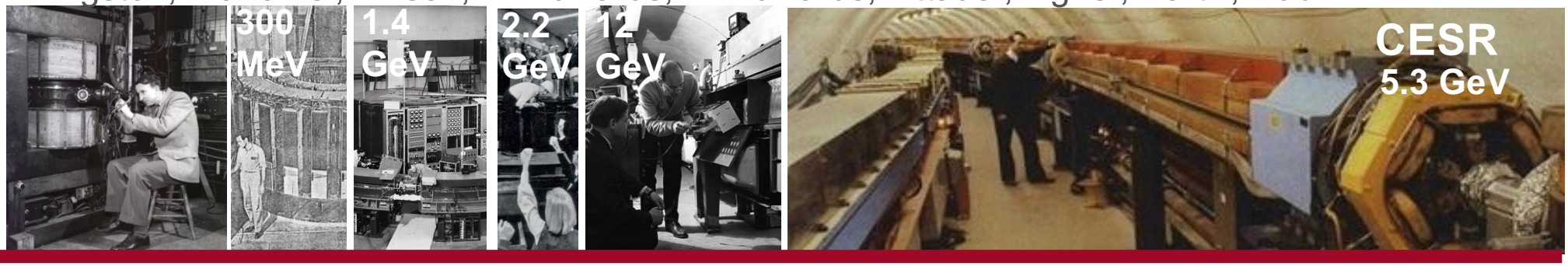
A sampler of past grad students, post-docs and faculty:

Ahrens, Lief	BNL, AGS operation Dir.
Belomestnykh, Sergey	FNAL, SRF Director
Byrd, John	LBL Fusion-Accel. Dev. Head
Blum, Eric	BNL
Chen, Tong	Teledyne, VP for Dev.
Cultrera, Luca	BNL
Dunham, Bruce	xLIGHT
Kersevan, Roberto	CERN
Decker, Glenn	ANL
Dixon, Roger	FNAL, Division Head
Edwards, Don	FNAL/DESY
Edwards, Helen	FNAL/DESY
Eremeev, Grigory	FNAL, Dep. Division Dir.
Erickson, Roger	SLAC, Dir. Accel. Ops & Safety
Gibbard, Bruce	BNL
Gonnella, Daniel	SLAC, Group Leader
Henderson, Stuart	JLAB, Director
Herb, Steven	DESY

Jackson, Gerald	President, Hbartech
Karkare, Sid	Prof. Arizona St. U.
Knobloch, Jens	HZB, Prof.
Maxson, Jared	Prof. Cornell
Mayes, Chris	xLIGHT
Milton, Stephen	Prof. CO State Univ.
Palmer, Mark	BNL, Director Acc. Sci.& Tech. Initiative
Phillips, Larry	JLAB
Peggs, Stephen	BNL / ESS, Group Leader
Posen, Sam	FNAL, Assoc. Director (Interim)
Proch, Dieter	DESY, Group Leader
Romanenko, Alex	FNAL, Assoc. Lab Director
Seeman, John	SLAC, Accel. Division Head (former)
Siemann, Robert	SLAC, Professor
Sinclair, Charlie	JLAB, Assoc. Director
Sundelin, Ronald	JLAB, Group Leader
Sutter, David	UMD / DOE
Young, Elizabeth	Raytheon

Stored beams

Livingston, McDaniel, Wilson, D. Edwards, H. Edwards, Littauer, Tigner, Hartill, Rubin

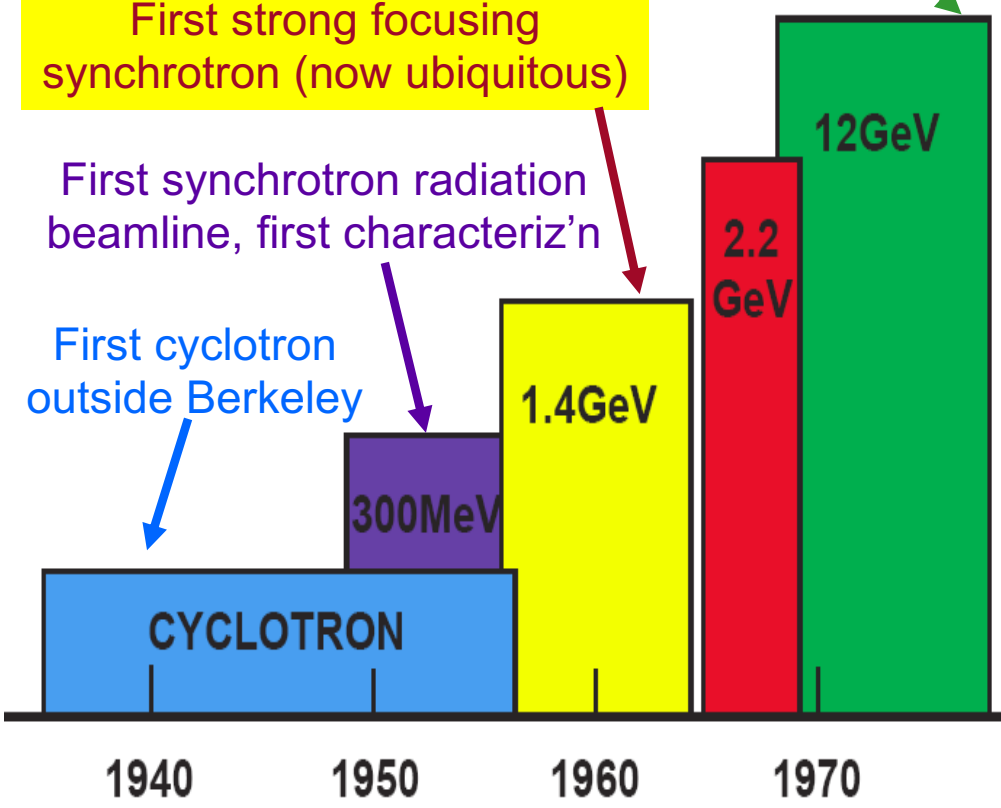


First chamber-less synchrotron
First use of SRF in a synchrotron

First strong focusing synchrotron (now ubiquitous)

First synchrotron radiation beamline, first characteriz'n

First cyclotron outside Berkeley



CESR

First bunched-beam crossing angle
→ **KEK-B, DAPHNE, STCF, LHC-HL, EIC**

First pretzel orbit → **Tevatron**

First permanent magnet IP

First SC magnet IP
→ **HERA, B-factories**

First ring with only SC cavities
→ **light sources, KEK-B, EIC, …**

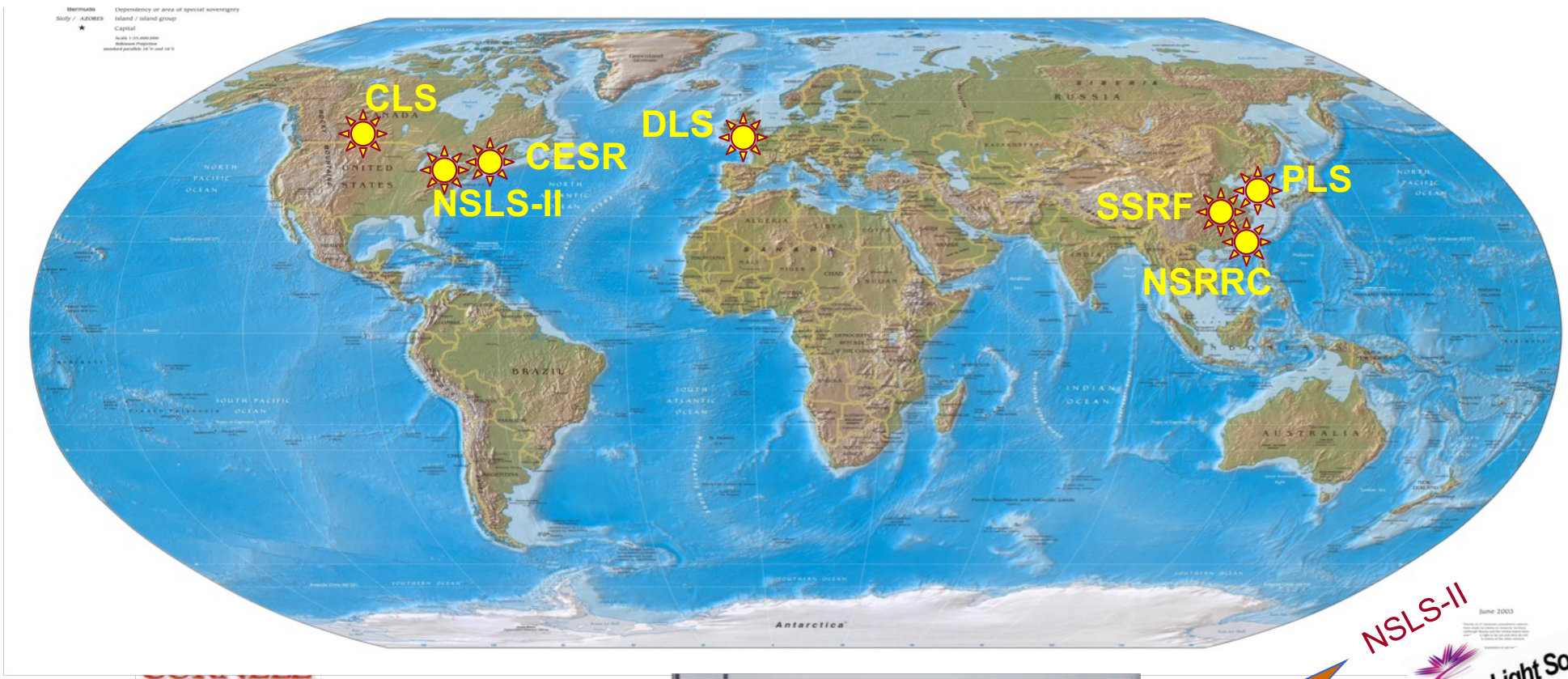
Electron cloud and wakefield results that informed design of the LHC injector and KEK-B ILC damping ring design

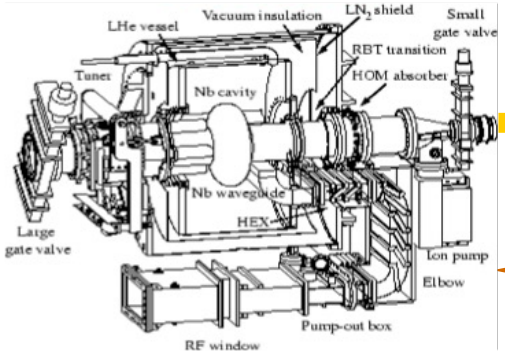
For a decade, CESR held the luminosity record

Design for active Optical Stochastic Cooling

Figure from K. Berkelman, "A personal History of CESR and CLEO

Cornell SRF cavities





Technology transfer

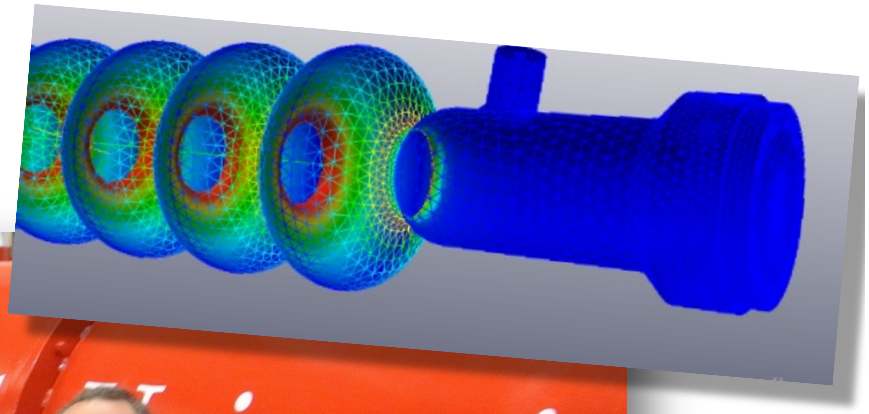
NSLS-II
Canadian Light Source
TPS 台灣光子源規劃構想 Taiwan Photon Source
diamond
SINAP SSRF
PLS

Cornell also provided the SRF cavities for CEBAF

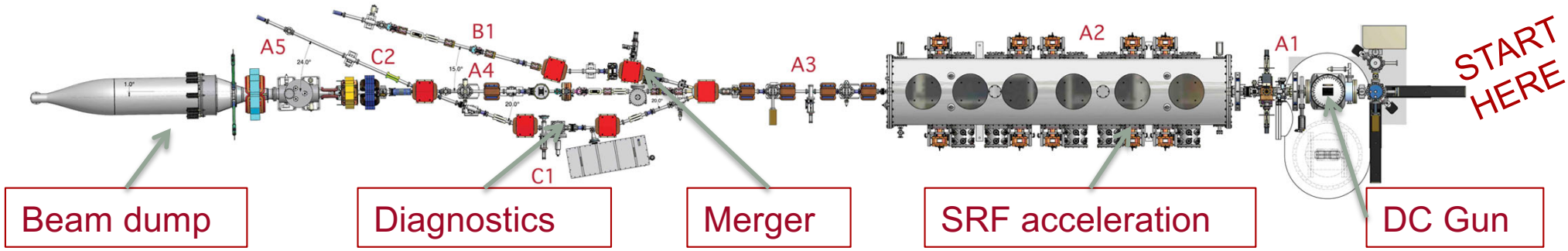
Superconducting linac

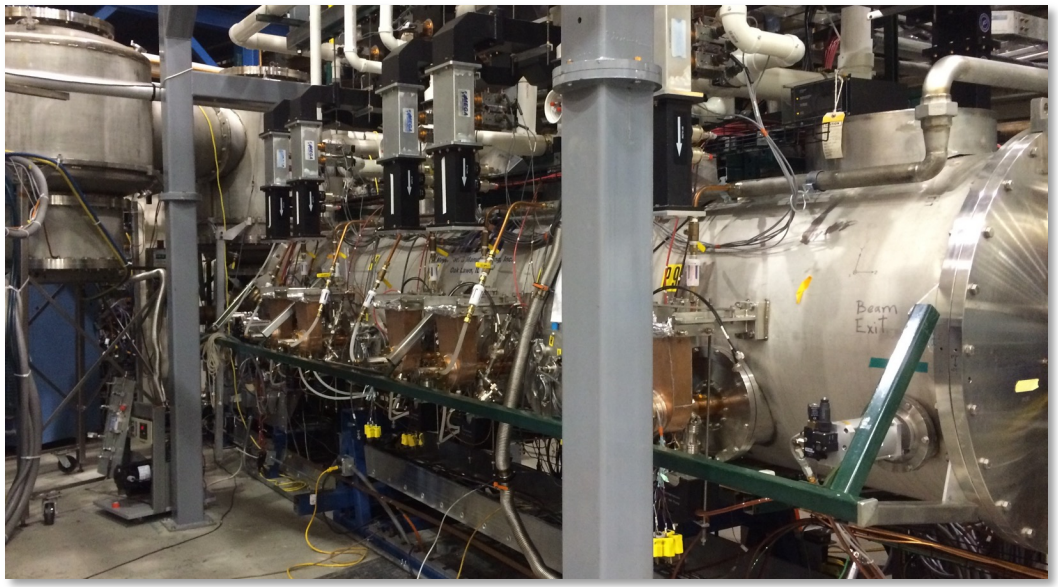
World's most energy efficient particle accelerator

Completed 2015

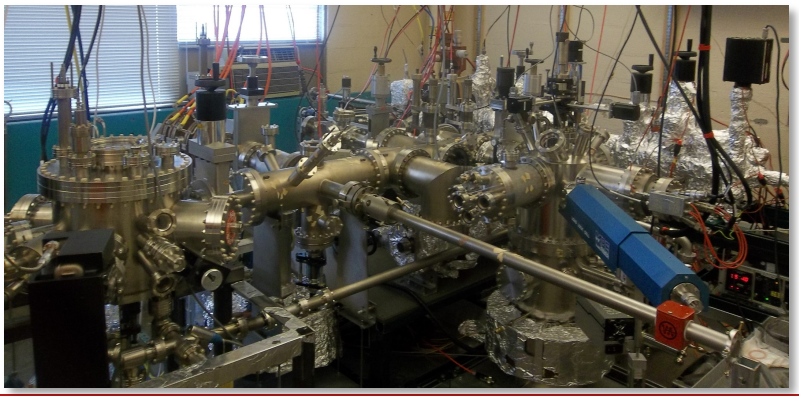


Bright source of electrons





- Record current for a low emittance source (>65 mA)
- Record low emittance
- Good cathode lifetime
- Bunch charges up to 2 nC
  PRSTAB 18, 083401 (2015)



Photocathode Lab

Alkali-antimonide growth and characterization

CBETA Energy Recovery Linac

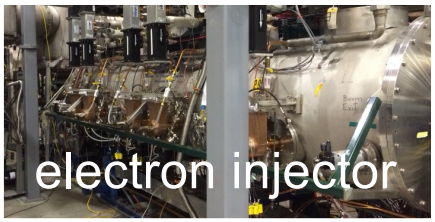
ERL concept invented at Cornell
Tigner 1965

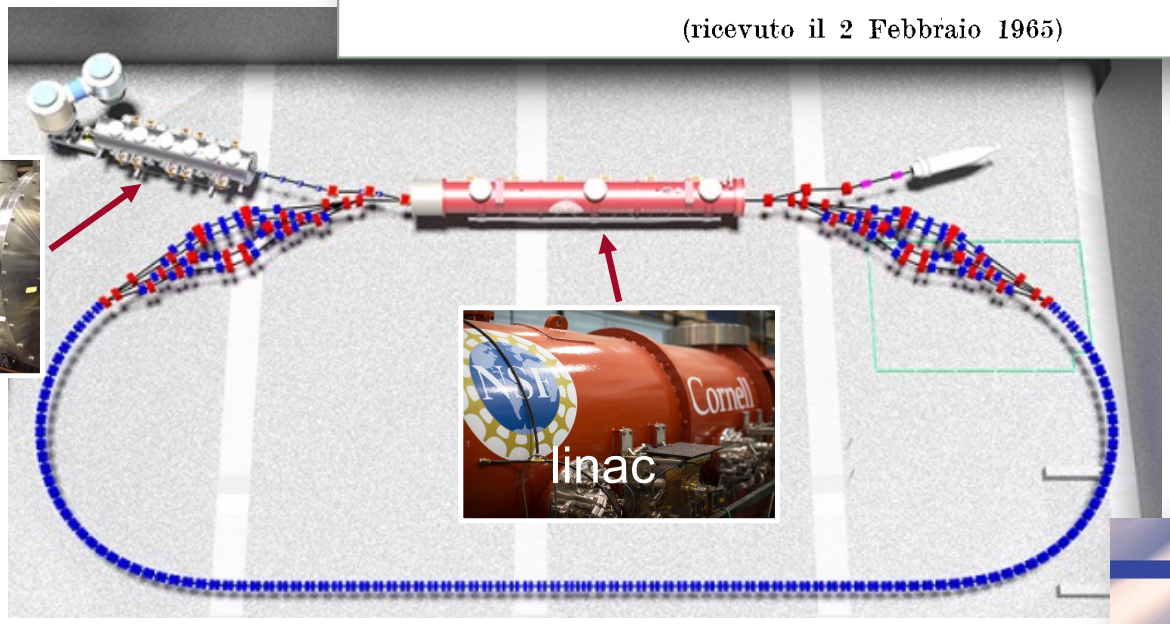
A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)

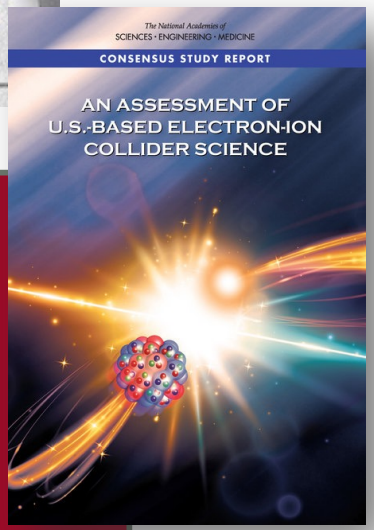




- First multi-turn ERL (4 turns)
- 99.4% energy recovery after turn 1
- Beams with 4 energies in a shared FFA beampipe
- Met all performance goals, December 2019

Partnership with BNL

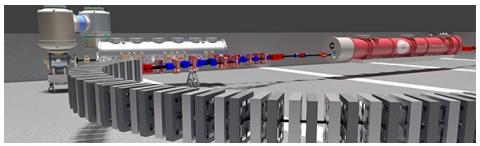
"CBETA will pioneer several energy-saving concepts in accelerator design."
-*National Academies Report, July 2018*

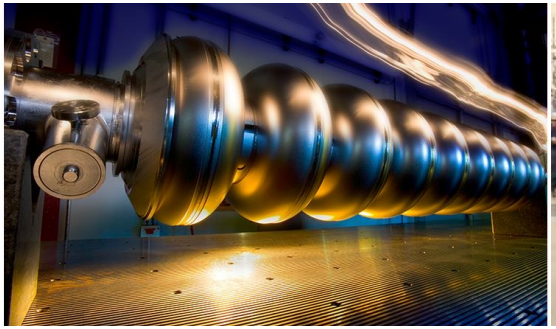


~90 expert engineers and technicians

RF systems, cryogenics, vacuum systems, electronics and mechanical design, systems design, computing, shops…

Extensive facilities





~$1 billion in infrastructure

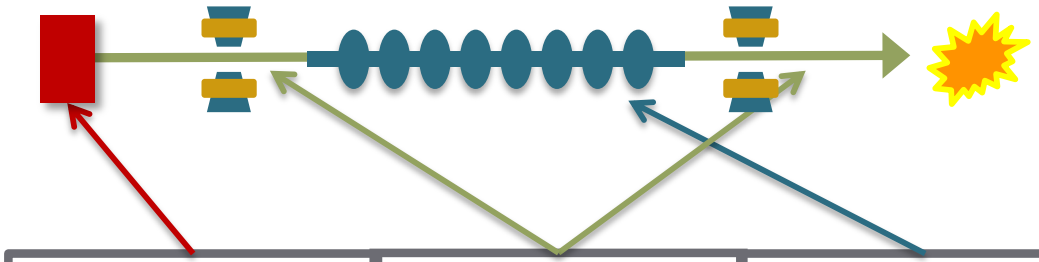
Current Activities and Plans

Center for Bright Beams

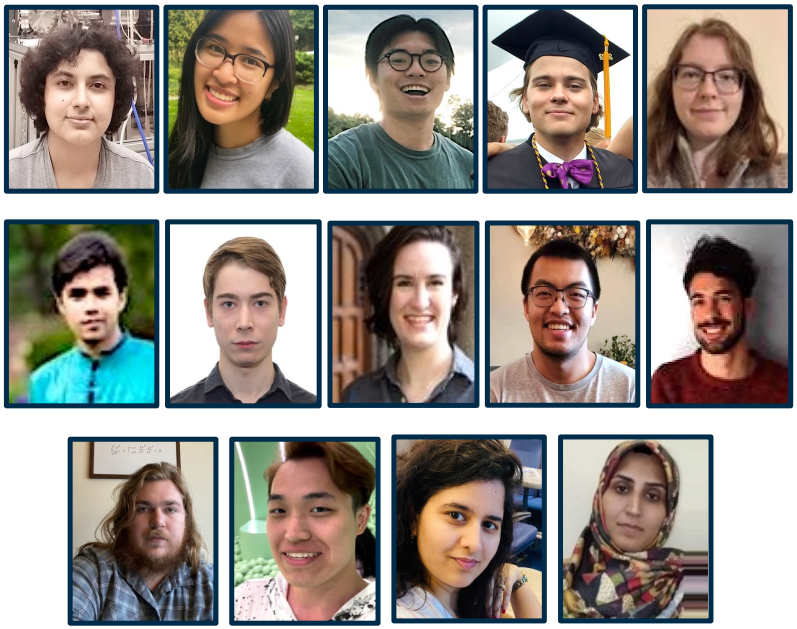
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

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 target	Better, simpler devices



CBB supports ~40 grad students and postdocs

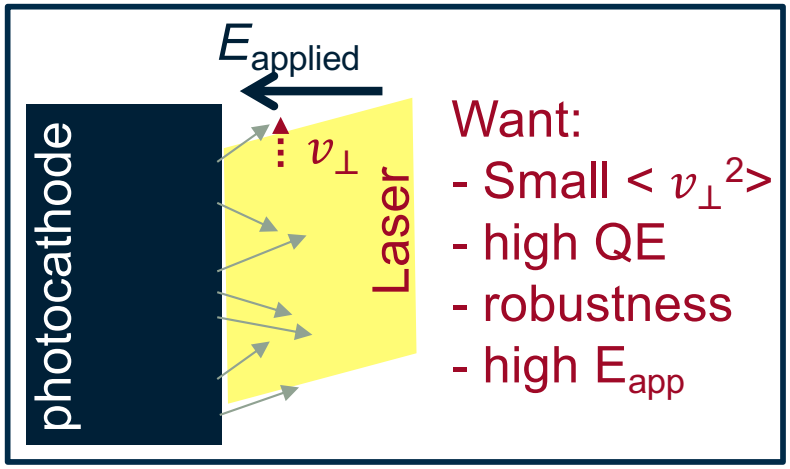
51 graduates to date

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

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

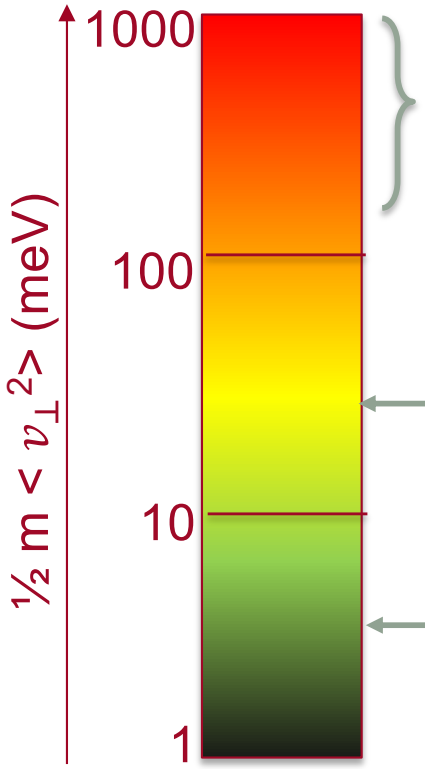
CBB joins chemists, surface scientists, condensed matter physicists, ab initio physicists, electron microscopists, and accelerator scientists

Photoemission Electron Sources



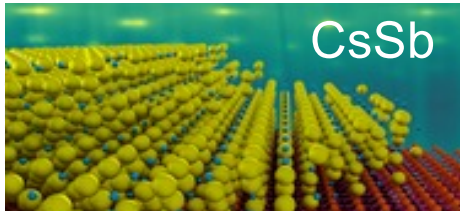
Applications

- X-ray FELs (both large and compact)
- Beam cooling systems, eg for FCC-hh
- Drive beam for wakefield accelerators
- Ultrafast electron microscopy/diffraction
- **Bright, spin-polarized bunches for e^+e^- colliders**



Typical cathodes

First single crystal cathode



*PRL, **128**, 114801 (2022)*
*APL **120**, 194102 (2022)*

Cold Cu (100) (low QE)
*PRL **125**, 054801(2020)*
Sid Karkare, ASU

Do they produce high current?

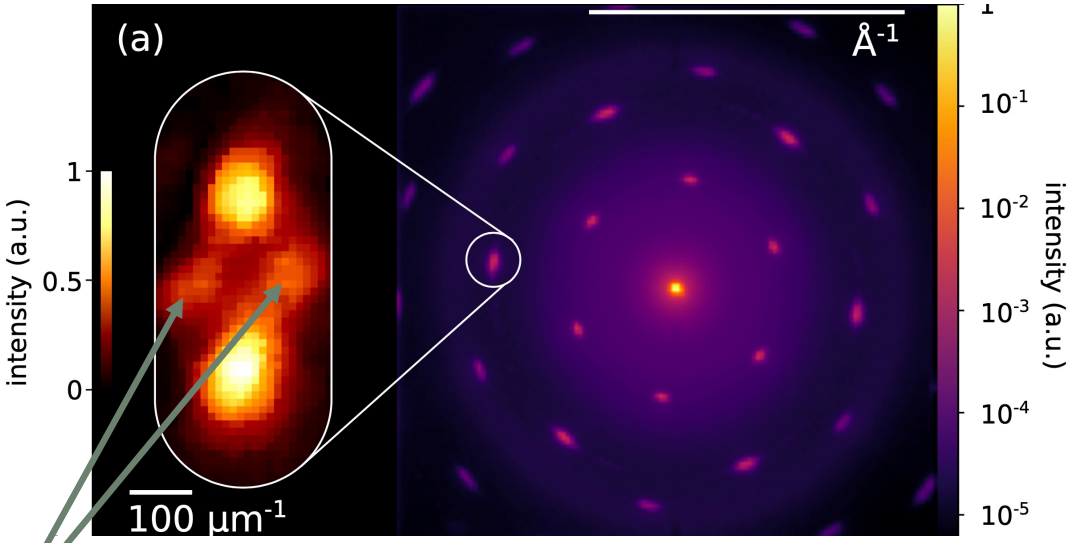
Can we make them robust?

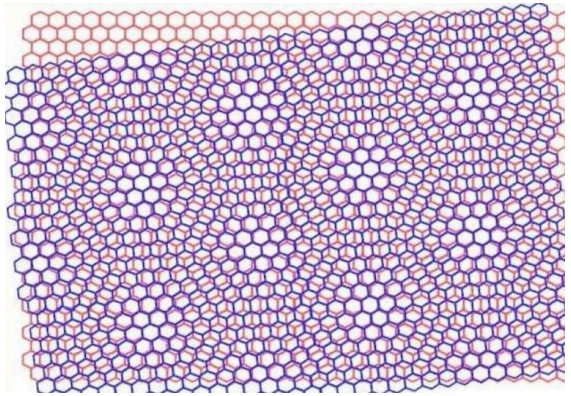
What about beam polarization?

Elena Echeverria, PD

Chad Pennington, grad std.

Single hexagonal atomic layers twist Moiré pattern





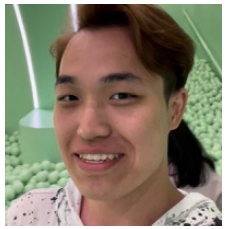
10 nm periodicity of the Moiré superlattice
First observation in an ultrafast setup

Large coherence length (10 nm) enabled by near-ideal beam emittance 0.7 nm
Arxiv: 2206.08404

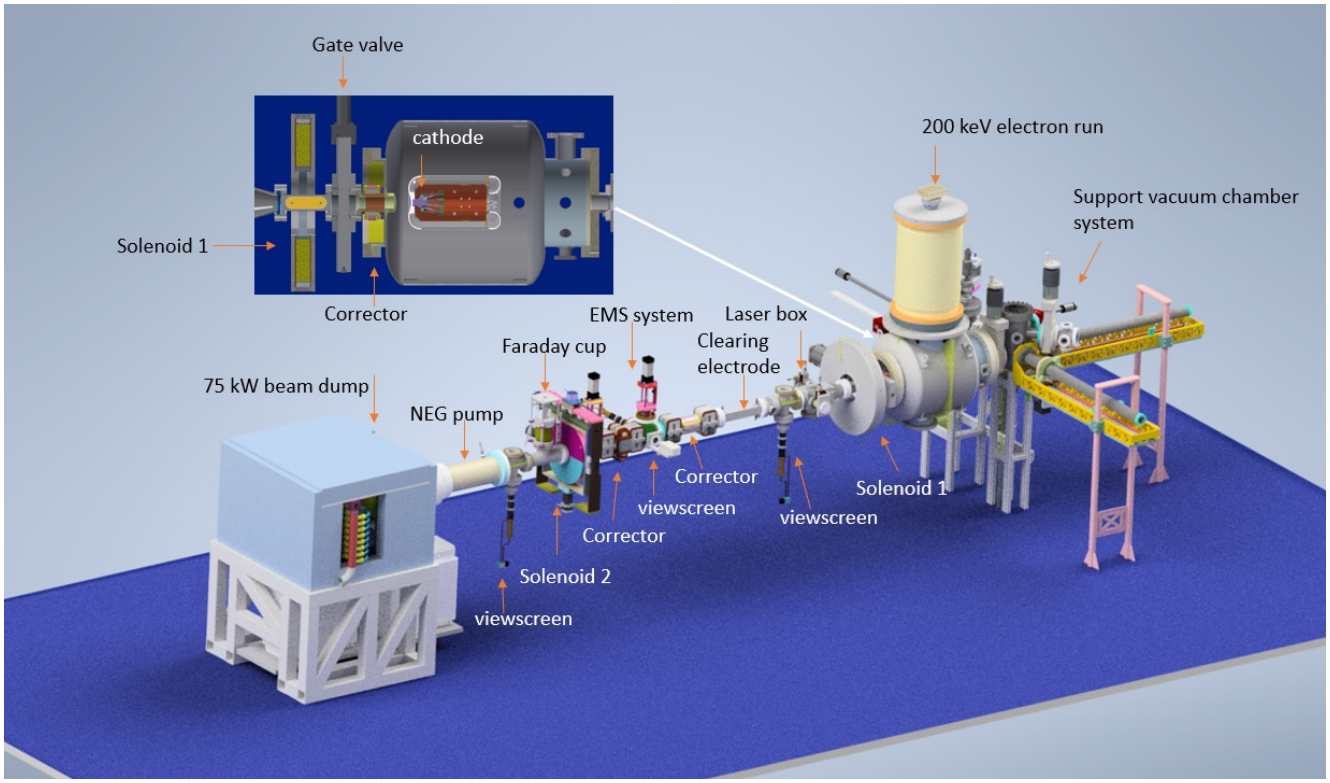
1kz rep rate; EMPAD high dynamic range detector

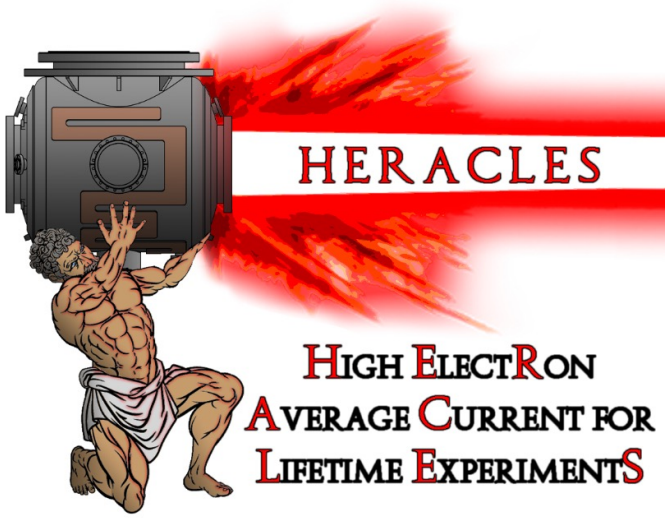

Michael Kaemingk grad std.


Chad Pennington grad std.


Charles Zhang grad std.

HERACLES beamline





Grad std Sam Levenson

- 200 keV electron gun at up to 10 mA average beam current
- Photocathode lifetime experiments:
  GaAs, alkali-antimonides, GaN
- Unique facility: only high current test gun on a university campus
- Upgrades in progress!
  New growth chamber for testing advanced GaAs activation coatings

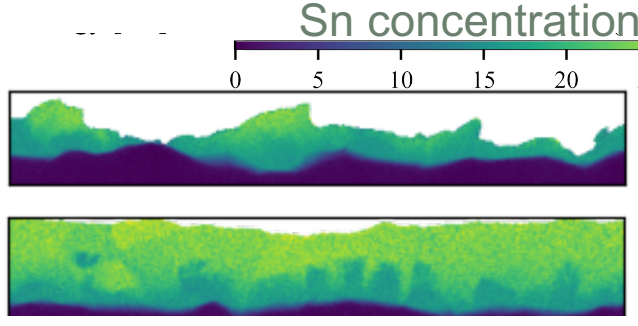
Recent SRF Highlights

- **Deeper explanation of N doping**
  normal-conducting states at the surface
  *Deyo et al, Phys Rev B **106**, 104502 (2022)*
- **First successful Nb_3Sn (2015)**
  Inspired FNAL and JLAB programs
- **Better Nb_3Sn Growth**
  via electrochemical synthesis
  Sun et al, arxiv:2302.02054
- **Nb-Zr: Better than Nb_3Sn?**
  Potential for high gradient, easy growth

  Ginsberg Landau: B_{sh} up to 350 mT
  →up to ~85 MV/m acc. Gradient

  T_c ~ 16 K, achieved

  Sitaraman et al, PRAppl(2023)
  Sun et al., Adv.Electr.Mat. (2023)



The BCS resistance is ½ that of vapor-diffused samples

Facilitated by Cornell's

outstanding electron microscope and nanofabrication facilities,

and **leading materials experts**

Cornell SRF: World-class research and training

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

- **Facilities**





Clean room, chemical facility, UHV furnaces, coating furnaces, cryogenic RF test facility…

- **Training**



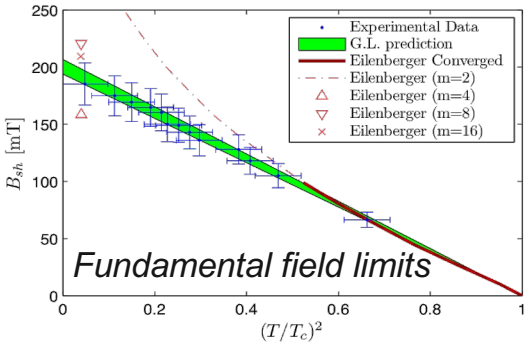


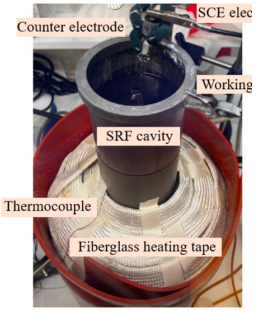
Current SRF grad students
Recent alums include SLAC SRF group leader and FNAL interim Assoc. Lab. Dir.

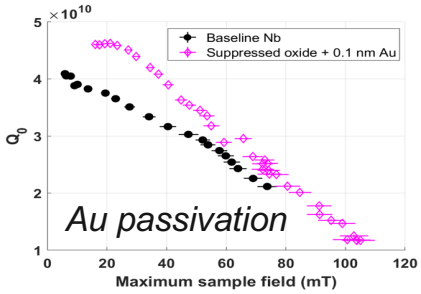
- **Impact** ***World record Q0*** *of an SRF cavity installed in an accelerator cryomodule;* ***world record accelerating gradient*** *in an SRF cavity;* ***world record continuous beam current*** *accelerated in an SRF injector;* ***first-ever alternative-material (Nb_3Sn) SRF cavities*** *that outperform traditional niobium cavities…*

Current SRF R&D Areas

- Fundamental superconductivity and material growth



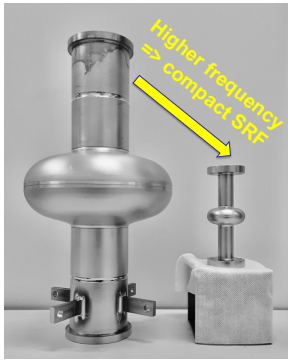




- SRF for the energy frontier

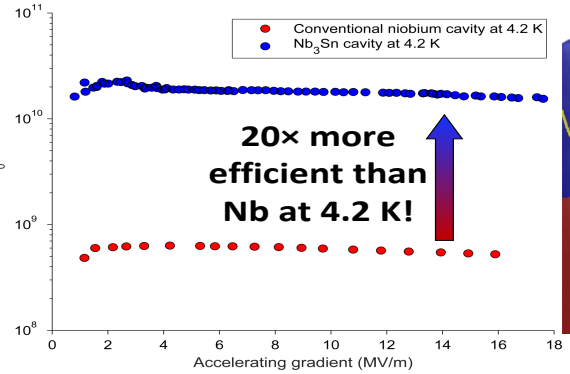
	Niobium	Nb-Zr
Predicted critical Temperature T_c	9.2 K	13 - 16 K
Predicted superheating field	220 mT	>300 mT ?

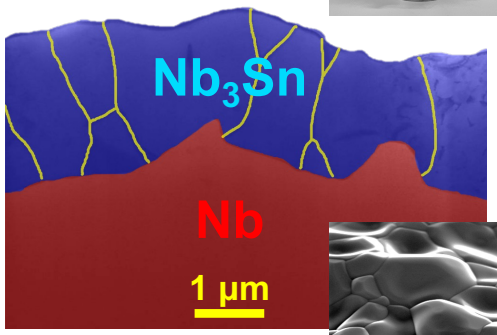
Nb-Zr alloy

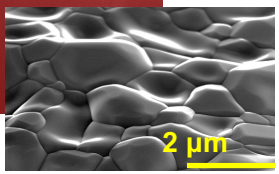


- SRF for sustainable science

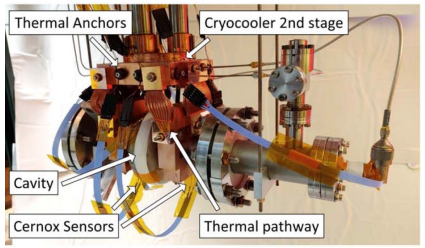
	Niobium	Nb_3Sn
Critical Temperature T_c	9 K	18 K
Q_0 at **4.2 K**	6 x 10^8	**6 x 10^{10}**
Q_0 at 2.0 K	3 x 10^{10}	>10^{11}

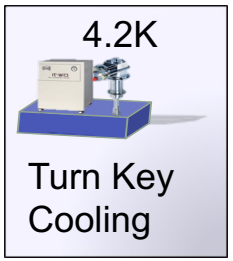




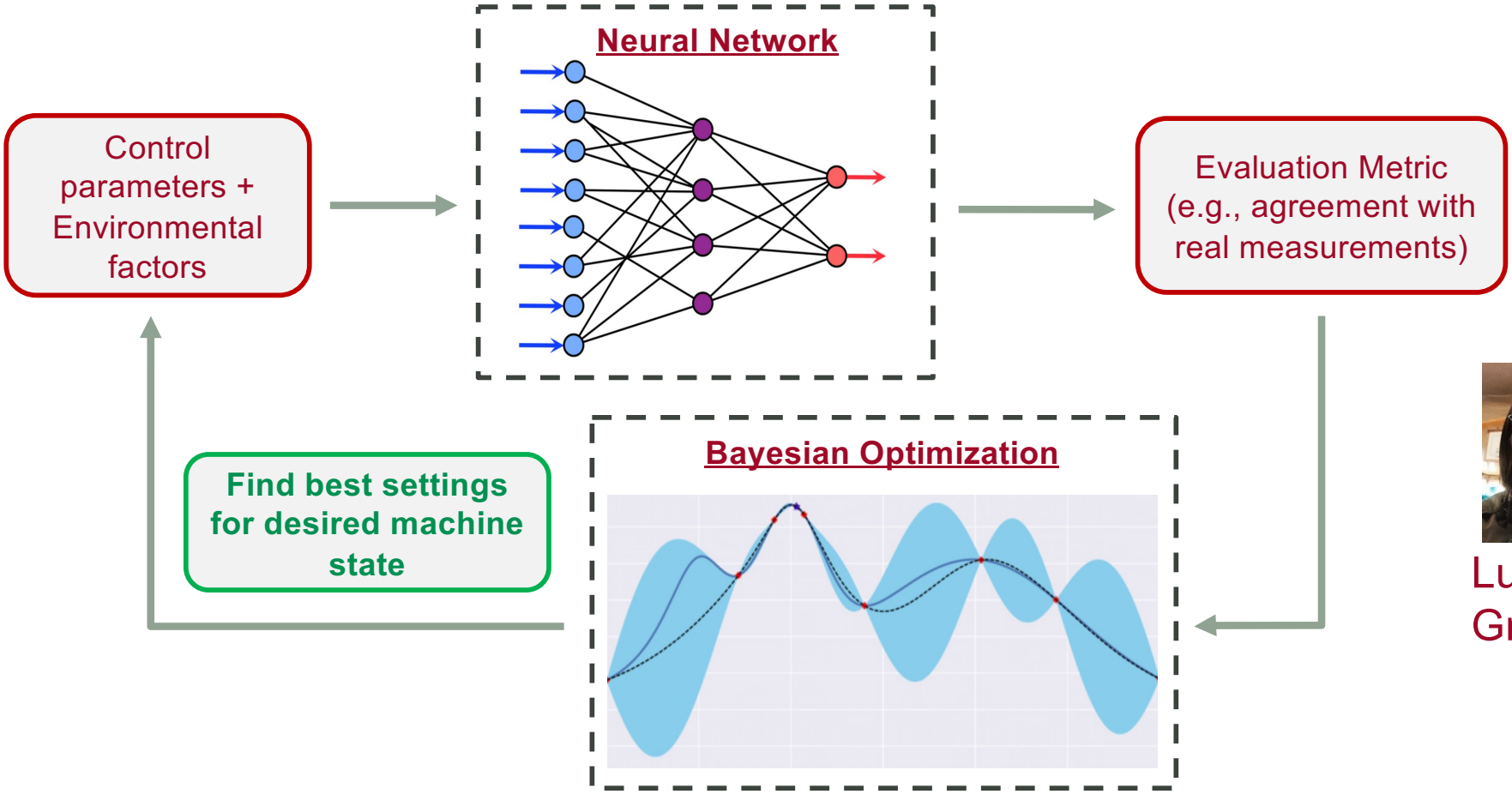


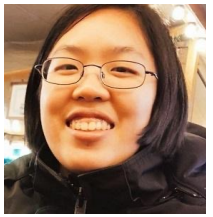
- SRF for medicine, environment, industry





ML optimization of the AGS booster and LEReC





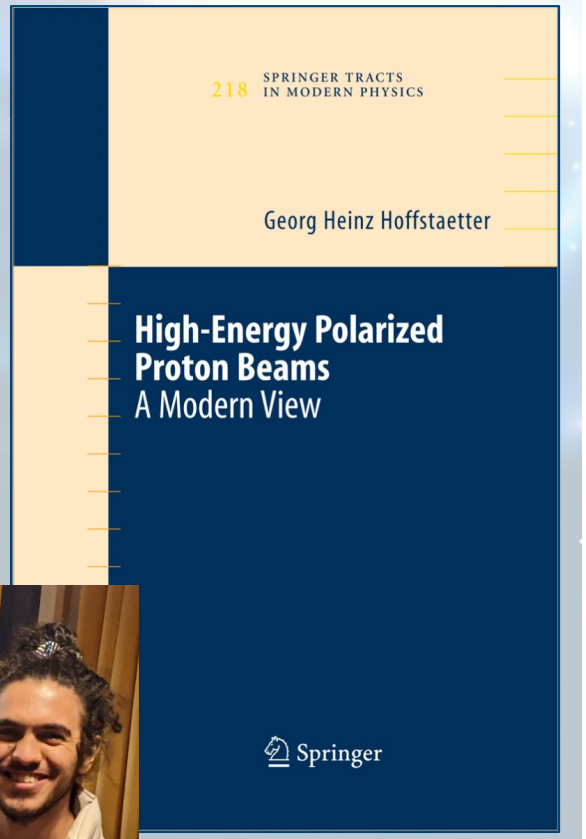
Lucy Lin
Grad std.

[1] W. Lin, et al., "Machine Learning Applications for Orbit and Optics Correction at the Alternating Gradient Synchrotron", in *Proc. IPAC'23*, Venice, Italy, May 2023.

[2] W. Lin, et al., "AGS Booster Beam-based Main Quadrupole Transfer Function Measurements", in *Proc. IPAC'23*, Venice, Italy, May 2023.

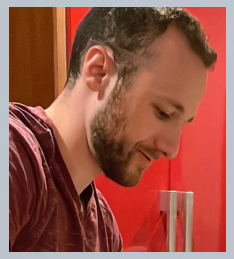
EIC Design in the ERL / EIC group

Beams are polarized to probe the spin structure of protons



Sample Graduate Student Projects:

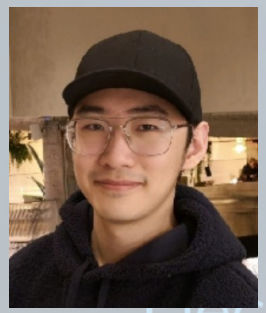
- Polarized electrons in the electron ring



Matt Signorelli

Eiad Hamwi

- Polarized Protons in RHIC and the hadron ring, implementation of polarization theory



Ningdong Wang

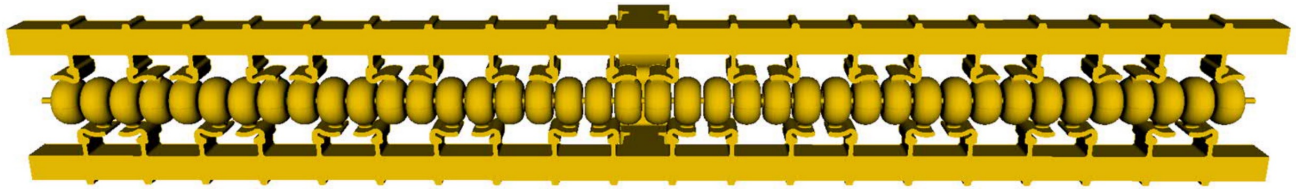
- Space charge beams in the ERL-cooler

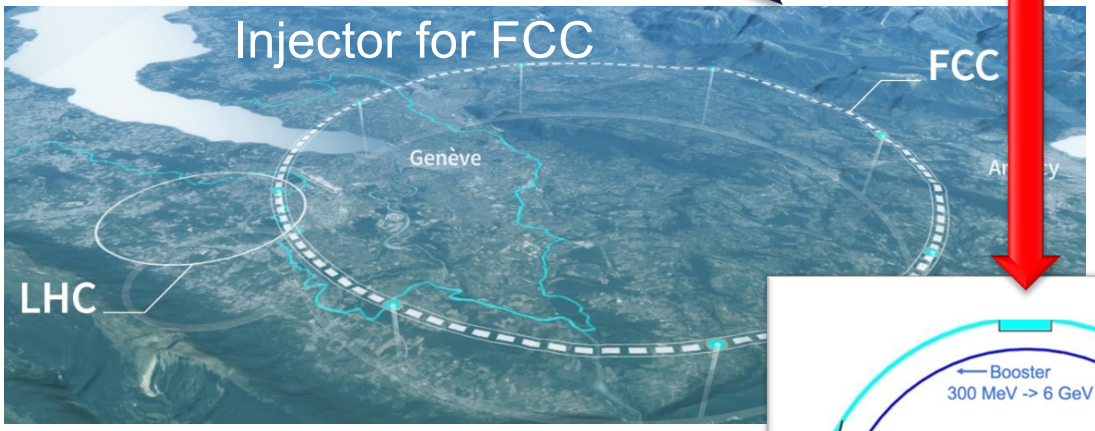
Jonathan Unger

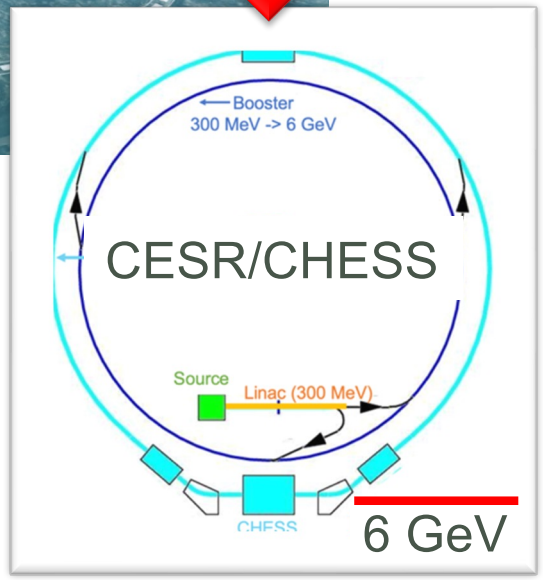
- Long-term stability in all EIC rings: Rapid Cycling Synchrotron, electron ring, ring-cooler

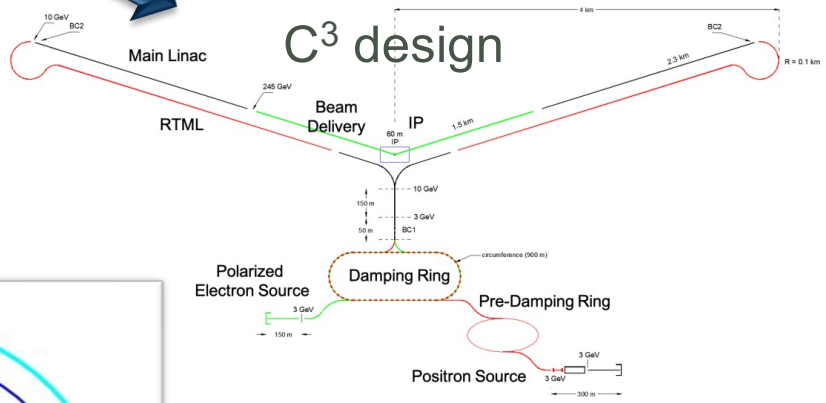
Cold Copper at Cornell

SLAC Design: 5.712 GHz, 120 MV/m @ 77 Kelvin









We envision hosting a 40-50 meter, 6 GeV linac demonstrator for these colliders.

Would revolutionize CESR injection and open new opportunities for x-ray science.

Technical Contributions

Damping Ring

- CESR TA
  Electron cloud, bunch-by-bunch diagnostics, low emittance tuning, intrabeam scattering
- ILC Damping Ring design
  Palmer, Rubin, Calvey, Ehrlichman, Shanks

First international TESLA Workshop
Cornell University, July 1990

Superconducting RF

- Reentrant cavity 52-59 MV/m
- High gradient, high Q R&D
- Vertical electropolishing
- Second-sound for quench location

Source

- High bunch charge photoinjector
  PRSTAB **18**, 083401 (2015)
- Polarized electrons
- Polarized positrons (helical undulator)
  A. Mikhailichenko, Cornell LEPP CBN 05-2 (2005); NIMA 610 (2009) 451–487

Committees

IDT Working Group 2
Rubin (DR/BDS/Dump)
Liepe (SRF)

ALCC
Liepe, Patterson

Tour stops

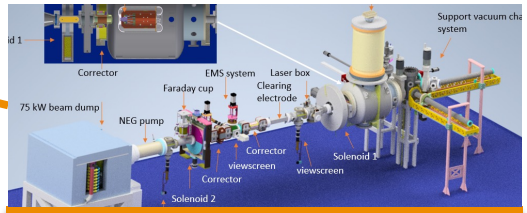
Physical Sciences Building
Particle and astrophysics

Newman Lab
Superconducting RF
accelerating cavities,
Photocathode lab,
Design and drafting,
Machine shop

Wilson Lab
CHESS, CESR, CBETA ,
Technical groups,
Business office

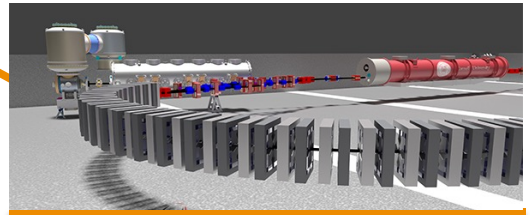
Annex
Undulator lab,
CHESS–U
magnet fab

SRF Lab



Electron source Lab

CESR



CBETA

Questions?