State of Accelerator R&D/GARD

*Update on P5 GARD subpanel recommendatio*ns

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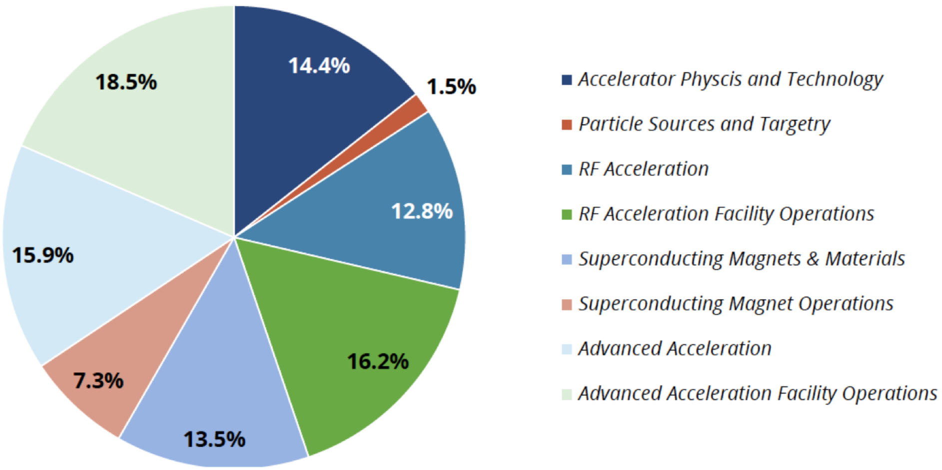
Given originally at HEPAP Meeting, November 22, 2019

P5 has provide physics drivers for accelerator research and development

	Intensity Frontier Accelerators	Hadron Colliders	e^+e^- Colliders
Current Efforts	PIP	LHC	
	PIP-II	HL-LHC	ILC
Next Steps	Multi-MW proton beam	Very high-energy proton-proton collider	1 TeV class energy upgrade of ILC *
Further Future Goals	Neutrino factory *	Higher-energy upgrade	Multi-TeV collider *

Table 1: Particle accelerators foreseen by the P5 strategic plan to carry out future accelerator-based particle physics research.

Mission: align GARD investments (2015 $68M) to these priorities



Recommendation scenarios

- Scenario A: GARD budget constant
  - Rebalancing of portfolio to meet P5
- Scenario B: Growth by 10-20%
  - Address deficiencies, deferred maintenance
- Scenario C: Aggressive R&D to embrace breakthroughs
  - Arrive at discovery machines

Ref.: https://science.osti.gov/~/media/hep/hepap/pdf/Reports/Accelerator_RD_Subpanel_Report.pdf

Recommendation 1. Fund generic high-power component R&D at a level necessary to carry out needed thermal shock studies and ionizing radiation damage studies on candidate materials that are not covered by project-directed research.

Comment: urgent need for intensity frontier, near term operations.

High Power Targetry R&D Status and Plans

RaDIATE

Multi-MW Targets & beam windows material R&D (FNAL, BNL)

- 2017-18: Multi-material RaDIATE irradiation run at BLIP, BNL
- 2015-18: Two thermal shock experiments at CERN's HiRadMat
- 2015-19: Examinations of spent targets & beam windows
- 2014-19: Grew RaDIATE to 14 institutions & over 70 participants
- 2015-19: Obtained relevant data for currently *in-use* materials:
  - Thermal Shock - up to $2x10^{15}$ p/cm^2/pulse, reaching multi-MW Nu target goal
  - Radiation Damage - $2x10^{21}$ integrated p/cm^2, multi-MW Nu target goal of $1x10^{23}$ p/cm^2

Current/Future Plans

- BLIP irradiation run in 2021 for *new* materials
  - Confirm operating parameters for LBNF target materials
  - Explore promising new targetry candidate materials (e.g. high entropy alloys)
- Ion irradiations for radiation damage studies to high-dose
  - Correlate to high-energy proton results and irradiate to $1x10^{23}$ p/cm^2
- Develop alternative thermal shock and radiation damage methods
  - Reduce cost and duration of R&D cycles
- Continue opportunities for students (3 students and 2 post-docs supported)

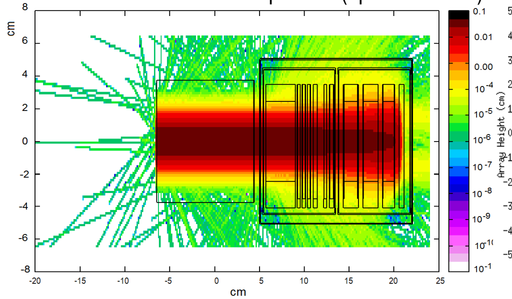
Benefits to multi-MW targets (e.g. LBNF):

- alloy/grade choice
- cooling system design
- tolerable beam intensities
- expected lifetimes

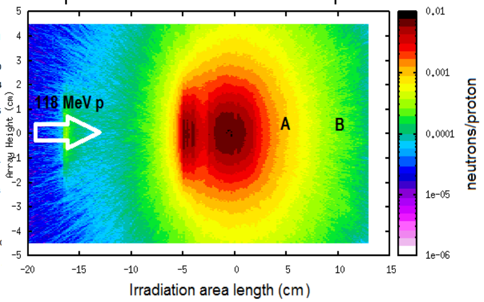
In-beam thermal shock testing of *BLIP irradiated* Be and Ti alloys at CERN

BLIP ⇨ NSLS-II: Opportunities for Irradiation Testing & Analysis

Irradiation with BNL Linac protons (up to 200 MeV)

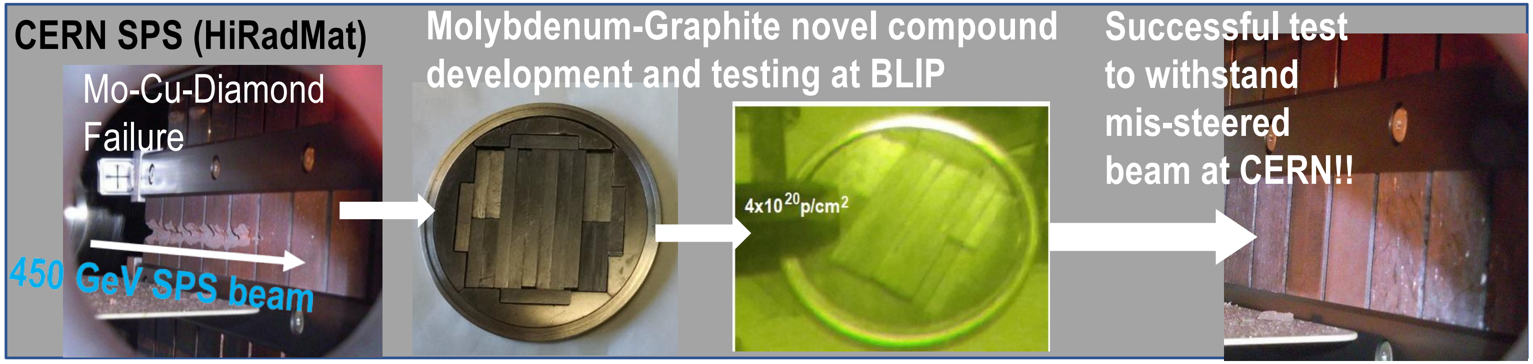


w/Spallation Neutron Irradiation Options

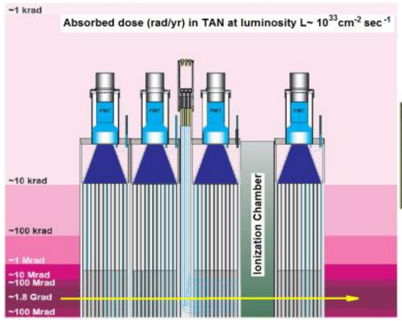


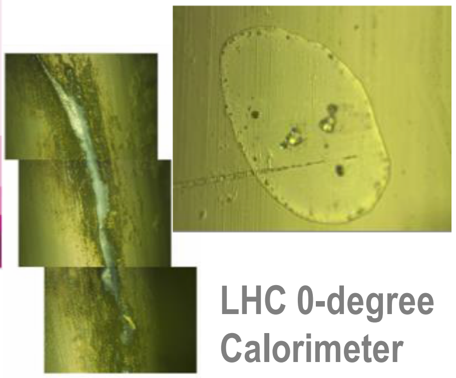
BNL capabilities BLIP + NSLS-II

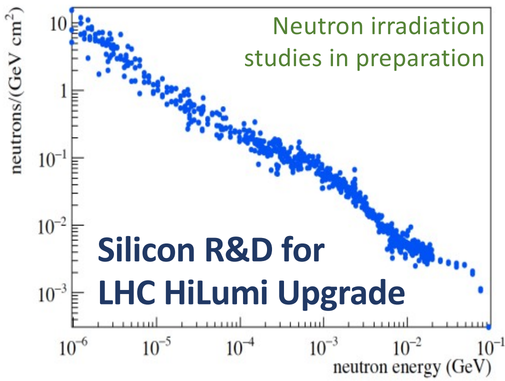
- Proton beam energy up to 200 MeV; 6.75 Hz, 165 μA
- Remote handling capabilities in place
- On-site Analysis capabilities at NSLS-II
  - Validated irradiated materials handling



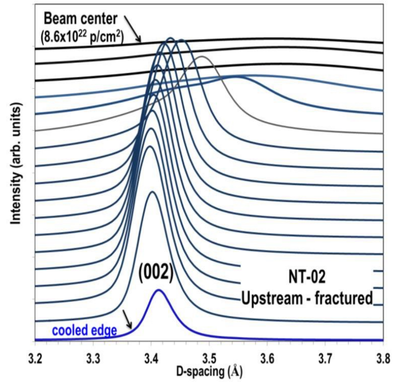
Detector Damage Studies

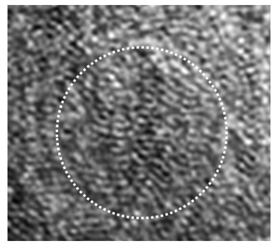






Diagnosis of NUMI Target Failure – NSLS-II



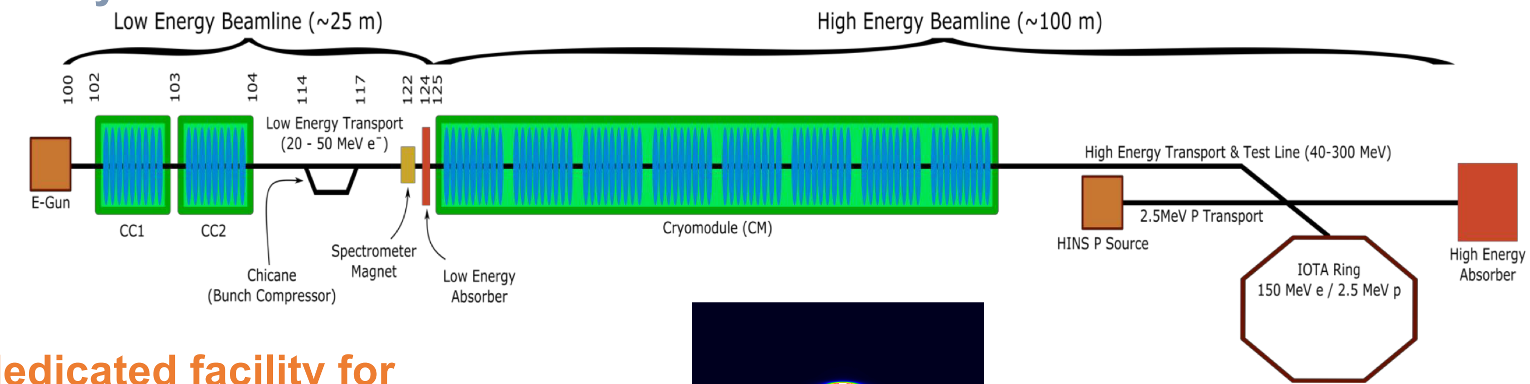


Recommendation 2. Construct the IOTA ring, and conduct experimental studies of high-current beam dynamics in integrable non-linear focusing systems.

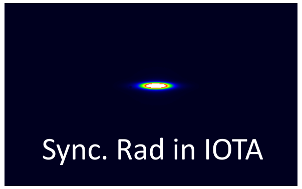
Comment: Open promising new front in intensity frontier physics machines.

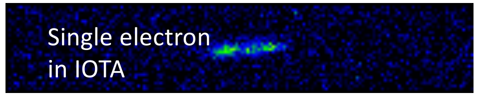
IOTA/FAST Facility: a center for Accelerar and Beam Physics

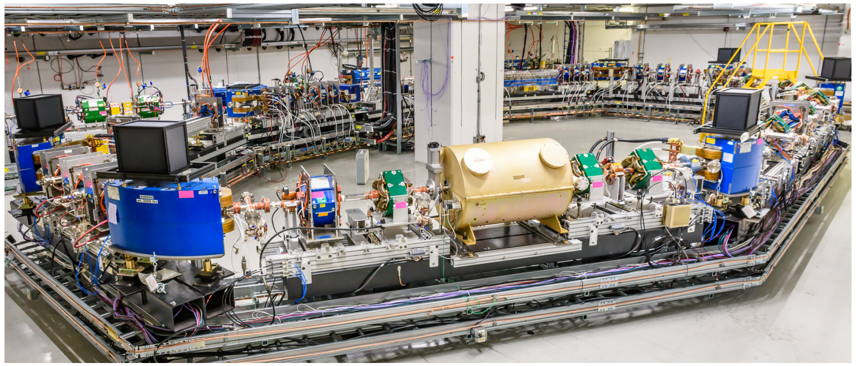
- **IOTA/FAST establishes a unique capability at FNAL to address frontier topics in Accelerator and Beam Physics**



- **The only dedicated facility for intensity-frontier accelerator R&D**
- ~30 Collaborating institutions
  - Student training with Chicago, NIU
- National Lab Partnerships: ANL, BNL, LANL, LBNL, ORNL, SLAC, TJNAF
- Opportunities for R&D with cross-office benefit in DOE/SC
  - **Nonlinear Integrable Optics**
  - Optical Stochastic Cooling
  - Space-charge compensation
  - Suppression of coherent instabilities







10/16/18 beam circulation at 100 MeV
Jan – Mar, 2019 – First Research Run

Recommendation 3. Support a collaborative framework among laboratories and universities that assures sufficient support in beam simulations and in beam instrumentation to address beam and particle stability including strong space charge forces.

"Virtual Accelerators" to reduce the cost of development, commissioning and operation of future accelerators

Vision

Fast – *runs in seconds to minutes*

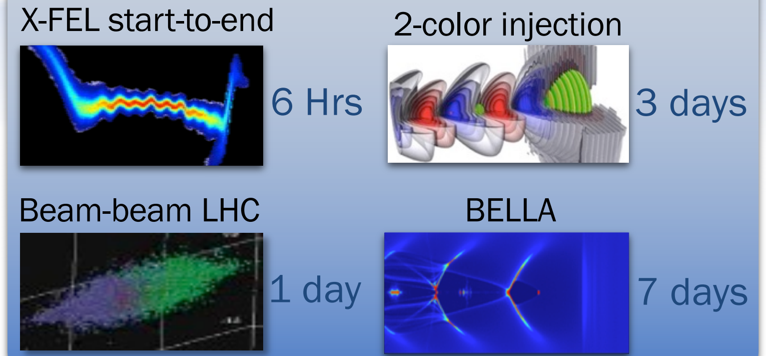
Hi-Fi – *full & accurate physics*

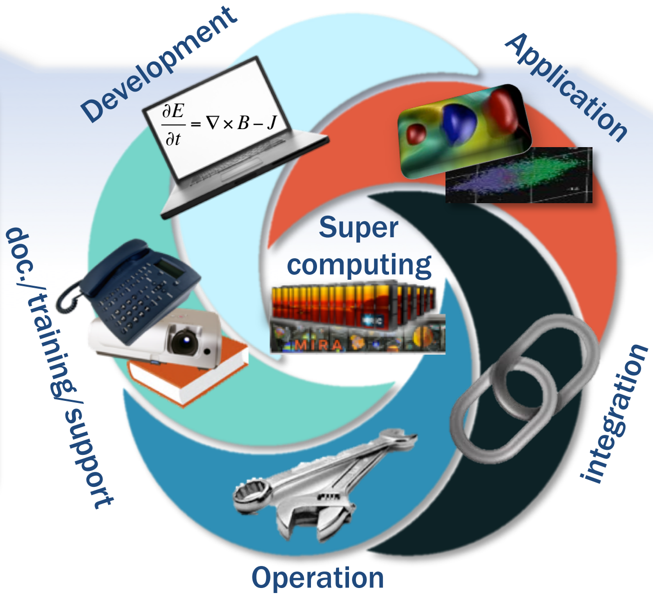
Link – *integrated ecosystem*

Real-time virtual prototyping of entire accelerators

with intuitive interface, dissemination & user support.

Today simulations still take too long





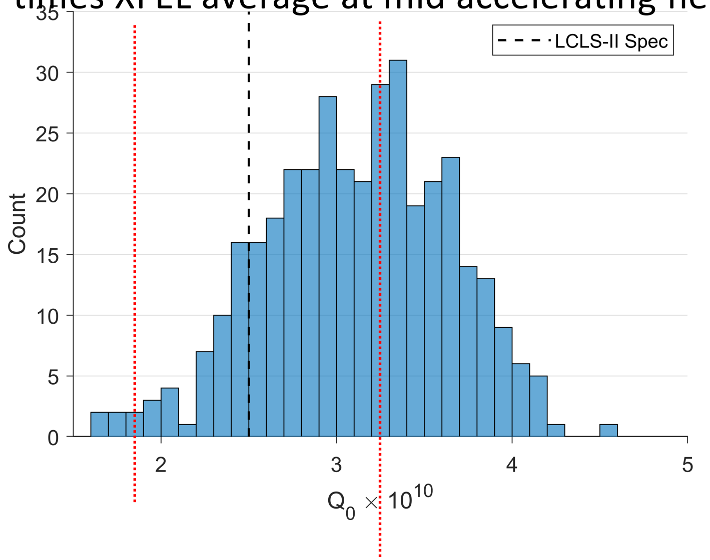
- ***LBNL-initiated Consortium for Advanced Modeling of Particle Accelerators (CAMPA)*** with SLAC, then FNAL, UCLA
- Top tiers ***NERSC Exascale Application program*** (NESAP)
- ***DOE-ECP*** application project ***"Exascale Modeling of Plasma Accelerators"***

Recommendation 4. Direct appropriate investment in superconducting RF R&D in order to inform the selection of the acceleration technology for the multi-MW proton beam at Fermilab.

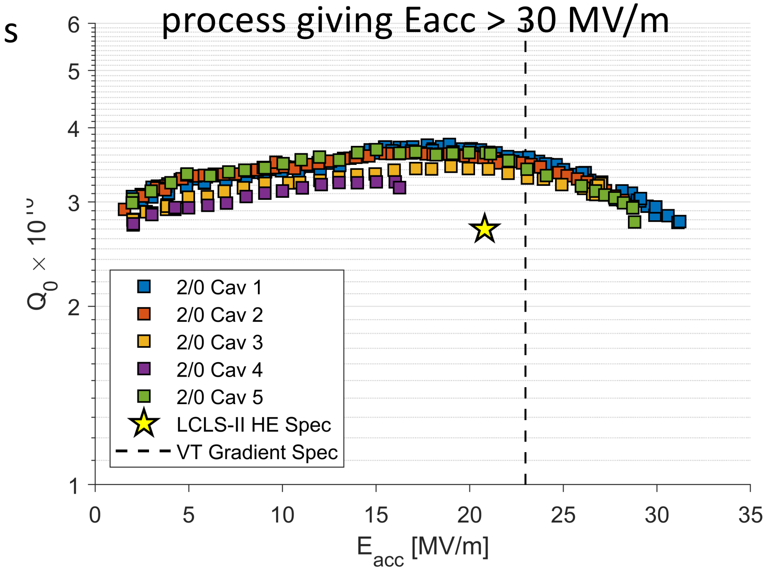
High *Q* advancements with N-doping

- Immediate impact on LCLS-II and LCLS-II HE**. *Q* at mid field > 2x previous state of the art**
- Production of >300 N-doped cavities shows that high Q process pioneered by Fermilab is now industrialized successfully: Q ~3E10 at mid field, average gradient ~ 24 MV/m
- Pushing 9-cell performance **from 24 MV/m to >30 MV/m** with Q at mid field ~3E10 at 2K enabling LCLS-II HE

Nine cell Q results for LCLS-II production, >2 times XFEL average at mid accelerating fields



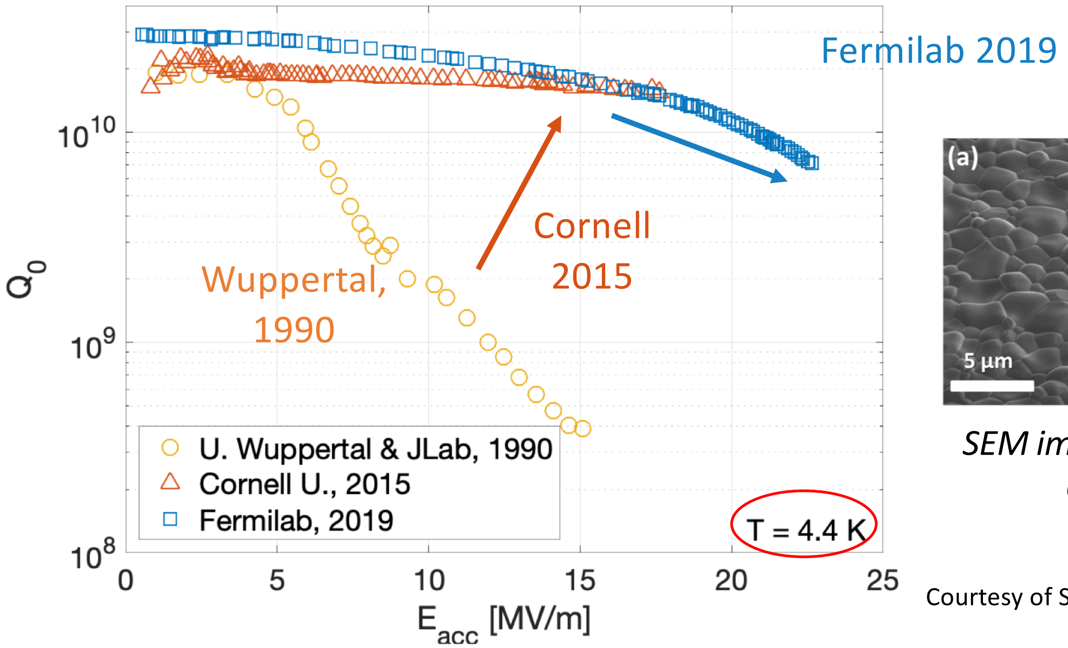
Nine cell results with new doping process giving Eacc > 30 MV/m

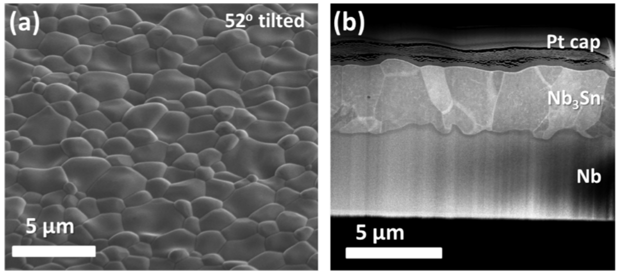


Courtesy of A. Grassellino, FNAL and D. Gonnella, SLAC

Progress in Nb_3Sn SRF performance

- Nb_3Sn coated cavities can operate at 4.4 K
  - to reduce cost of cryogenics, enable compact accelerator applications
  - Theory predicts **E_{acc} up to 90 MV/m**
- Progress: world record gradient of 24 MV/m at Fermilab





SEM images of Nb_3Sn film coated on Nb: a) surface, b) cross section

Courtesy of S. Posen, FNAL

Recommendation 5. Participate in international design studies for a very high-energy proton-proton collider in order to realize this Next Step in hadron collider facilities for exploration of the Energy Frontier. Vigorously pursue major cost reductions by investing in magnet development and in the most promising superconducting materials, targeting potential breakthroughs in cost-performance.

Comment: Participation in FCC studies strongly encouraged. Issues on compatibility of host nation have arisen; CERN leadership mitigates these.

Recommendation 5a. Support accelerator design and simulation activities that guide and are informed by the superconducting magnet R&D program for a very high-energy proton-proton collider.

Recommendation 5b. Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies for a very high-energy proton-proton collider. The over-arching goal is a large improvement in cost-performance.

Recommendation 5c. Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider.

Recommendation 5d. Establish and execute a high-temperature superconducting (HTS) material and magnet development plan with appropriate milestones to demonstrate the feasibility of cost-effective accelerator magnets using HTS.

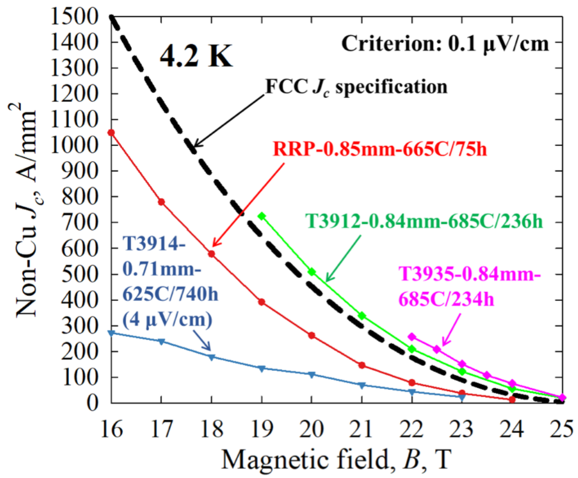
Recommendation 5e. Engage industry and manufacturing engineering disciplines to explore techniques to both decrease the touch labor and increase the overall reliability of next-generation superconducting accelerator magnets.

Recommendation 5f. Significantly increase funding for superconducting accelerator magnet R&D in order to support aggressive development of new conductor and magnet technologies.

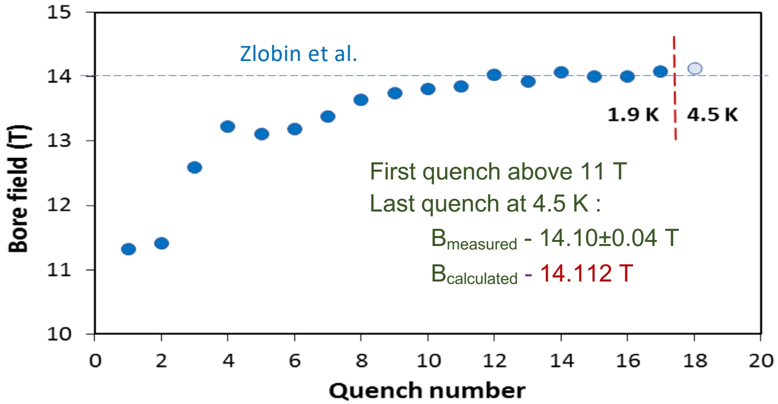
Comment: **Committee has been very specific** concerning strategies going forward in superconducting magnet research.

SC high-field magnet & conductor R&D

- LBNL is lead-lab for the multi-lab program: LBNL, FNAL, BNL, ASC/NHMFL
- **Artificial pinning center (APC) work**
  - Nb_3Sn wires, record J_c, meet/exceed FCC specs (**X. Xu,** *et al.*)
  - Conductor is expected to be a "work horse" for future pp colliders



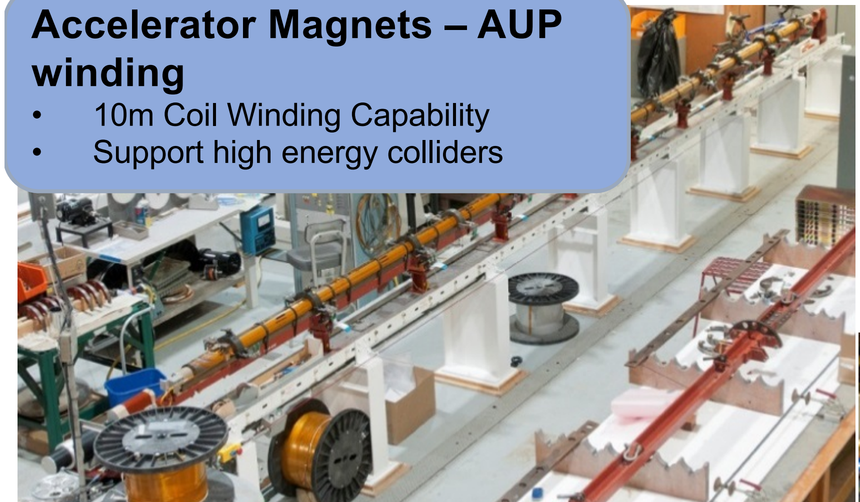
- In June 2019 the FNAL SC Magnet R&D group, tested a **new accelerator-type dipole demonstrator, based on SC Nb_3Sn**
  - Magnet produced a world record field of 14.1 T (at 4.5 K) for an accelerator type dipole (limited by mechanical pre-stress)
  - Demonstrated re-assembly with increased pre-stress to allow reaching the design field of **15 T**



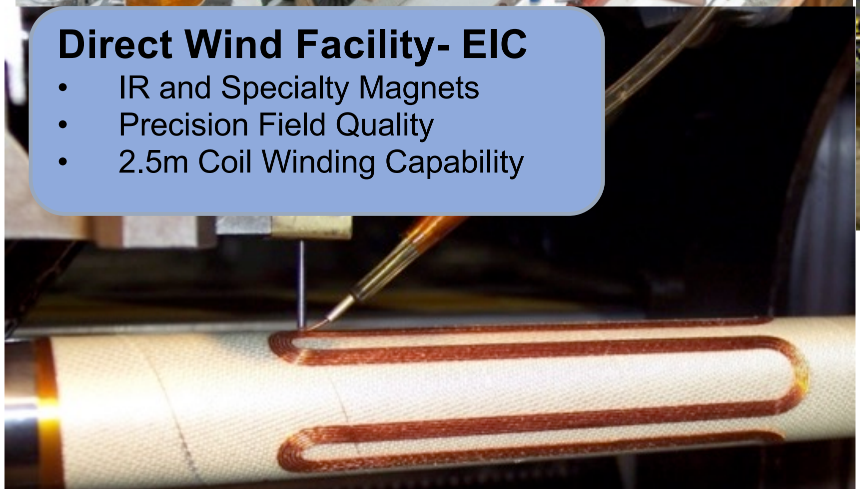
BNL Superconducting Magnet Research: Synergies with EIC

- **Expertise in superconducting magnet technology, development, manufacturing and testing**

Accelerator Magnets – AUP winding
- 10m Coil Winding Capability
- Support high energy colliders

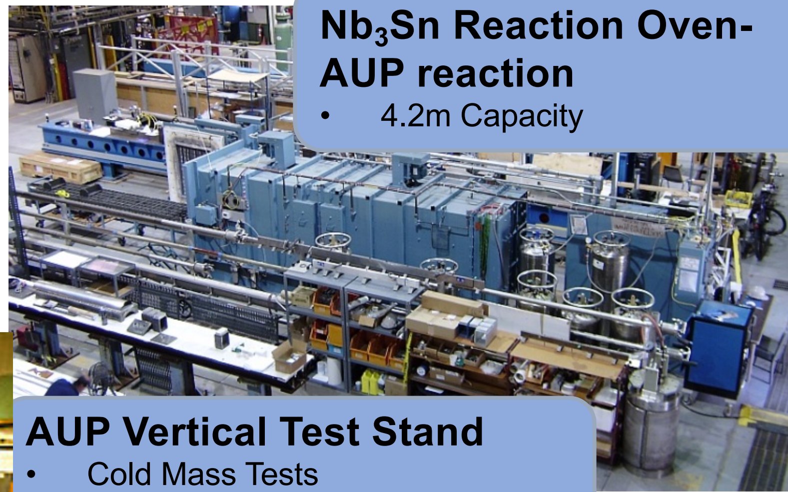


Direct Wind Facility- EIC
- IR and Specialty Magnets
- Precision Field Quality
- 2.5m Coil Winding Capability

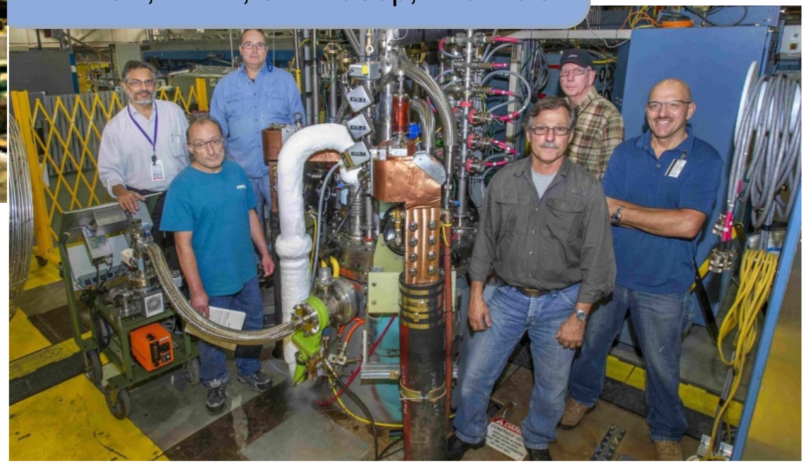


FES INFUSE Program
HTS fusion cable design and testing with industry (Commonwealth Fusion)

Nb_3Sn Reaction Oven- AUP reaction
- 4.2m Capacity



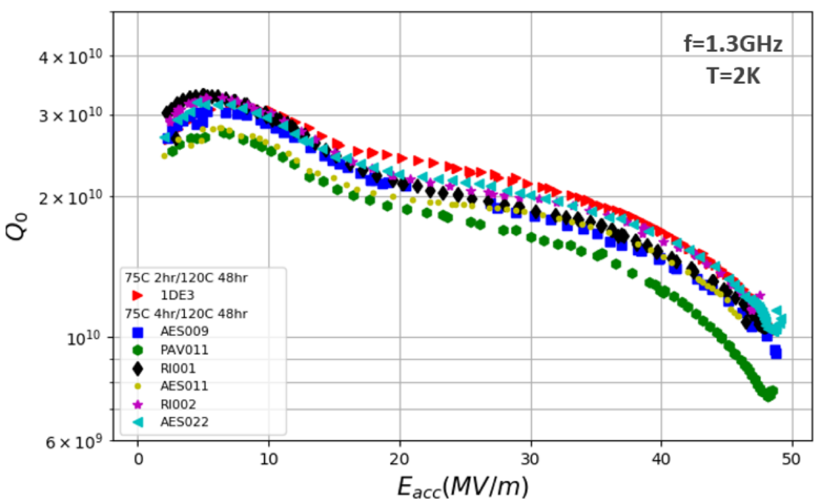
AUP Vertical Test Stand
- Cold Mass Tests
- 1.9K, 22KA, 6.1m deep, 71cm dia.

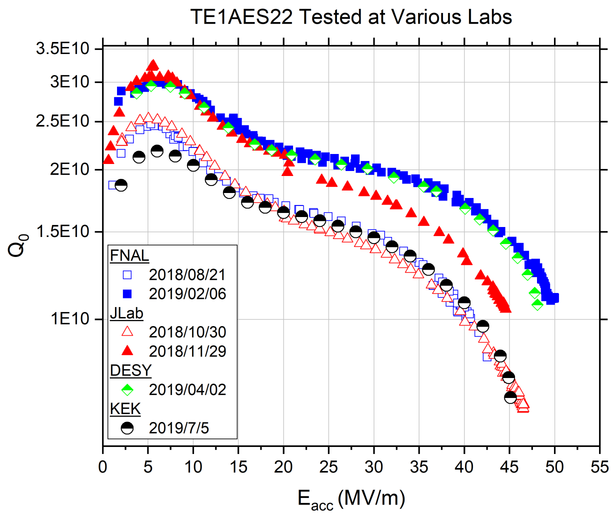


Recommendation 6. Increase funding for development of superconducting RF (SRF) technology with the goal to significantly reduce the cost of a ~1 TeV energy upgrade of the ILC. Strive to achieve 80 MV/m accelerating gradients with new SRF materials on the 10-year timescale.

FNAL SRF results: very high E_{acc} up 50 MV/m

- Advancements in low temperature bake and electropolishing produce **accelerating fields never previously achieved**
  - Repeated across collaborating labs
  - Complementary NSF CBB-funded work at Cornell





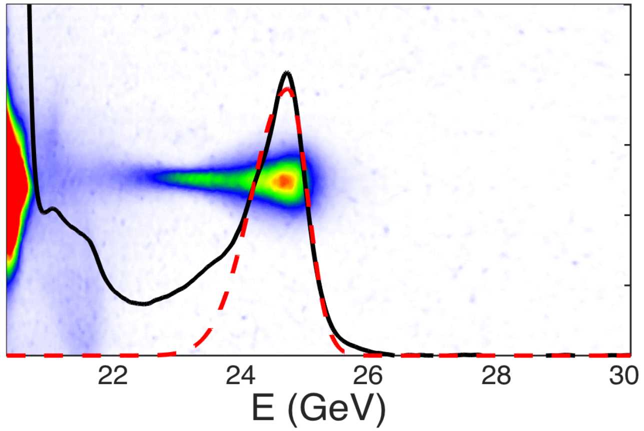
Courtesy of A. Grassellino, FNAL

Recommendation 7. Vigorously pursue particle-driven plasma wakefield acceleration of positrons at FACET in the time remaining for the operation of the facility. Between the closing of FACET and the operation of a follow-on facility, preserve the momentum of particle-driven wakefield acceleration research using other facilities.

Multi-GeV Acceleration of Positrons in Plasma Wakefields at FACET

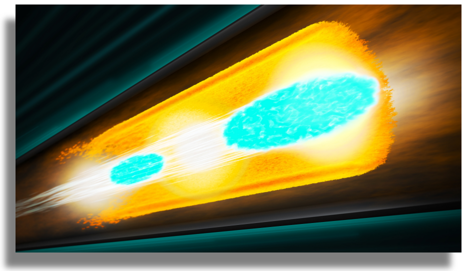
Non-linear wakes (4 GeV energy gain)

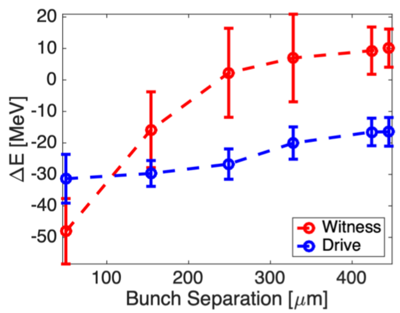
- New self-loaded regime of PWFA



Corde et al., ***Nature*** August 2015

Hollow Channel Plasma
Wakefield Acceleration

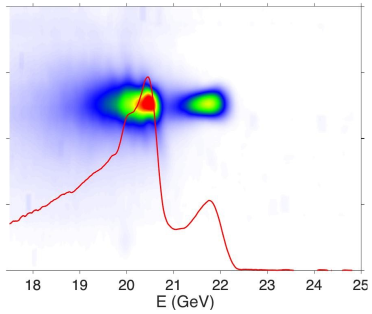


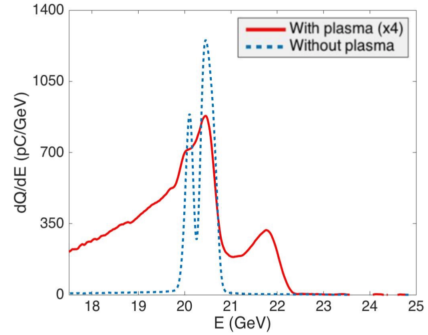


Gessner et al., ***Nature* Communications** 2016
Lindstrom et al., ***Phys. Rev. Lett.*** 2018

Quasi-linear Wakefield Acceleration

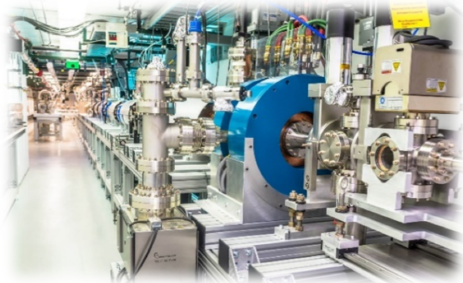
- > 1 GeV energy gain

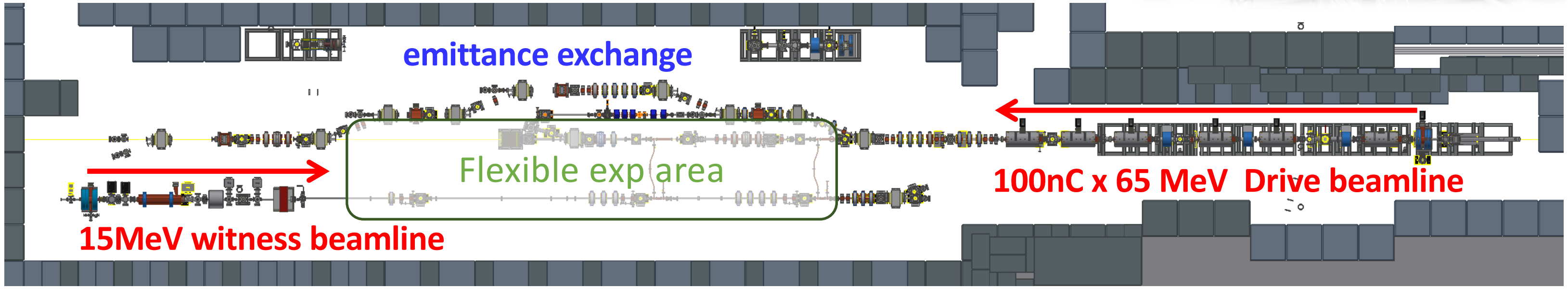




Doche et al., ***Scientific Reports*** 2017

Argonne Wakefield Accelerator emerges as user facility





AAC
- SWFA (core program)
  - Low cost (High gradient & efficiency)
  - High quality acceleration with Staging
  - Integration of advanced concepts
- PWFA (Newly started synergetic work)
  - UCLA: transformer ratio, plasma lens

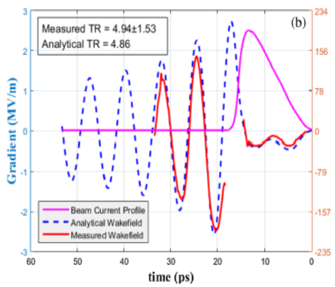
ABP
- 6D phase space manipulation
- Single shot or high resolution diagnostics (beam instrumentation)

Strong collaboration network

Industry

Universities

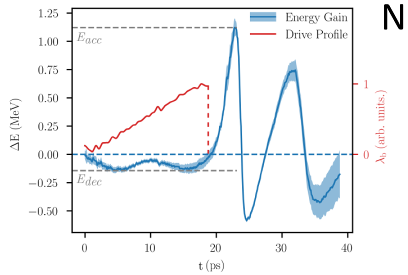
National Labs



Transformer ratio improvement

R= 3 → 5

(record)



New PWFA work

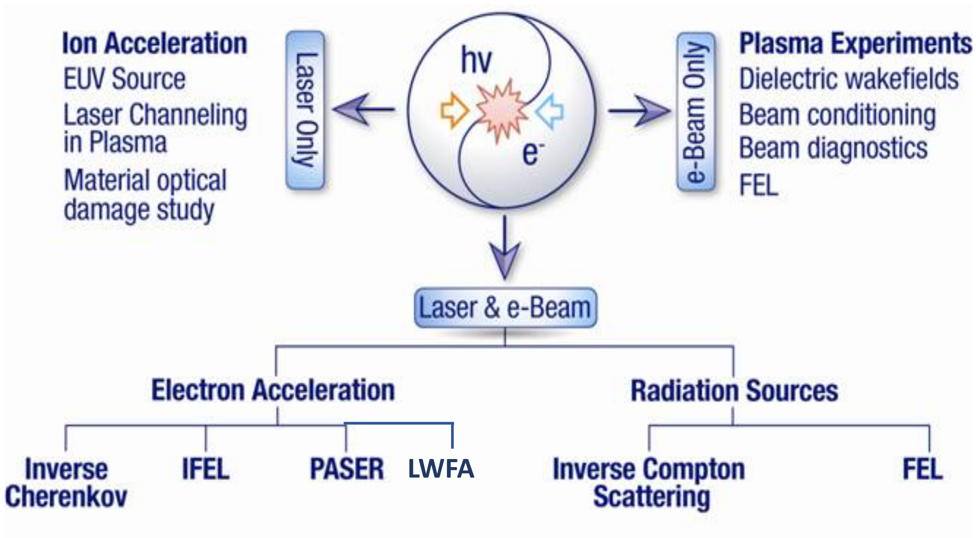
R= 1→7

(record)

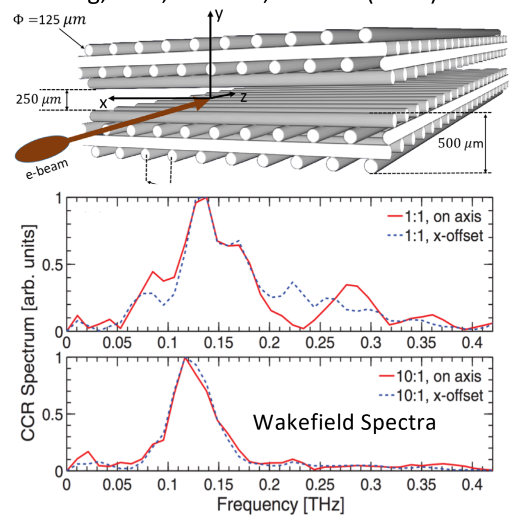
Brookhaven Accelerator Test Facility

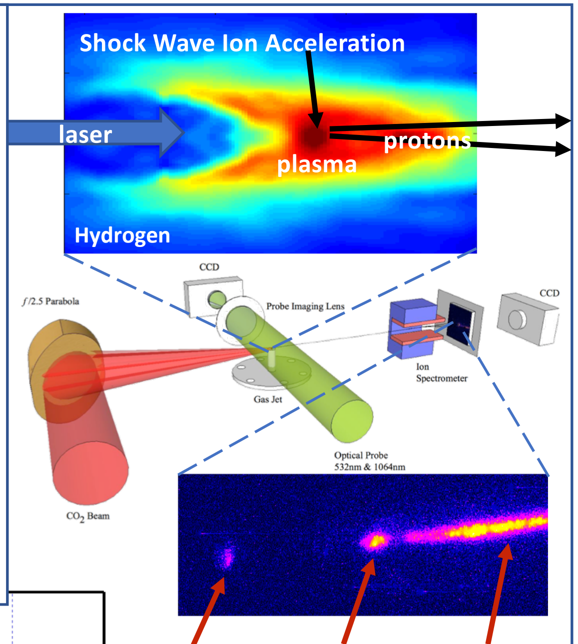
Accelerator Stewardship Lab

- Supports User-Driven Research Spanning:
  - ***Novel particle acceleration techniques***
  - **High-brightness radiation sources**
  - ***Beam manipulation and beam instrumentation***
  - **Ion generation and acceleration**
  - **Ultrafast Electron Diffraction/Microscopy (UED/M)**
- Facility provides ~2500 user hours/year
  - **~20% supports GARD-funded efforts**
  - **Recent advances in CO_2 Laser Performance enable new studies of plasmas and acceleration processes**



High Gradient Dielectric Wakefield Studies
P. Hoang, et al, PRL **120**, 164801 (2018)

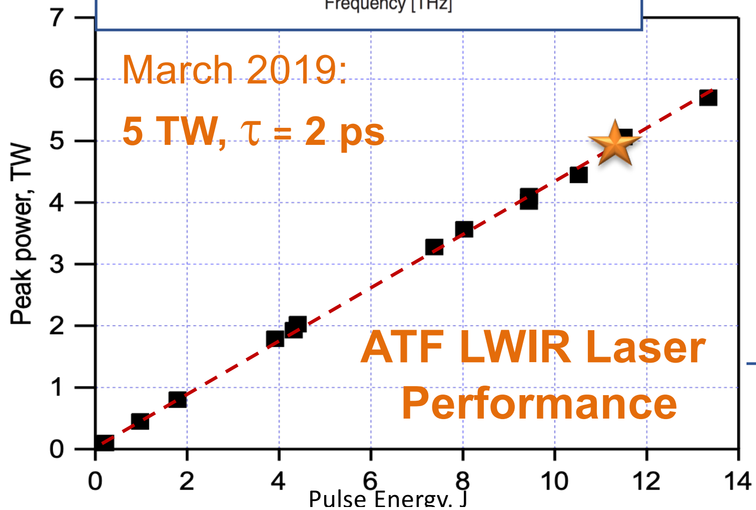




AE-66: NRL & ICL MURI Grant

Monoenergetic protons from supersonic H_2 jet via shock wave acceleration

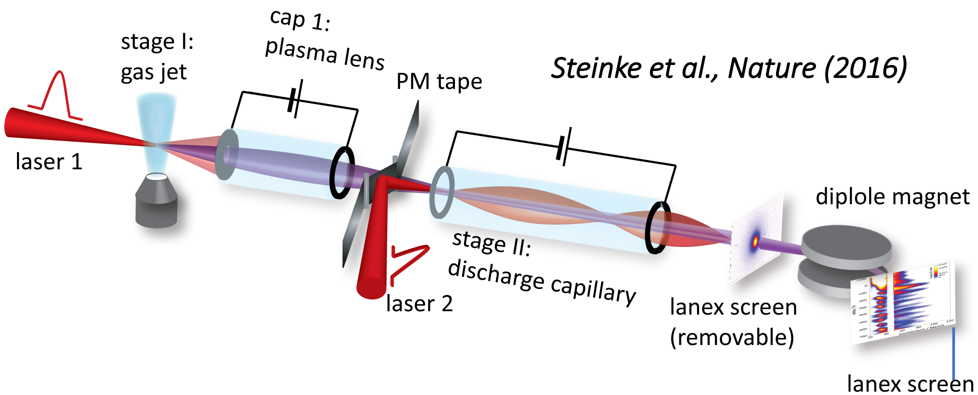
PRL **115**, 9 (2015)



Recommendation 8. Continue to support laser-driven plasma wakefield acceleration experiments on BELLA at the current level.

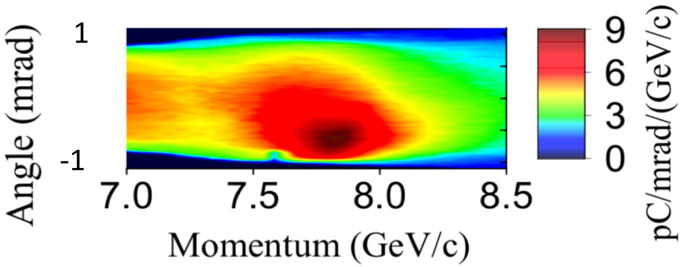
LBNL BELLA Center leading R&D center for Laser Wakefield Acceleration

- BELLA Center is the world-leading research center for LWFA R&D:
  - First demonstration of staging of laser-plasma accelerators (2016)
  - Achieved world-record 8 GeV demonstrated in 20 cm plasma channel (2019)
  - Developed new beam transport, high quality beams, & high power laser methods
  - Spin-offs to LPA-based FEL, other radiation sources



Steinke et al., Nature (2016)

BELLA @ 0.85PW with laser-heated capillary



Gonsalves et al., PRL (2019)

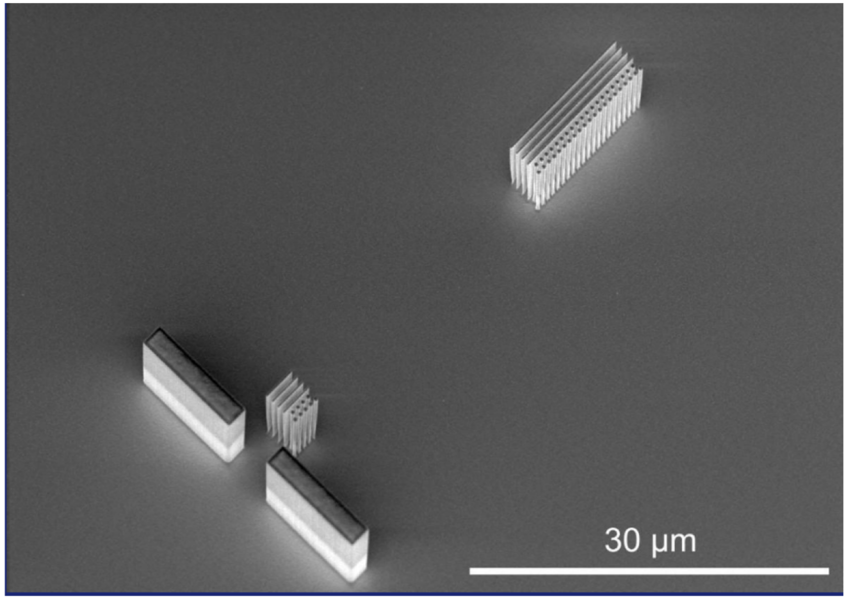
- International competition increasing – *new initiatives (kBELLA-like) progressing overseas*

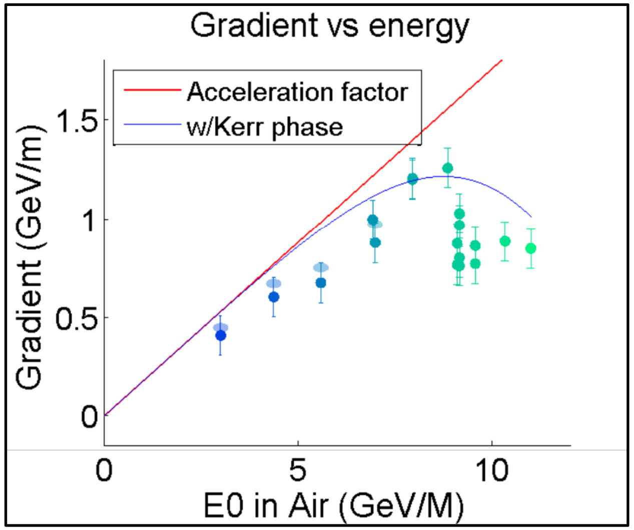
Recommendation 9. Reduce funding for direct laser acceleration research activities.

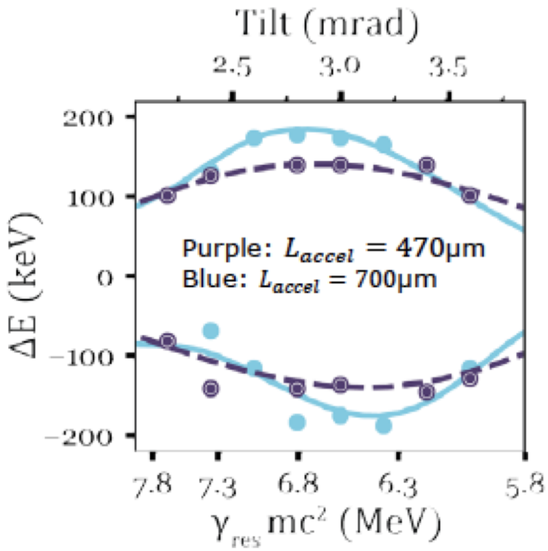
Activity successfully spun-off to ACHIP (Moore Foundation program)

- Residual GARD funding for SLAC participation in ramp-down
- Up to GV/m fields
- Application outside HEP (*e.g.* medicine)

D.Cesar et. al. Opt.Exp. 2018

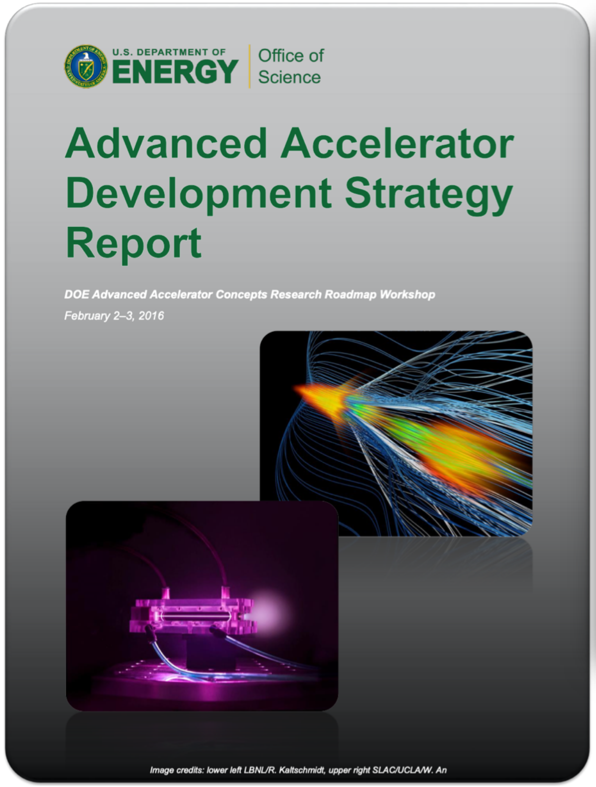


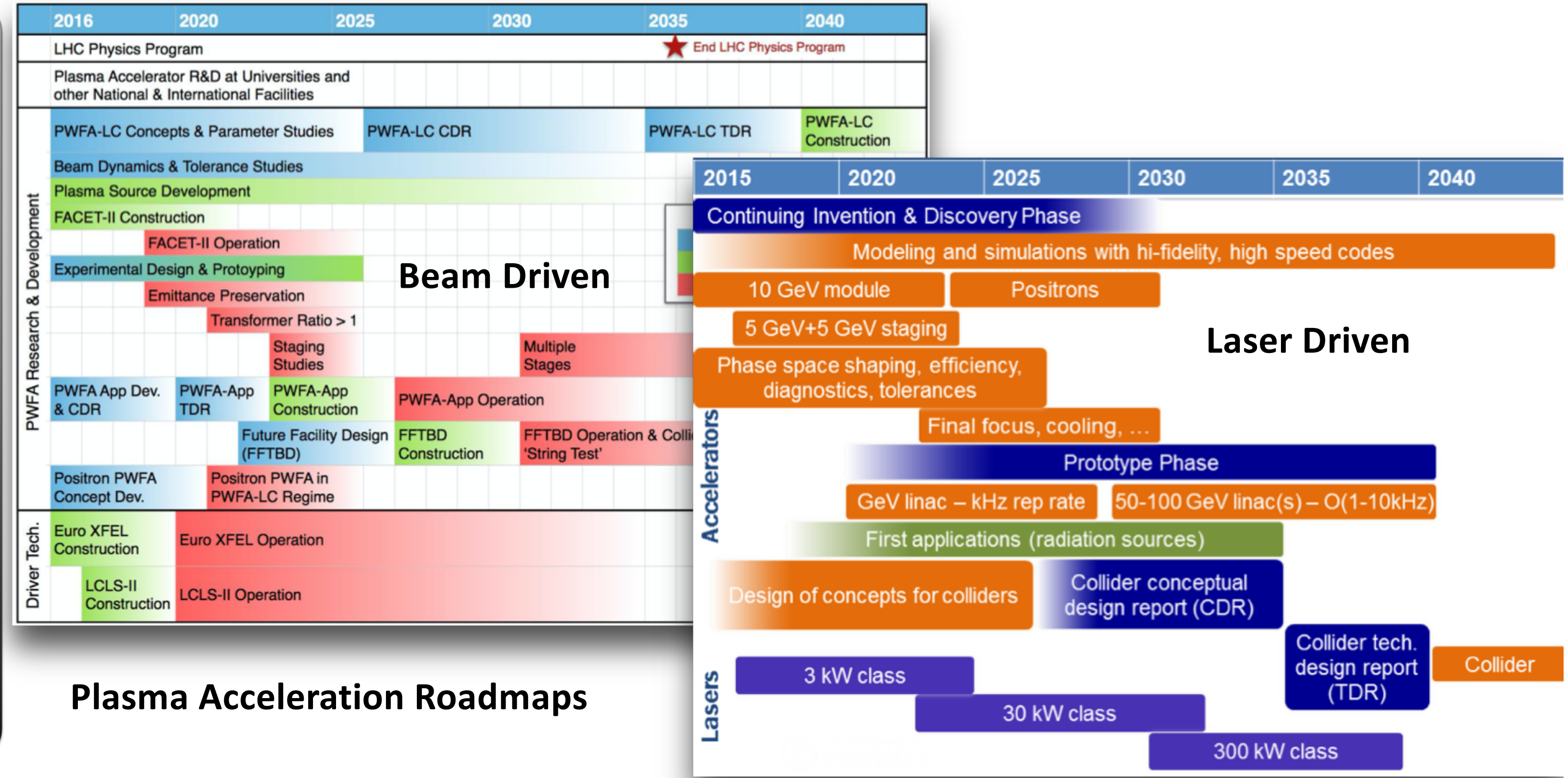




Recommendation 10. Convene the university and laboratory proponents of advanced acceleration concepts to develop R&D roadmaps with a series of milestones and common down-selection criteria towards the goal of constructing a multi-TeV e^+e^- collider.

Advanced Accelerator Strategy: Roadmaps





Plasma Acceleration Roadmaps

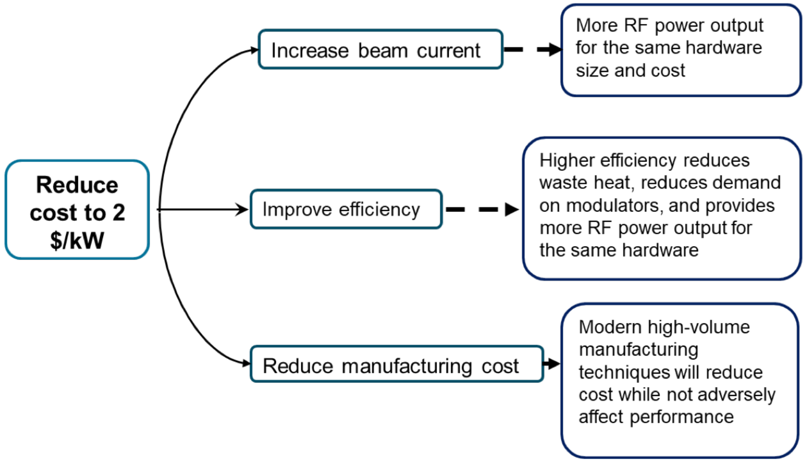
Community representatives from universities and laboratories organized workshops and summarized priorities in the report

http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

Recommendation 11. Continue research on high-efficiency power sources and high-gradient normal conducting RF structures.

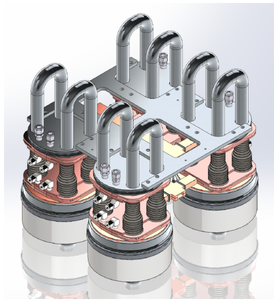
Progress on high-gradient RF acceleration and high-power RF systems at SLAC and collaborators

- Reducing cost & size of RF sources for future science facilities



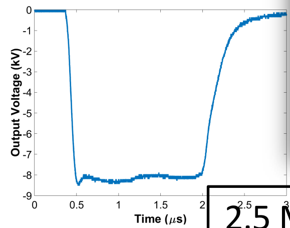
- Extremely High-Gradient (>160 MV/m) High-Efficiency (>60% rf-beam)
- Distributed-coupling and cryogenic-copper accelerating structures:
    - New frontier for beam brightness
    - New linear collider models

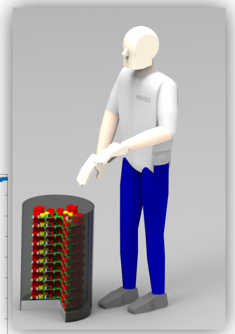
Low-Voltage RF Source Development Realized Low-Cost Prototypes



Modular klystron array operating at extremely low voltages

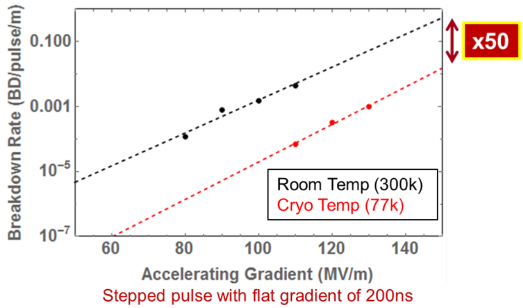
Modulator w/ >90% *extremely* high throughput methodologies

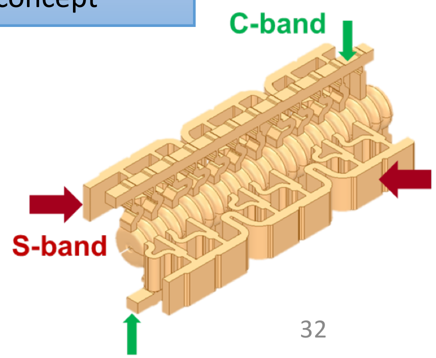




2.5 MW Modulator

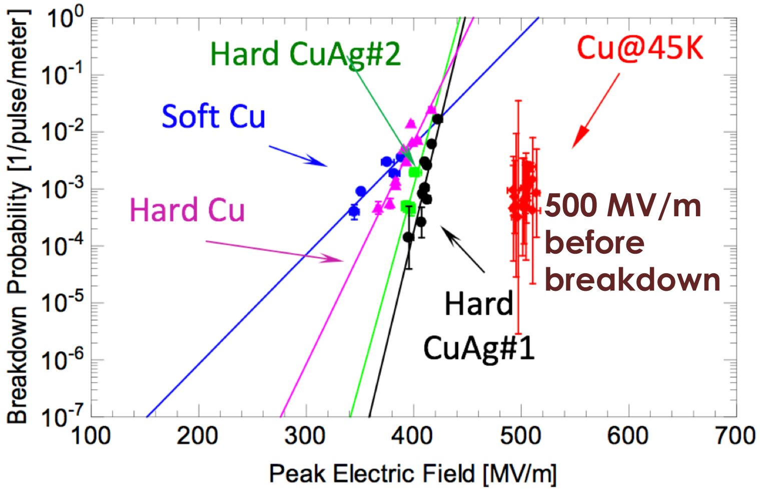
Enhanced efficiency, reduced breakdown w/ Cryo-Cu and multi-frequency concept



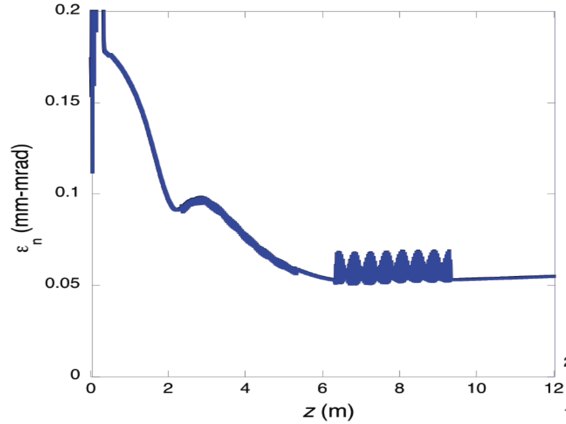


Dramatically higher gradients in cryogenic structures

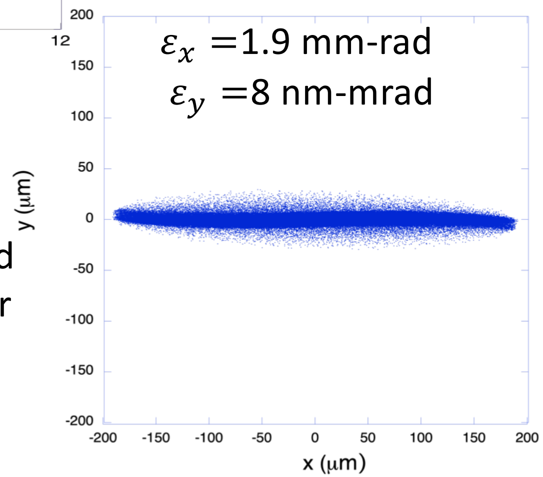
- SLAC X-band studies on hard Cu, CuAg alloy show great improvement
- ***Cryogenic structures*** (SLAC-UCLA) give **lower dissipation, higher yield strength, small coefficient of thermal exp.**
  - **Very high fields achievable**
  - **New possibilities in injectors, colliders, FELs**



A. D. Cahill, et al., *Physical Review Accel. Beams* 21, 102002 (2018)

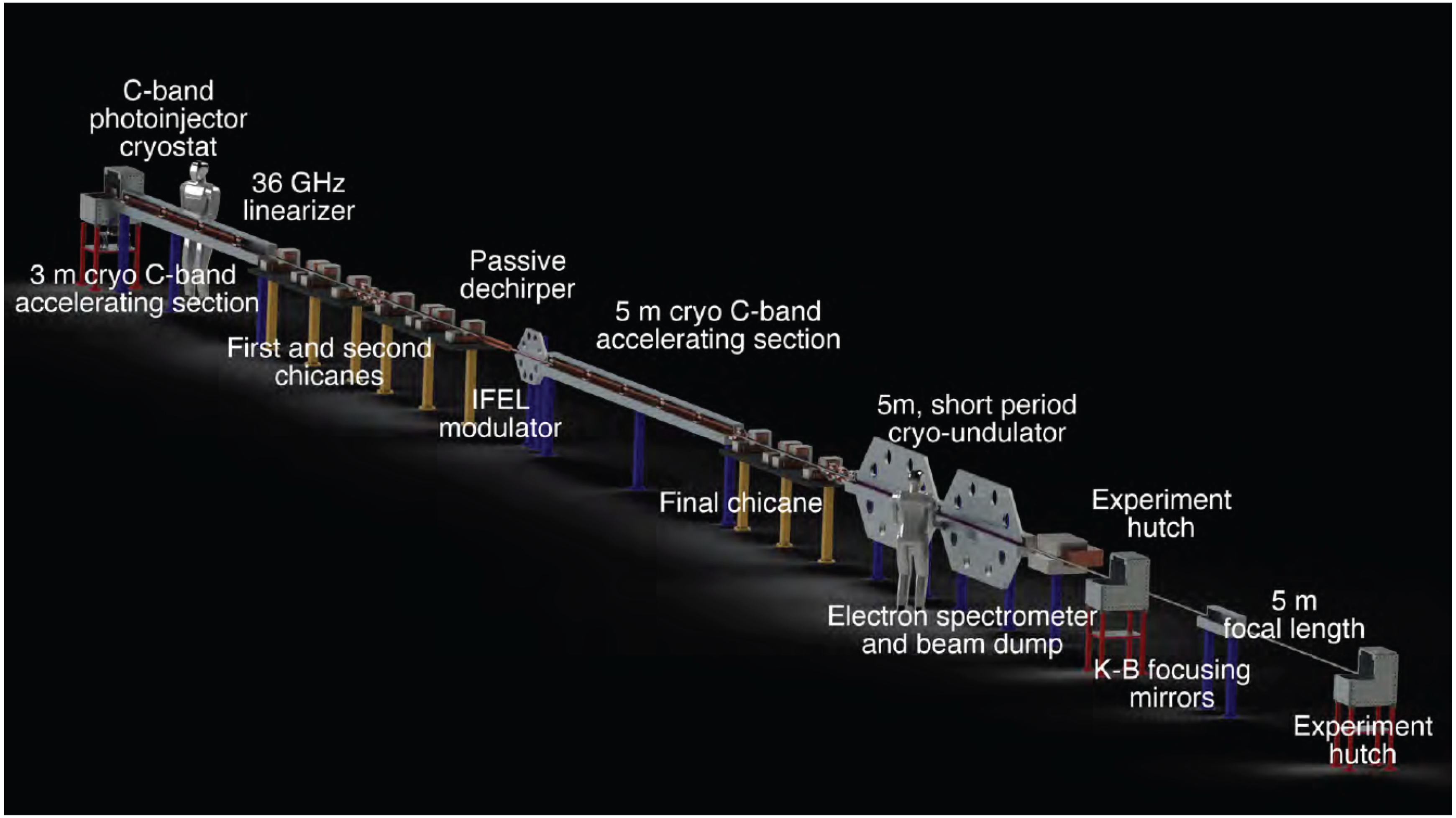


Order of magnitude higher brightness beams for advanced FEL (MaRIE, ultra-compact



Asymmetric emittance electron beam after skew-quad transformation – linear collider Values obtainable

Cryo-RF enables proposed ultra-compact XFEL

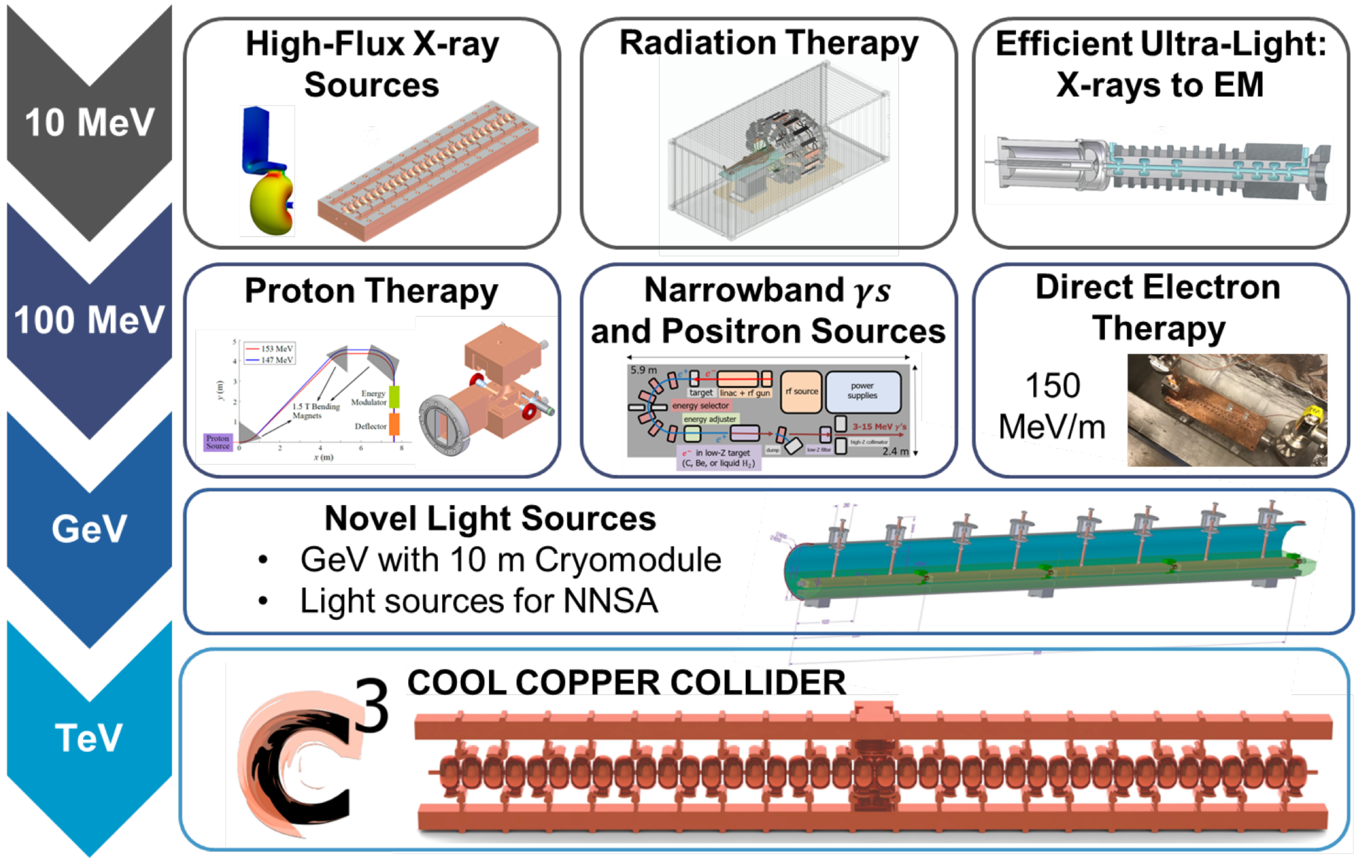


J. Rosenzweig, et al., submitted to *NJP,* https://arxiv.org/abs/2003.06083

Recommendation 12. Make NLCTA available for RF structure tests using its RF power and beam sources.

NLCTA is only GARD beam test facility at SLAC (with many other stakeholders involved)

- Supports SLAC HEP-GARD and Stewardship programs
- Also SPP programs (paying for incremental costs)

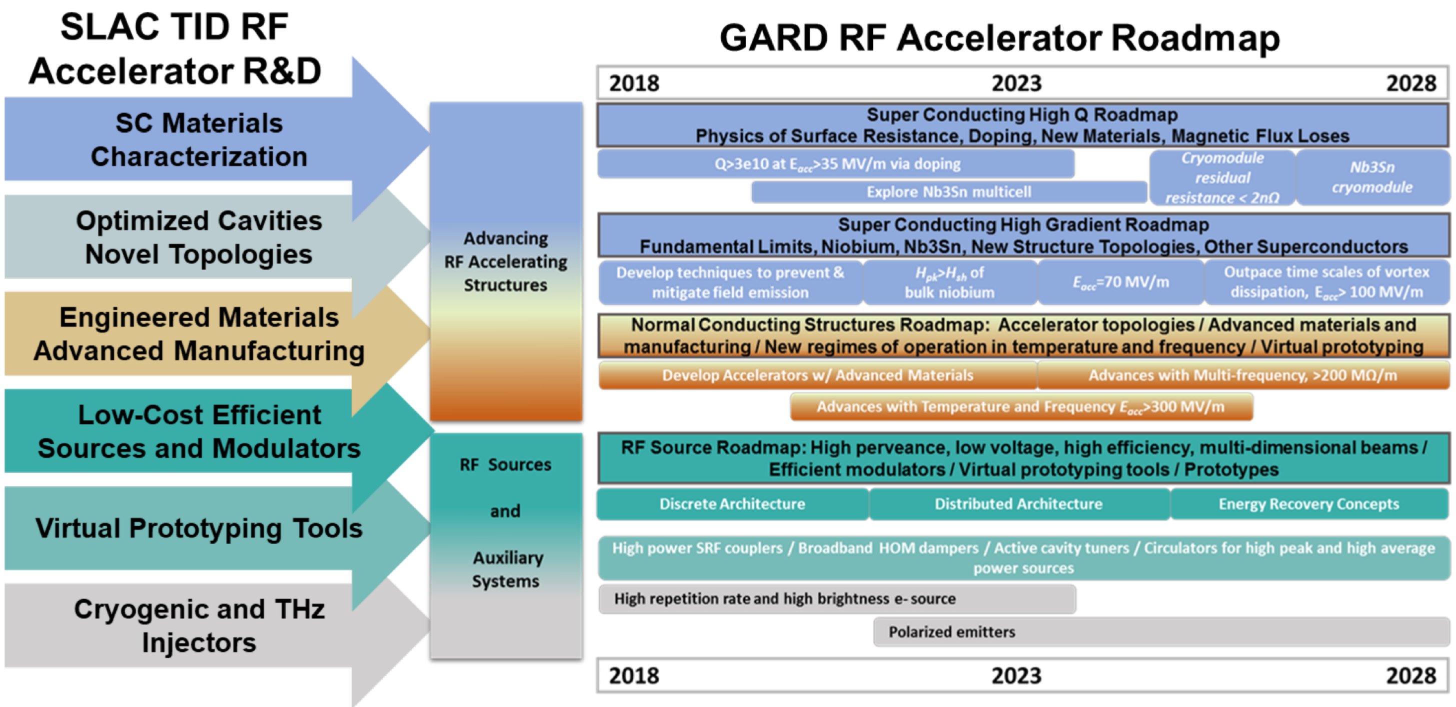


C3 straw-man design developed on cryo-RF, up to 150 Mev/m

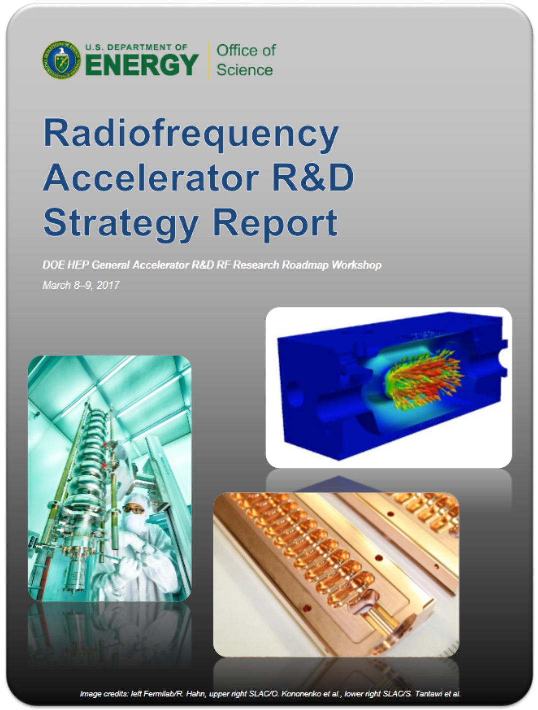
Recommendation 13. Focus normal conducting RF R&D on developing a multistage prototype based on high-gradient normal conducting RF structures and high-efficiency RF power sources to demonstrate the effectiveness of the technology for a multi-TeV e^+e^- collider.

Comment: Envisioned as evolution of NLCTA.
First steps being taken at SLAC, UCLA, LANL (NNSA and GARD).
Formation of C^3 collaboration

High Gradient RF Accelerator Research Roadmap (Including SRF) Developed



*DOE RF Accelerator R&D Strategy Report, June 2017



Recommendation 14. Continue accelerator and beam physics activities and beam instrumentation and control R&D aimed at developing the accelerators defined in the Next Steps and the Further Future Goals. Develop coordination strategies, both nationally and internationally, to carry out these studies in an efficient manner.

Comment: efforts are continuing, responsive to current projects.

Example: RF control R&D at BACI

BACI (Berkeley Accelerator Controls and Instrumentation) develops high precision digital RF controls in

- FPGA (field programmable gate array) based high precision LLRF/timing control system ;
- Strong capability in hardware, firmware and software development and system integration.

Develops open hardware and open source BIDS (Beam Instrument Development System)

- New LLRF board: finished Marble-mini prototype and currently in testing phase;
- Actively involved in high *Q* resonance control of SRF cavities.

Application of the advanced RF control already played a critical role in the fiber-based coherent laser combination. BACI has major responsibilities in synergetic projects

- LLRF system for PIP-II accelerator complex
- LCLS-II LLRF technical lead and LCLS-II injector LLRF lead
- SNS power upgrade project
- HEP QIS with controls for superconducting circuit qubits

Marble-mini board

Recommendation 15. To ensure a healthy, broad program in accelerator research, allocate a fraction of the budget of the Accelerator Physics and Technology thrust to pursue fundamental accelerator research outside of the specific goals of the Next Steps and Further Future Goals. Research activities at universities should play a particularly important role.

Comment: New research areas from new infrastructure: single electron physics at IOTA, strong field QED at FACET-II, fundamental THz research at SLAC, UCLA. Stewardship Track 2 addresses this need. Expected synergy from NSF only partially materialized.

NSF STC Center for Bright Beams (CBB)

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

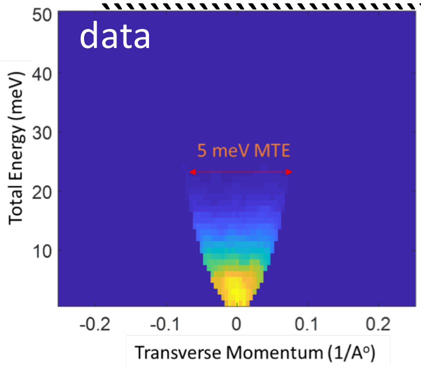
Cornell University
The University of Chicago
UCLA
Arizona State University
Northern Illinois University
BYU
University of Florida
Clark Atlanta University
Berkeley Lab
Fermilab

NSF Science and Technology Center

NSF PHY-1549132

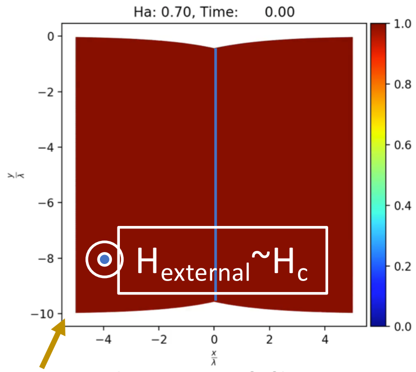
Ritchie Patterson, Director
Phase I: 2016-2021
Phase II: 2021-2026 (upon renewal)

100× brighter electron source for low current density applications, such as stroboscopic UED/UEM.



The 3D energy-momentum distribution from a photo-emission source showing 5 meV mean transverse energy.

CBB at LBNL with additional DOE support (DE-SC0017621)



Toward superconducting RF acceleration at 4K. CBB improved the growth process for Nb_3Sn coated cavities and developed a theory of the main source of heating, vortex motion.

Simulation of flux entry at a grain boundary in a Nb_3Sn SRF cavity,. blue is NC. Main culprit is the surface deformation at the boundary.

Recommendation B1. Increase base GARD funding modestly in order to open numerous critical R&D opportunities that do not fit in the current base, as well as to invigorate fundamental accelerator science research, and to step up development of the national accelerator workforce.

Comment: Expanded DOE role in workforce development (SCGSR program).
NSF CBB has large new role.

CBB Workforce Development

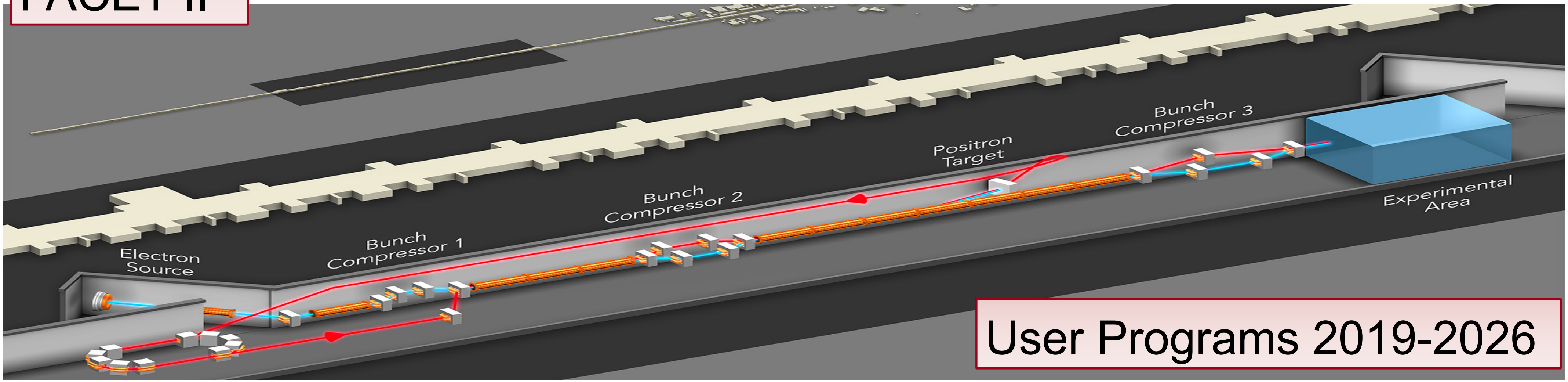
28 grad-students and 8 Post-docs,
3 of whom have gone onto faculty positions in accelerator science in the last 2 years.

Recommendation C1b. Develop, construct, and operate a next-generation facility for particle-driven plasma wakefield acceleration research and development, targeting a multi-TeV e^+e^- collider, in order to sustain this promising and synergistic line of research after the closure of the FACET facility.

Comment: US leadership in wakefield acceleration not ceded with FACET-II construction, contributions from AWA and ATF. Fast rising competition from DESY.

FACET-II has been constructed at SLAC

FACET-II



User Programs 2019-2026

Three stages:

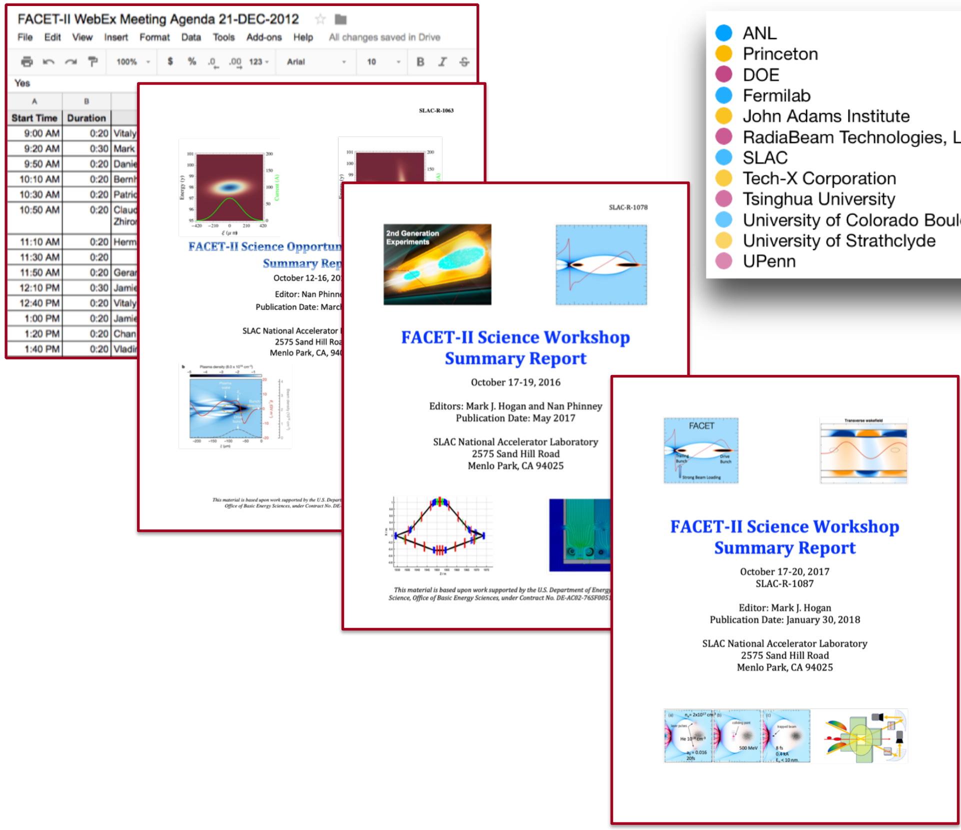
- Photoinjector (e- beam only) 2020
- e+ damping ring (e+ or e- beams) 2023
- "sailboat" chicane (e+ and e- beams) 2023

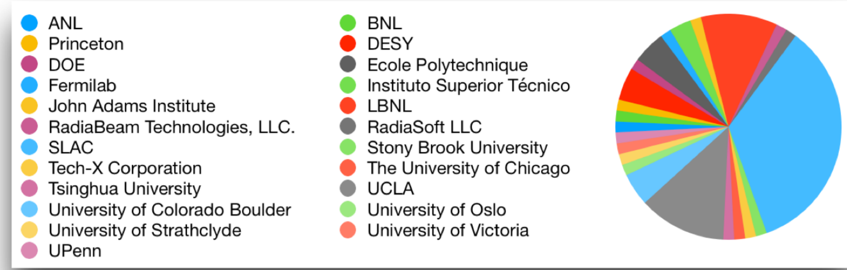
Only Stage 1 is committed at this time

Key R&D Goals:

- High brightness beam generation, preservation, characterization
- e^+ acceleration in e^- driven wakes
- Staging challenges with witness injector
- Generation of high flux gamma radiation

FACET-II Science Program and capabilities are defined by community with annual workshop





Latest Science Workshop discussed:

- Facility status
- Technical readiness of first experiments
- Science case for positrons & new ideas
- FEL applications

Second Program Advisory Committee Meeting: October 2020 (after commissioning)

Summary

- GARD Subpanel to P5 report issued in 2015
- Community has been responsive to planning
- DOE HEP has provided a steady hand, and enabled research to go forward
  - *Much progress reported* in execution
- Breakthroughs not quite here, but very promising developments are in hand. Next years are critical
- Looking for: synergistic investments from other agencies and stakeholders; ability to match efforts with foreign colleagues.