GARD Program and US Accelerator R&D

P5 Townhall at SLAC

Mei Bai, Deputy director for Science, AD, SLAC

May 3, 2023

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT OF ENERGY

Outline

- GARD (OHEP General Accelerator R&D Program) and its Impact

- R&D needs for future goals
  - GARD five thrust R&D needs

- Universities, GARD funded USPAS and traineeship

- Summary

DOE OHEP GARD: General Accelerator R&D Program

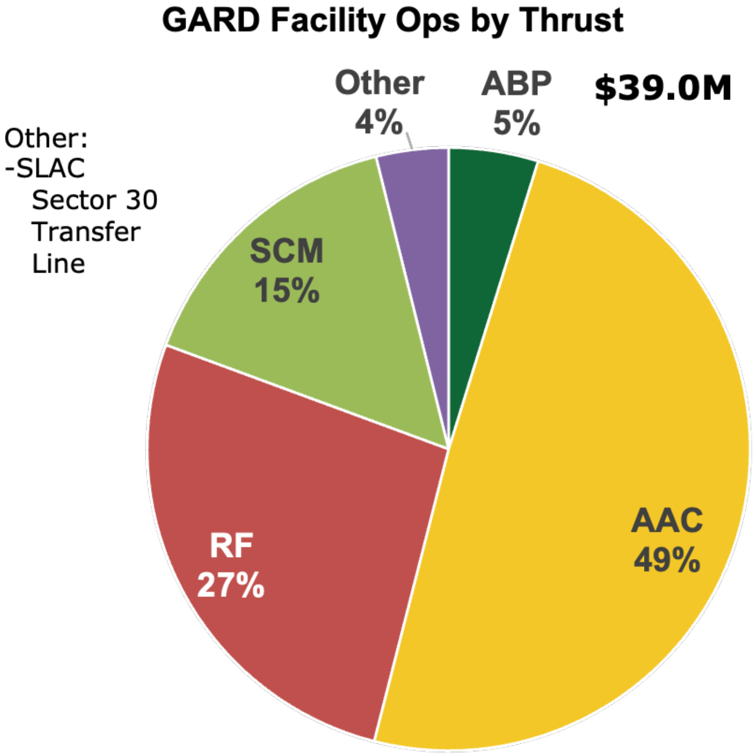
The OHEP GARD program has been one of the main funding resources for the US national laboratories and universities to carry out R&Ds in developing new accelerator concepts, materials, designs and pushing the performance limits for High Energy Physics mission, out of which the long-term generic R&D may also benefit other applications.

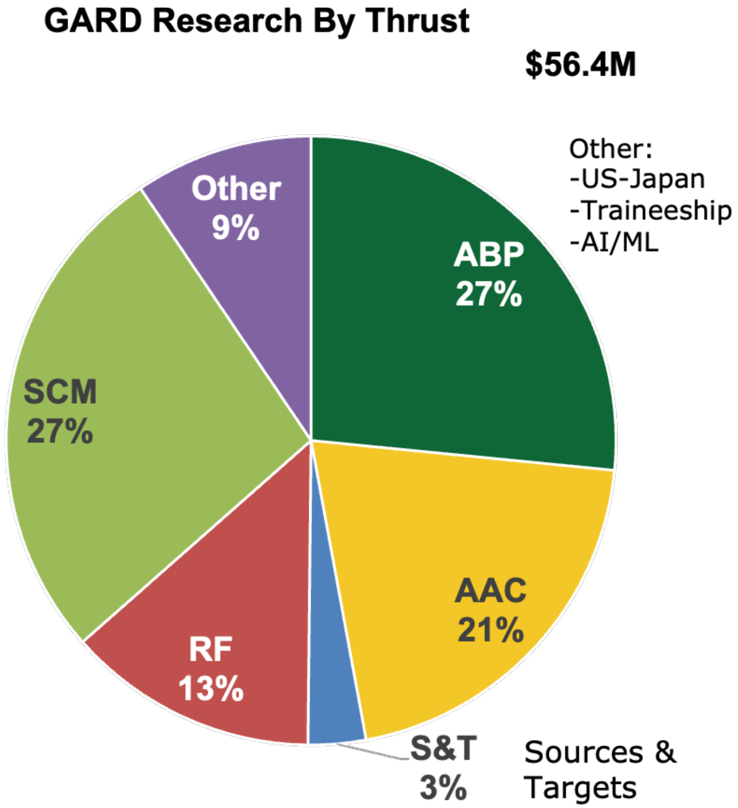
GARD program consists of five core research thrusts, facility operations, workforce development, US-Japan collaborative ARD and ILC cost reduction R&D

- **Core research thrusts**
  - Accelerator and beam physics *[beam phys. exp'ts, modeling, instrumentation, theory]*
  - Advanced acceleration concepts *[beam-, laser- and structure- wakefields]*
  - Particle sources and targets *[photoinjectors, e+, high power targetry]*
  - RF acceleration technology *[SRF, NCRF, high gradient research and RF sources]*
  - Superconducting magnet and materials *[SRF, NCRF, high-G research and RF sources]*
- **Workforce development**: US Particle Accelerator School, DOE Accelerator Traineeships

GARD portfolio (FY22)

GARD portfolio contains a set of mid-term, long-term including generic R&Ds that are aligned with the **2014 P5 recommendations**, i.e PIP-II, HL-LHC, and ILC, and future goals, i.e. multi-MW neutrino factory, very high energy pp collider and multi-TeV lepton collider





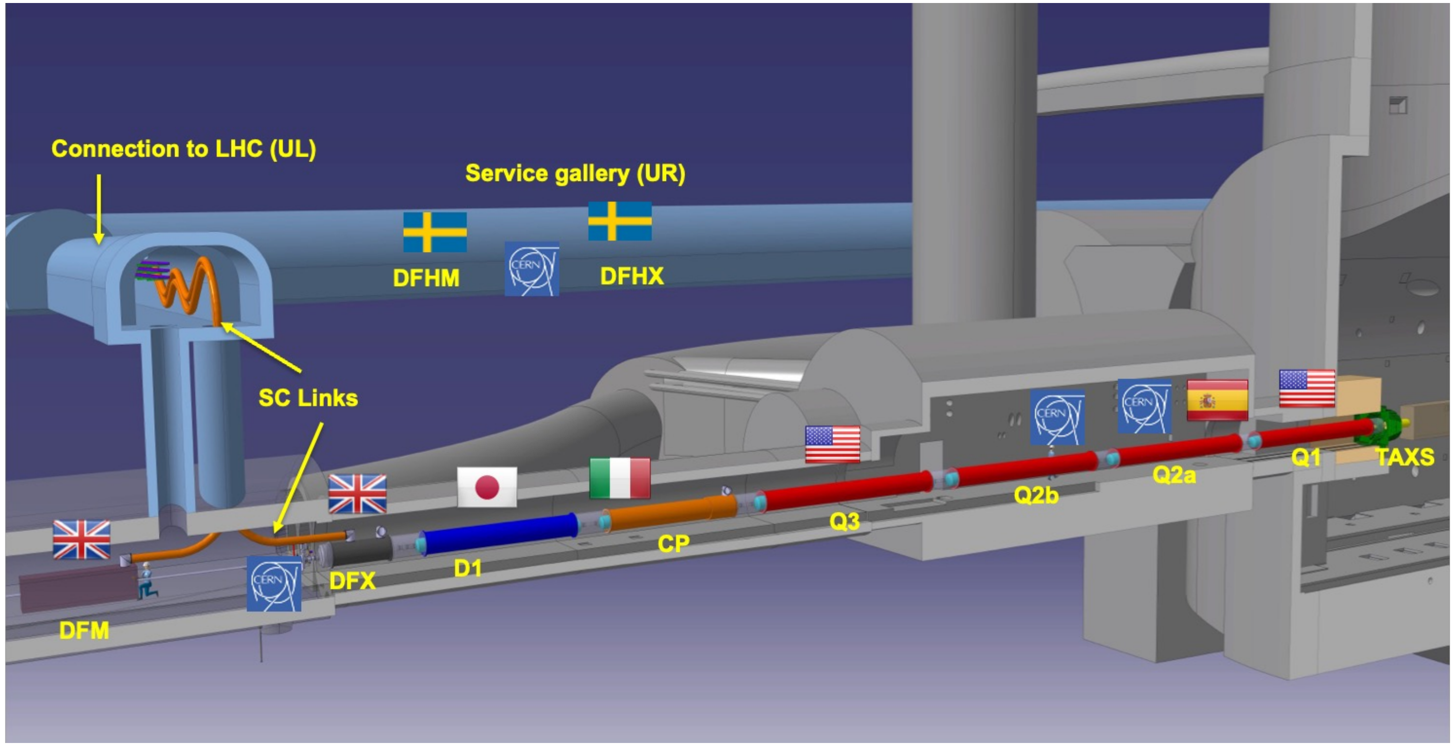
Impact of general accelerator R&D

yesterday's R&D led to today's success

US contributing enabling technology to the HL-LHC

US-Accelerator Upgrade Project (US-AUP) contributes 50% of the HL-LHC final focusing triplets and SRF crab cavities, a total of $260M investment.

With the sizable funding from 2006 to 2018 for generic and complementary R&D efforts, such as **Conductor Development Program**, **General Accelerator R&D GARD**, **US-LARP, university programs**, etc., cutting edge technologies in Nb3Sn superconductor and SRF crab cavity were successfully developed to enable the luminosity upgrade of LHC.



First usage in accelerator for Nb3Sn superconductor, which is ~50% higher than present LHC

First usage in hadronic collider of SRF crabbing technology to compensate the luminosity reduction due to large crossing angle for mitigating long range beam-beam effect

Superconducting RF technology thrust

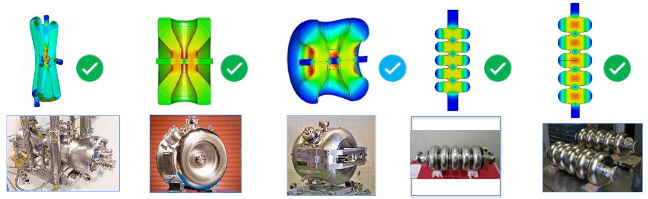
The HEP investment in basic SRF R&D earlier allowed built-up of expertise, workforces and critical infrastructures that are **indispensable for PIP-II,** the upcoming workhorse for the US HEP neutrino program

The basic R&D of improving Nb SRF cavity performance has led to the **first CW based XFEL**

PIP-II for world’s most intense neutrino beams

- 800 MeV, 2mA H^- SRF linac
- 1.2 MW proton beam
- Upgradeable to multi-MW

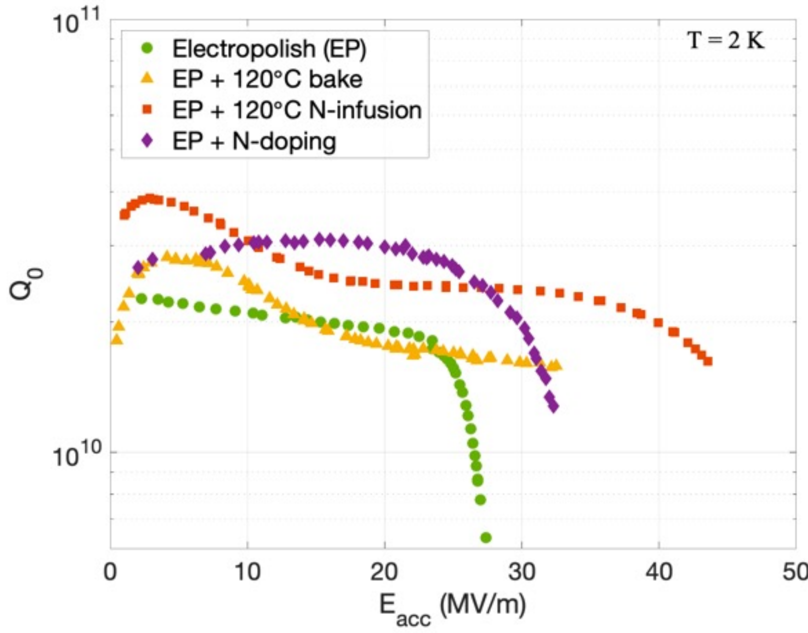
PIP-II SRF cavities



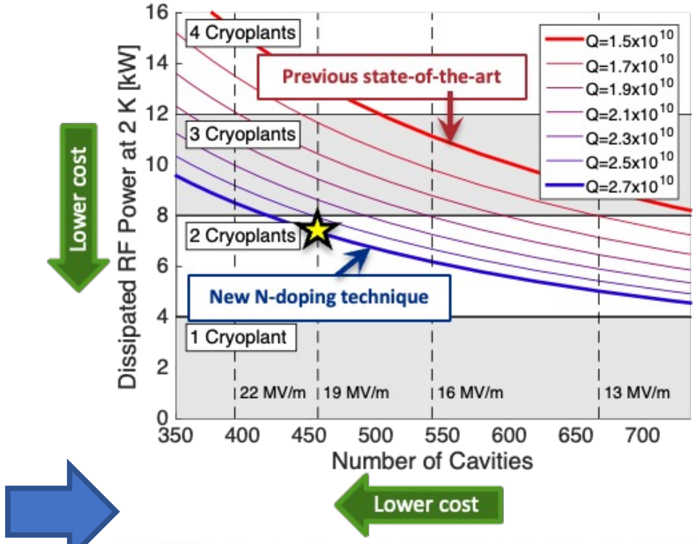
Name (Qty.)	**HWR (8)**	**SSR1 (16)**	**SSR2 (35)**	**LB650 (36)**	**HB650 (24)**
Type	Half-Wave	Single Spoke	Single Spoke	Elliptical	Elliptical
β	0.11	0.22	0.47	0.61	0.92
Frequency	162.5 MHz	325 MHz	325 MHz	650 MHz	650 MHz
Q_0	$8.5 \cdot 10^9$	$8.2 \cdot 10^9$	$8.2 \cdot 10^9$	$2.4 \cdot 10^{10}$	$3.3 \cdot 10^{10}$
Gradient	9.7 MV/m	10 MV/m	11.5 MV/m	16.8 MV/m	18.7 MV/m
Doping	No	No	No	Yes	Yes

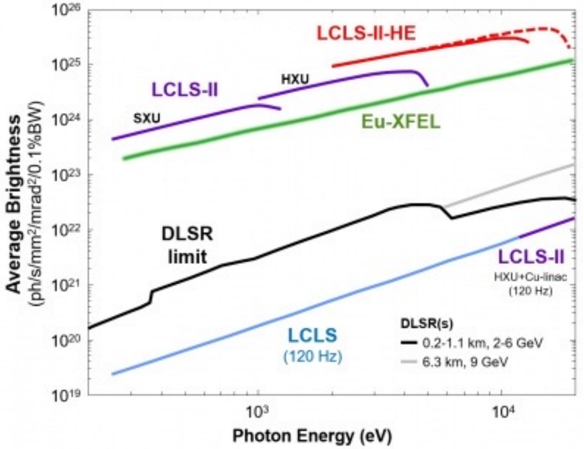
✓ *Prototype built* ✓ *Prototype validated*

Nitrogen doping and infusion



LCLSII/HE **8 GeV CW SRF Linac**





Leading institutions: FNAL, Jlab and Cornell University

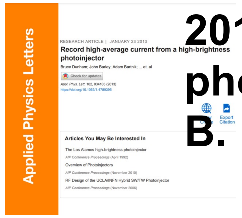
High brightness photoinjectors

1985, invention of RF photoinjector by Fraser, Sheffield, et al, LANL

2020 Wilson Prize "*For the discovery and subsequent implementation of emittance compensation in photoinjectors that has enabled the development of high brightness, X-ray free electron lasers such as the Linac Coherent Light Source"*

High brightness e-gun development by BNL, SLAC, and UCLA

1990s



Applied Physics Letters

RESEARCH ARTICLE | JANUARY 23 2013

Record high-average current from a high-brightness photoinjector

Bruce Dunham; John Barley; Adam Bartnik; ... et. al

Appl. Phys. Lett. 102, 034105 (2013)

https://doi.org/10.1063/1.4789395

Articles You May Be Interested In

The Los Alamos high-brightness photoinjector

AIP Conference Proceedings (April 1992)

Overview of Photoinjectors

AIP Conference Proceedings (November 2010)

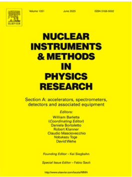
RF Design of the UCLA/INFN Hybrid SW/TW Photoinjector

AIP Conference Proceedings (November 2006)

2013, world record 65mA photoinjector was achieved B. Dunham et al, Cornell

1980s

2020



Volume 1051 June 2023 ISSN 0168-9002

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Section A: accelerators, spectrometers, detectors and associated equipment

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http://www.elsevier.com/locate/NIMA

1989, RF and space charge effects in photo RF e-gun, K.J. Kim, ANL

1995, emittance compensation, B. Carlsten, LANL

2007, successful commissioning of LCLS photoinjector with <1um slice emittance achieved! D. H. Dowell et al, SLAC

1997, detailed theory of emittance compensation, J. Rosenzweig, UCLA

The breakthrough of high brightness electron source has enabled **today's X-FEL** performance and could result to cost reduction in tomorrow's linac based discovery science facilities

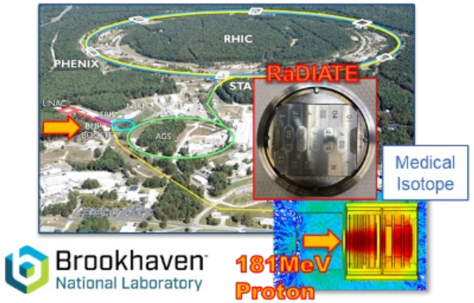
GARD enabled successful R&D in high power target

Prototypic irradiation to closely replicate material behavior in accelerator target facilities

Experiment Preparation

2014/2017

Brookhaven Linac Isotope Producer



Brookhaven National Laboratory

2017/2018

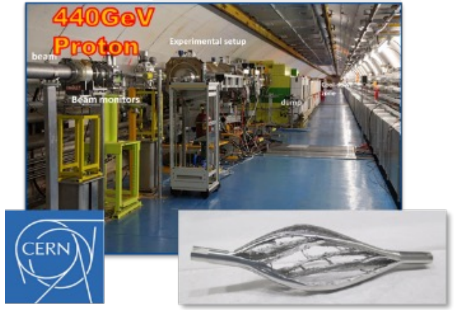
High-energy proton irradiation

Pacific Northwest NATIONAL LABORATORY

2019-2023

Post-Irradiation Examination (PIE)

HiRadMat High-Radiation to Materials



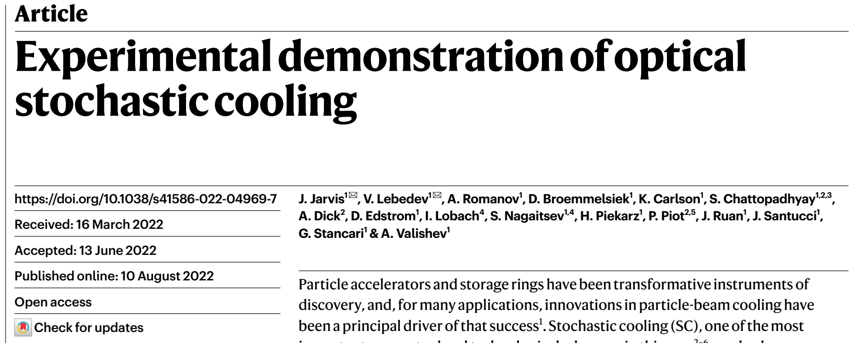
2015 / 2018 / 2022

In-beam thermal shock experiment

Full cycle of R&D: ~ 5-10 years

IOTA/FAST: a dedicated intensity frontier beam physics facility

Recommended by the 2014 P5, **IOTA (Integrable Optics Test Accelerator) at FNAL** as the first and only intensity frontier beam test facility has been constructed and operated for beam physics research



Article

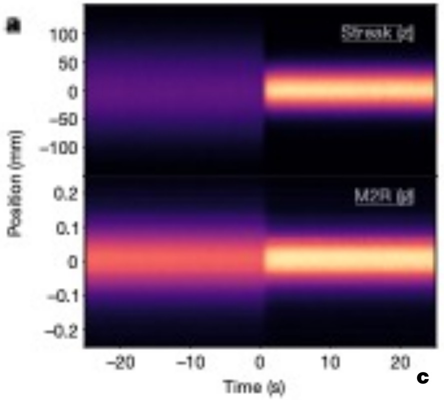
Experimental demonstration of optical stochastic cooling

https://doi.org/10.1038/s41586-022-04969-7
Received: 16 March 2022
Accepted: 13 June 2022
Published online: 10 August 2022
Open access
Check for updates

J. Jarvis[1]✉, V. Lebedev[1]✉, A. Romanov[1], D. Broemmelsiek[1], K. Carlson[1], S. Chattopadhyay[1,2,3], A. Dick[2], D. Edstrom[1], I. Lobach[4], S. Nagaitsev[1,4], H. Piekarz[1], P. Piot[2,5], J. Ruan[1], J. Santucci[1], G. Stancari[1] & A. Valishev[1]

Particle accelerators and storage rings have been transformative instruments of discovery, and, for many applications, innovations in particle-beam cooling have been a principal driver of that success[1]. Stochastic cooling (SC), one of the most

5th Annual IOTA/FAST CM 2017



Dependence on time of single-dimensional beam distributions in z(streak camera) and y(M2R SR monitor) during an OSC toggle. The system is initially detuned by 30λr and is snapped to the maximum cooling setting at t = 0.

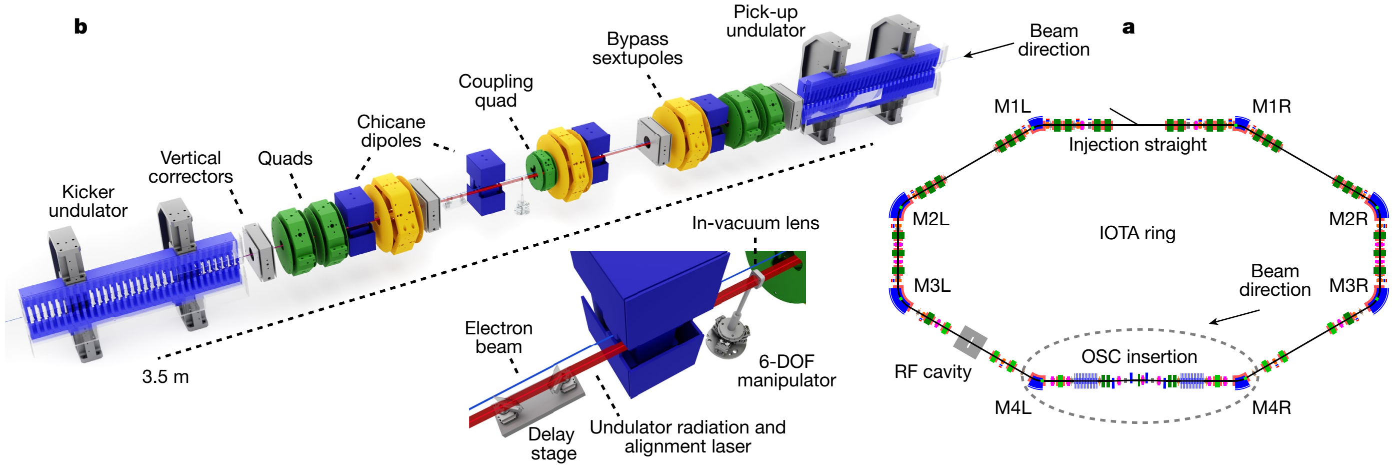
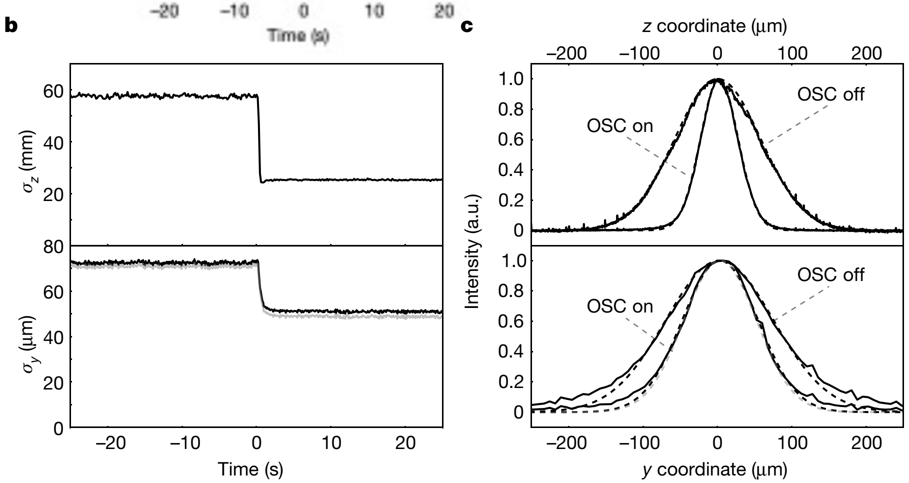


Fig. 2 | Schematic of the IOTA OSC system. a, Schematic of the IOTA ring and the location of the OSC insertion. **b**, Diagram of the OSC insertion including the undulators, chicane and light optics (inset). RF, radio frequency; DOF, degrees of freedom.



b is the r.m.s. beam sizes from Gaussian fits of the raw projections presented in **a**. **c**, Distributions averaged over time (solid lines) and their Gaussian fits (dotted lines) for the OSC-off and OSC-on states for the intervals of [−20, −10] s and [10, 20] s. In **b** and **c**, the M2R fits use only the central ±110 µm to reduce contamination by the non-Gaussian tails resulting from gas scattering. Diffraction-corrected curves are shown in grey, and the distributions in each case have been normalized to a peak value of one for comparison.

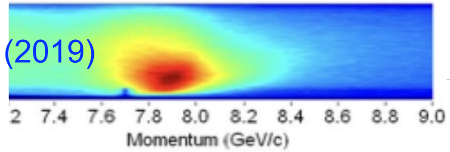
Advanced Acceleration Concepts

Plasma based accelerators

- Acceleration gradient:

  Laser Wake Field Acceleration (LWFA)

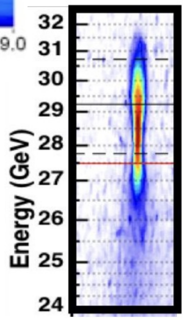
  - 8GeV energy gain in 20cm plasma with 3x10^{17} cm^{-3} was achieved at BELLA, LBL



A. J. Gonsalves et al. PRL (2019)

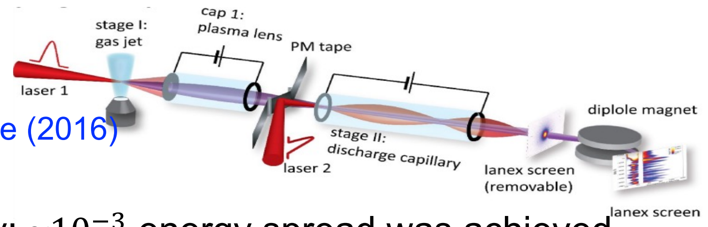
  Beam driven plasma wakefield(PWFA)

  - 9GeV energy gain in 1.3m was achieved at FACET SLAC



M. Litos et al. PPCF (2015)

- Staging:
  - Proof-of-principle staging of LWFAs (~100 MeV energy gain) using high gradient plasma-lenses

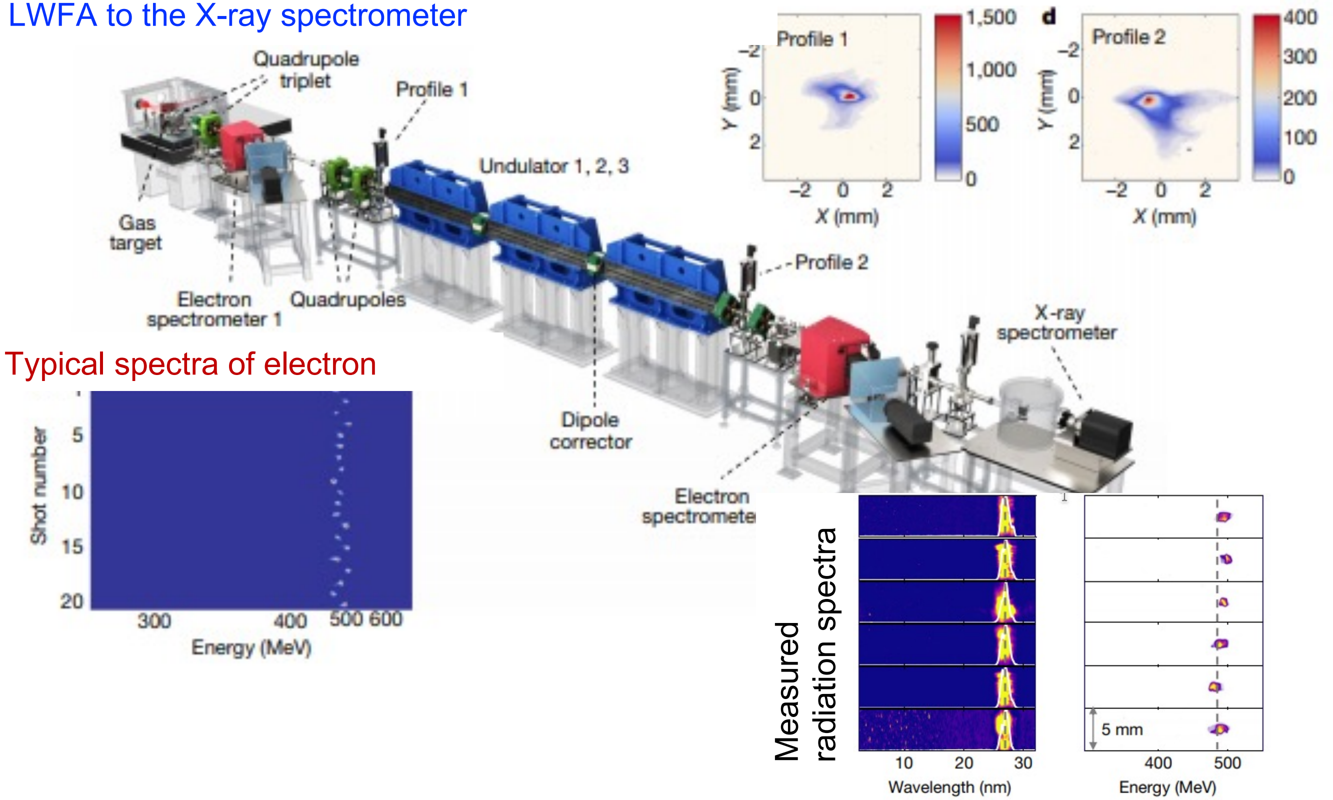


S. Steinke et al. Nature (2016)

  - Beam quality: ~10^{-3} energy spread was achieved
  - Plasma recovery at high repetition rate was recent observed at FLASH Forward, R. D'Arcy et al., Nature (2022)

Recent demonstrated proof-of-principle LWFA and PWFA based **compact FELs**

1st demonstration of **laser wakefield accelerator driven FEL** [W. Wang, et al Nature, July 2021]. Radiation of 27 nm was observed at the end of undulator. The maximum photon is around 10^{10} per shot, which corresponds to a maximum radiation energy of about 150 nanojoules.



Undulator beamline with a total length of approximately 12 m from the gas target for the LWFA to the X-ray spectrometer

Measured transverse profiles of the electron beam at the entrance

Typical spectra of electron

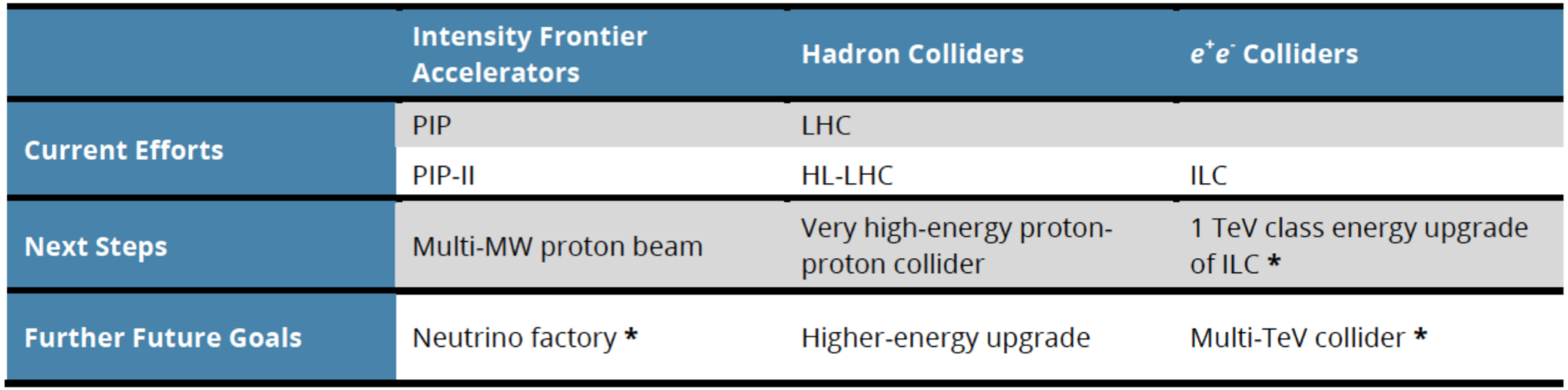
Measured radiation spectra

Current US ARD vs. future goals

reaching future goals requires today's investment in R&D including test facilities and future workforce

Key technology needs for current and future goals

Current GARD funding is aligned with the **2014 P5 physics priorities:**



	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 *

A number of new ideas/initiatives were brought up during the **Snowmass2021 process:**

- Intensity frontier: ACE (aka PIP-III) to double the proton beam power for LBNF/DUNE
- Precision frontier: facilities for rare process oriented (CP violation, dark matter/dark energy, CLFV, etc) such as Advanced Muon Facility (AMF)
- Higgs/EW collider:
    - **International:** Future **C**ircular **C**ollider-ee, **C**ircluar **e**lectron **p**ositron **C**ollider
    - **US**: Cool Copper Collider (C3), Higgs-Energy LEptoN (HELEN)
- Energy frontier: multi-TeV muon collider, FCC-hh

Snwomass'21: R&D needs for these future goals

Particle sources and target:

- Efficient high intensity e+ sources including polarized for Higgs/EW factory colliders
- 2.4 MW for ACE (PIP-III)
- 4.8 MW for a muon collider

Superconducting magnets and materials (coordinated with US MDP)

- 16-20 T dipole for hadron collider
- 40 T solenoid for muon collider
- Fast ramping magnets with 1kT/s for muon collider

Accelerator and beam physics:

- Experimental, High intensity/brightness beams acceleration and control
- High performance computer modeling and AI/ML approaches
- Design integration and optimization, including energy efficiency

Advanced acceleration concept

- Collider quality beams including positrons
- Efficient drivers and staging
- Coordinate with international efforts

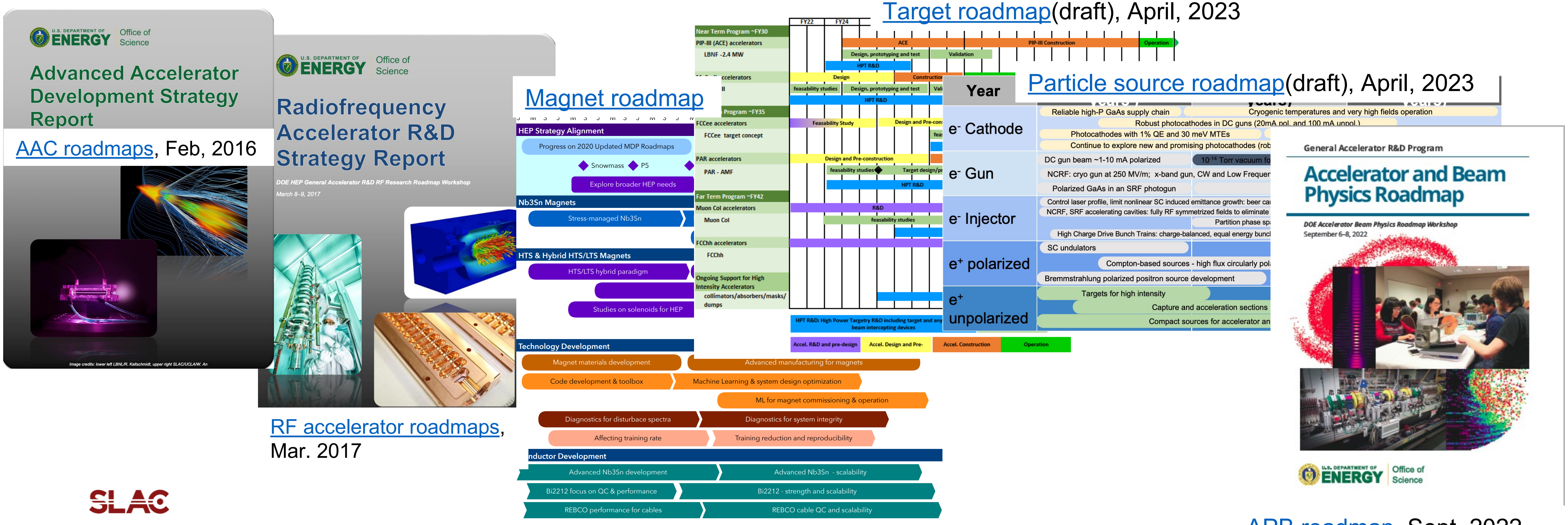
RF acceleration technology:

- High gradient:
  - SRF >50MV/m, NC RF: 70-150MV/m
- High quality factor for cost efficient
- High efficiency RF power source

More details are in the Snowmass **AF summary report** as well as each AF subgroups summary report

GARD Thrusts: Roadmaps

- Recommended by the 2014 P5, a set of roadmaps along with milestones was established for Advanced Acceleration Concept (AAC), RF technology, SC Magnets, Accelerator and beam physics (ABP), around 2016-2017
- Very recently, sources and targets have also established their roadmap. ABP has also just updated theirs shortly after the Snowmass2021 process.



U.S. DEPARTMENT OF ENERGY Office of Science

Advanced Accelerator Development Strategy Report

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An

AAC roadmaps, Feb, 2016

U.S. DEPARTMENT OF ENERGY Office of Science

Radiofrequency Accelerator R&D Strategy Report

DOE HEP General Accelerator R&D RF Research Roadmap Workshop

March 8–9, 2017

RF accelerator roadmaps, Mar. 2017

Magnet roadmap

Target roadmap(draft), April, 2023

Particle source roadmap(draft), April, 2023

General Accelerator R&D Program

Accelerator and Beam Physics Roadmap

DOE Accelerator Beam Physics Roadmap Workshop

September 6–8, 2022

U.S. DEPARTMENT OF ENERGY Office of Science

APB roadmap, Sept, 2022

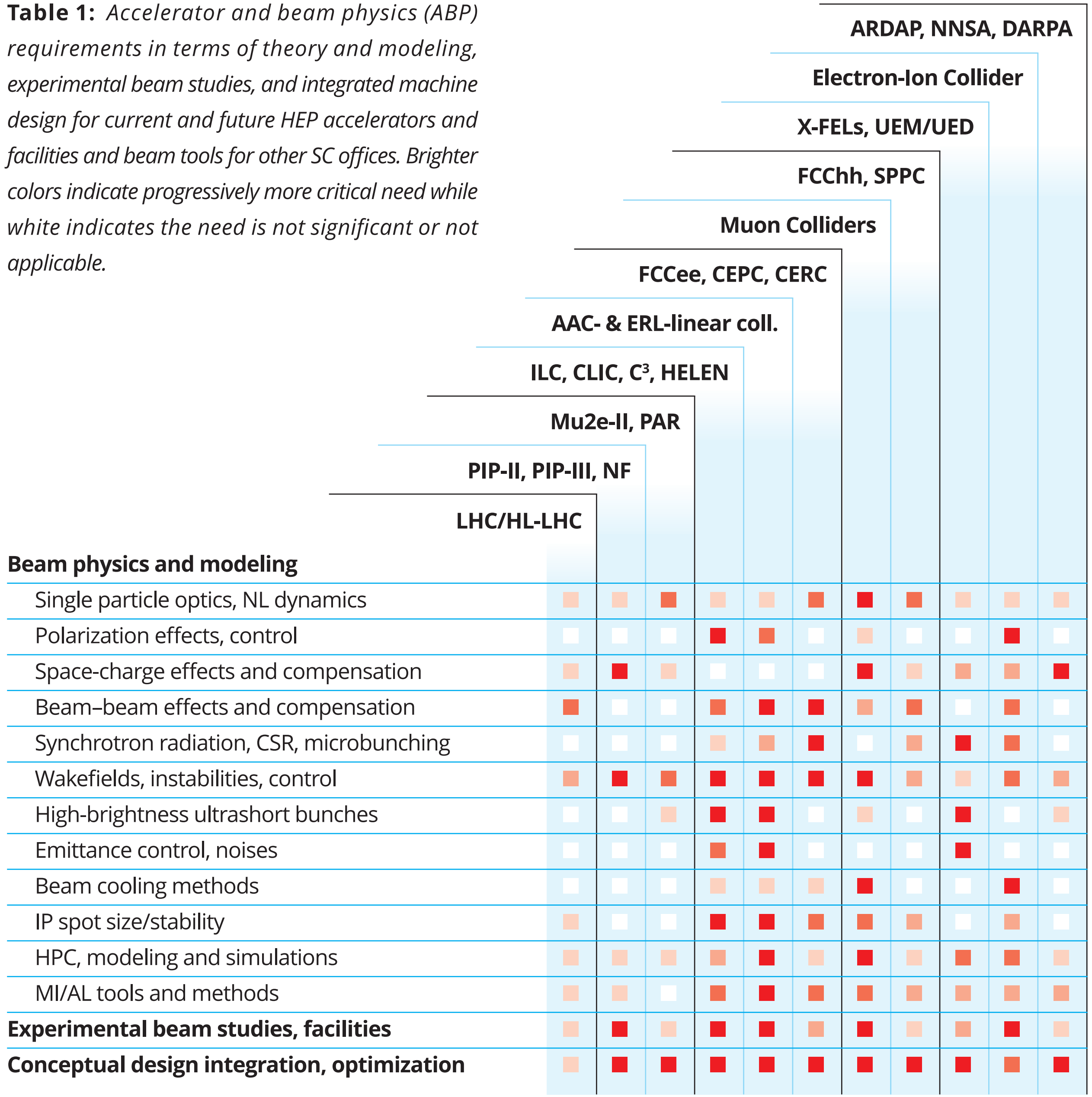
Accelerator and Beam Physics

The main focus of Accelerator and Beam Physics (ABP) research is beam intensity, beam quality, beam control and beam prediction (modeling).

It is the most cross-cutting GARD core research thrust, critical for **supporting current and future HEP missions** but also essential for all other accelerator and beam-based science and societal needs.

ABP also works very closely with USPAS as well as universities in education, outreach and training.

Table 1: *Accelerator and beam physics (ABP) requirements in terms of theory and modeling, experimental beam studies, and integrated machine design for current and future HEP accelerators and facilities and beam tools for other SC offices. Brighter colors indicate progressively more critical need while white indicates the need is not significant or not applicable.*

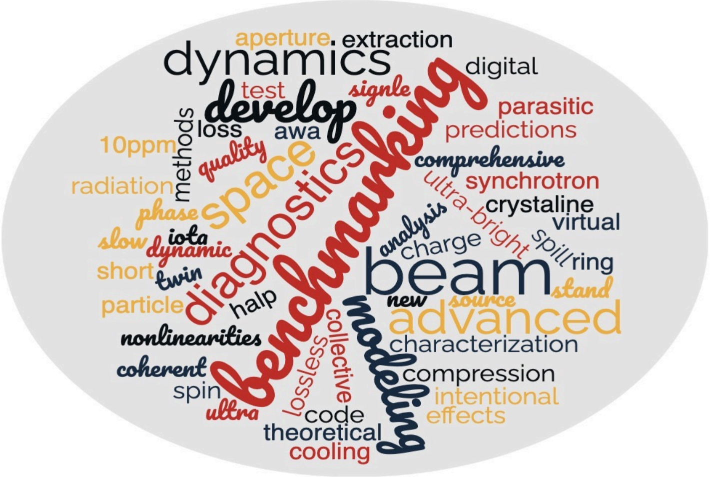


	LHC/HL-LHC	PIP-II, PIP-III, NF	Mu2e-II, PAR	ILC, CLIC, C^3, HELEN	AAC- & ERL-linear coll.	FCCee, CEPC, CERC	Muon Colliders	FCChh, SPPC	X-FELs, UEM/UED	Electron-Ion Collider	ARDAP, NNSA, DARPA
Beam physics and modeling											
Single particle optics, NL dynamics	░	░	▓	░	░	▓	🟥	▓	░	░	░
Polarization effects, control	⬜	⬜	⬜	🟥	▓	⬜	░	⬜	⬜	🟥	⬜
Space-charge effects and compensation	░	🟥	░	⬜	⬜	⬜	🟥	░	▒	▒	🟥
Beam–beam effects and compensation	▓	⬜	⬜	▓	🟥	🟥	▒	▓	⬜	▓	⬜
Synchrotron radiation, CSR, microbunching	⬜	⬜	⬜	░	▒	🟥	⬜	▒	🟥	▓	⬜
Wakefields, instabilities, control	▒	🟥	▓	🟥	🟥	🟥	🟥	▒	░	▓	▒
High-brightness ultrashort bunches	⬜	⬜	░	🟥	🟥	⬜	░	⬜	🟥	⬜	░
Emittance control, noises	⬜	⬜	⬜	▓	🟥	⬜	⬜	⬜	🟥	⬜	⬜
Beam cooling methods	⬜	⬜	⬜	░	░	░	🟥	⬜	⬜	🟥	⬜
IP spot size/stability	░	⬜	⬜	🟥	🟥	▓	▓	▒	⬜	▒	⬜
HPC, modeling and simulations	░	░	░	▒	🟥	░	🟥	░	▓	▓	░
MI/AL tools and methods	░	░	⬜	▓	🟥	▓	▓	▒	▒	▒	▒
Experimental beam studies, facilities	░	🟥	░	🟥	🟥	▒	🟥	░	▒	🟥	░
Conceptual design integration, optimization	░	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	▓	🟥

Accelerator and Beam Physics R&D needs

The accelerator and beam physics community has recently held the workshop to address its R&D needs. The summary report of the workshop along with updated the roadmaps is recently approved by DOE and published. In there,

- The grand challenges are identified
- The approach to **exploit facilities, support codes/modeling, advance AI/ML/VTS, education/training** is emphasized
- Needs of centralized collaboration framework such as the Magnet Development Program (MDP) to facilitate resource sharing and communication among various R&D activities were raised. Concept of **US Center for Accelerator Physics (CAP)** was proposed.



Grand challenge #1 (beam intensity): How do we increase beam intensities by orders of magnitude?

Grand challenge #2 (beam quality): How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?

Grand challenge #3 (beam control): How do we control the beam distribution down to the level of individual particles?

Grand Challenge #4 (beam prediction): How do we develop predictive “virtual particle accelerators”?

R&D needs: High power targetry

In-Beam Studies: *Evaluate in-beam performance of candidate materials*

- **Irradiated Material Studies:** high energy proton beam at BNL-BLIP
    - Estimated beam cost for 4 weeks ~ $1M
- **Thermal shock testing:** HiRadMat facility at CERN
    - Through proposal submission but need 2 years of preparation (proposal, safety, irradiated material transport, PIE…)

0.77 FTE/y + $108k/y M&S → 1.5 FTE + $2M + $200k/y M&S

Novel Target Materials: *New materials with enhanced thermal shock and radiation damage resistance*

- **High-Entropy Alloys:** complex multi-element alloys
- **Nanofibers:** Electrospun ceramic and metallic nanofibers
    - HEAs and nanofiber covered by DOE ECRP, 2022, K. Ammigan
    - Need funds at the same level to support more target material development for specific applications

ECRP: $500k/y

GARD (including US-JP)= $ 1.7M (to FNAL: 2.25 FTE + ~$270k M&S)

We need to ramp up activities to fully respond to the needs for next generation accelerator

Significant High Power Targetry R&D is needed and more resources are essential to be ready to support future accelerators

Alternative Methods: *Emulate high energy proton irradiations for accelerated and cost-effective material screening*

- **Low Energy Ion** for assessing radiation damage effects
- **Electron beam** for thermal shock and fatigue testing
- **Novel Testing Methods** (fatigue studies)
    - Need 0.5 FTE and at least $100k per year per project for 3 years

0.63 FTE/y + $145k/y M&S → 1.5 FTE/y + $300k/y M&S

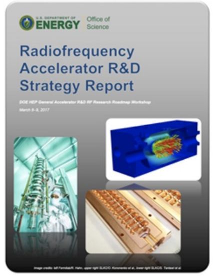
Develop Modeling: *Prediction of fundamental response of various materials to irradiation and thermal shock*

- **Helium gas bubbles** formation and segregation
- **Radiation damage effects** on HEAs
- **Heat transfer mechanism** in nanofiber media
    - Need more development and experimental data for specific application

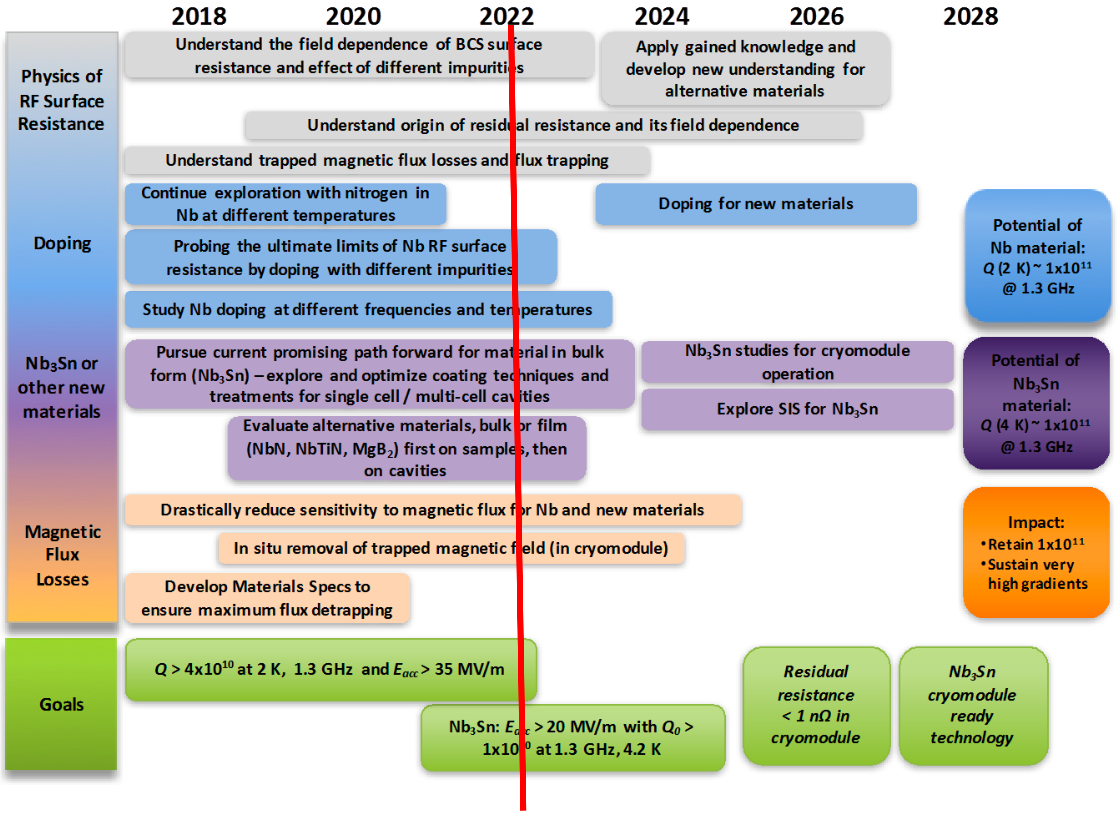
0.85 FTE/y + $16k M&S → 1.5 FTE/y + $100k/y M&S

R&D coordinated through the RaDIATE Collaboration. Lead by FNAL since 2012,
Goal to share knowledge on radiation damage and thermal shock in materials within the 20 national and international participants.
Not a fund resource ⇨ Not effective enough to reach HEP goals

SRF acceleration technology R&D needs



- SRF R&D is guided by the DOE/HEP GARD RF Accelerator R&D Strategy Report (developed in 2017), which contains several 10-year roadmaps
- Two of the roadmaps set directions for **high Q** and **high gradient** SRF frontiers
  - Push the SRF cavity beyond the LCLS-II cavities, i.e. < 1 nΩ residual resistance in cryomodule
  - Continue to explore new cavity design and material to push the SRF cavity gradient to 50MV/m and beyond
- In addition, there is a description of **common elements** (e.g., new SRF materials, advanced cavity geometries, field emission mitigation) and **auxiliary systems** (HOM dampers, FPCs, tuners, etc.)



2018 2020 2022 2024 2026 2028

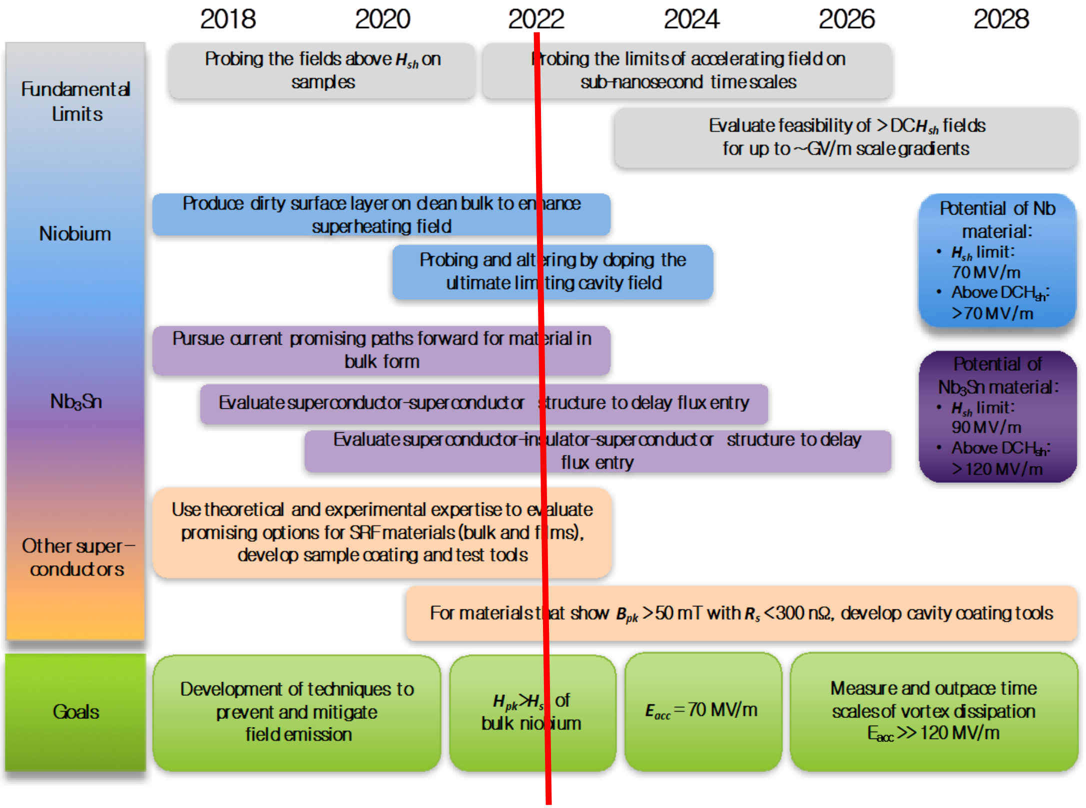
Physics of RF Surface Resistance
Understand the field dependence of BCS surface resistance and effect of different impurities
Apply gained knowledge and develop new understanding for alternative materials
Understand origin of residual resistance and its field dependence
Understand trapped magnetic flux losses and flux trapping

Doping
Continue exploration with nitrogen in Nb at different temperatures
Doping for new materials
Probing the ultimate limits of Nb RF surface resistance by doping with different impurities
Study Nb doping at different frequencies and temperatures
Potential of Nb material: Q (2 K) ~ 1x10^{11} @ 1.3 GHz

Nb$_3$Sn or other new materials
Pursue current promising path forward for material in bulk form (Nb$_3$Sn) – explore and optimize coating techniques and treatments for single cell / multi-cell cavities
Nb$_3$Sn studies for cryomodule operation
Explore SIS for Nb$_3$Sn
Evaluate alternative materials, bulk or film (NbN, NbTiN, MgB$_2$) first on samples, then on cavities
Potential of Nb$_3$Sn material: Q (4 K) ~ 1x10^{11} @ 1.3 GHz

Magnetic Flux Losses
Drastically reduce sensitivity to magnetic flux for Nb and new materials
In situ removal of trapped magnetic field (in cryomodule)
Develop Materials Specs to ensure maximum flux detrapping
Impact:
- Retain 1x10^{11}
- Sustain very high gradients

Goals
Q > 4x10^{10} at 2 K, 1.3 GHz and E_{acc} > 35 MV/m
Nb$_3$Sn: E_{acc} > 20 MV/m with Q_0 > 1x10^{10} at 1.3 GHz, 4.2 K
Residual resistance < 1 nΩ in cryomodule
Nb$_3$Sn cryomodule ready technology



2018 2020 2022 2024 2026 2028

Fundamental Limits
Probing the fields above H_{sh} on samples
Probing the limits of accelerating field on sub-nanosecond time scales
Evaluate feasibility of > DC H_{sh} fields for up to ~GV/m scale gradients

Niobium
Produce dirty surface layer on clean bulk to enhance superheating field
Probing and altering by doping the ultimate limiting cavity field
Potential of Nb material:
- H_{sh} limit: 70 MV/m
- Above DCH_{sh}: >70 MV/m

Nb$_3$Sn
Pursue current promising paths forward for material in bulk form
Evaluate superconductor-superconductor structure to delay flux entry
Evaluate superconductor-insulator-superconductor structure to delay flux entry
Potential of Nb$_3$Sn material:
- H_{sh} limit: 90 MV/m
- Above DCH_{sh}: >120 MV/m

Other super–conductors
Use theoretical and experimental expertise to evaluate promising options for SRF materials (bulk and films), develop sample coating and test tools
For materials that show B_{pk} >50 mT with R_s <300 nΩ, develop cavity coating tools

Goals
Development of techniques to prevent and mitigate field emission
H_{pk}>H_{sh} of bulk niobium
E_{acc} = 70 MV/m
Measure and outpace time scales of vortex dissipation E_{acc} >> 120 MV/m

NC-RF acceleration technology R&D needs

- Similarly, NC-SRF R&D is also guided by the DOE/HEP GARD RF Accelerator R&D Strategy Report developed in 2017), which contains both NC conducting RF structure and RF source 10-year roadmaps

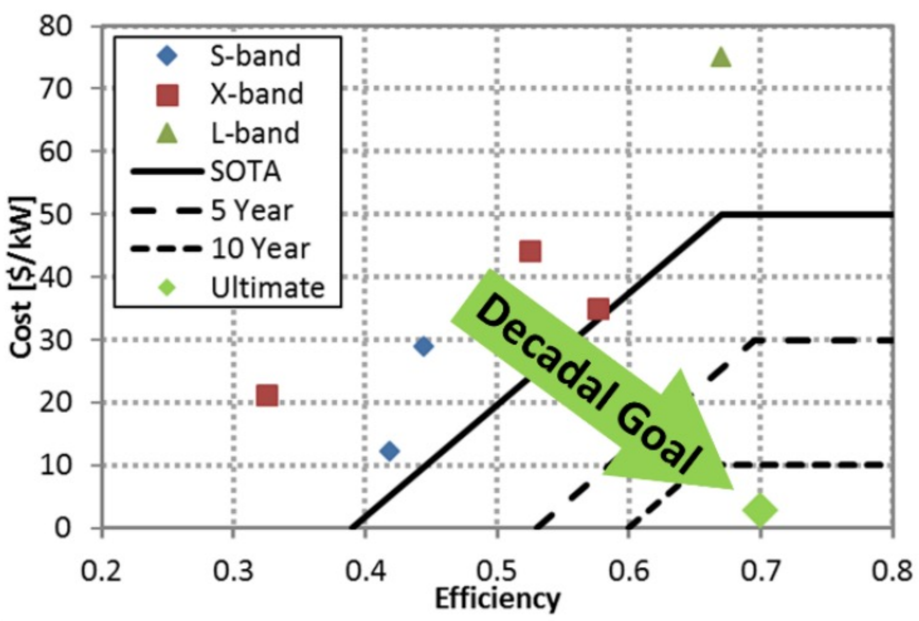
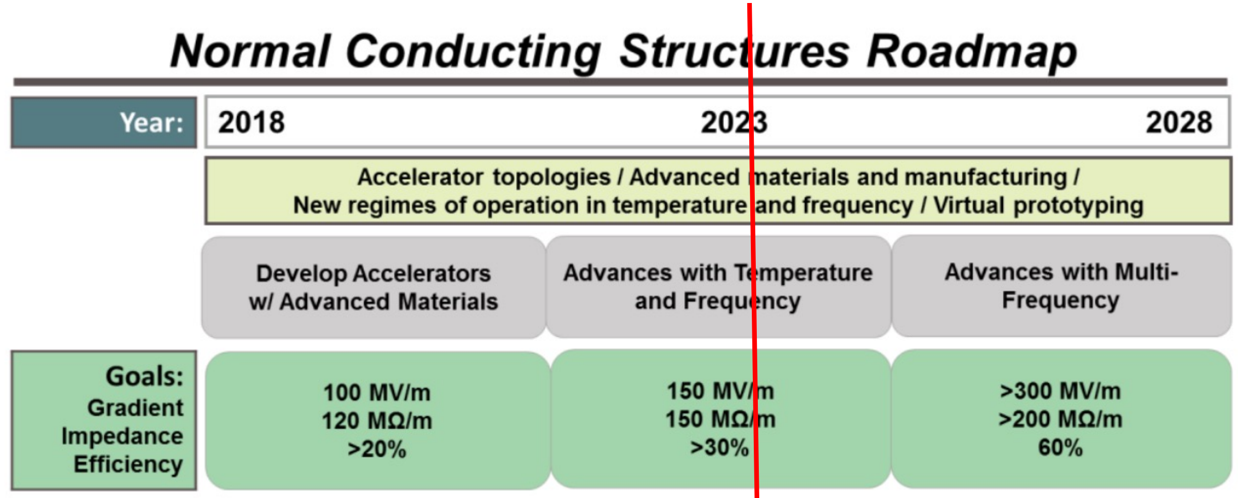


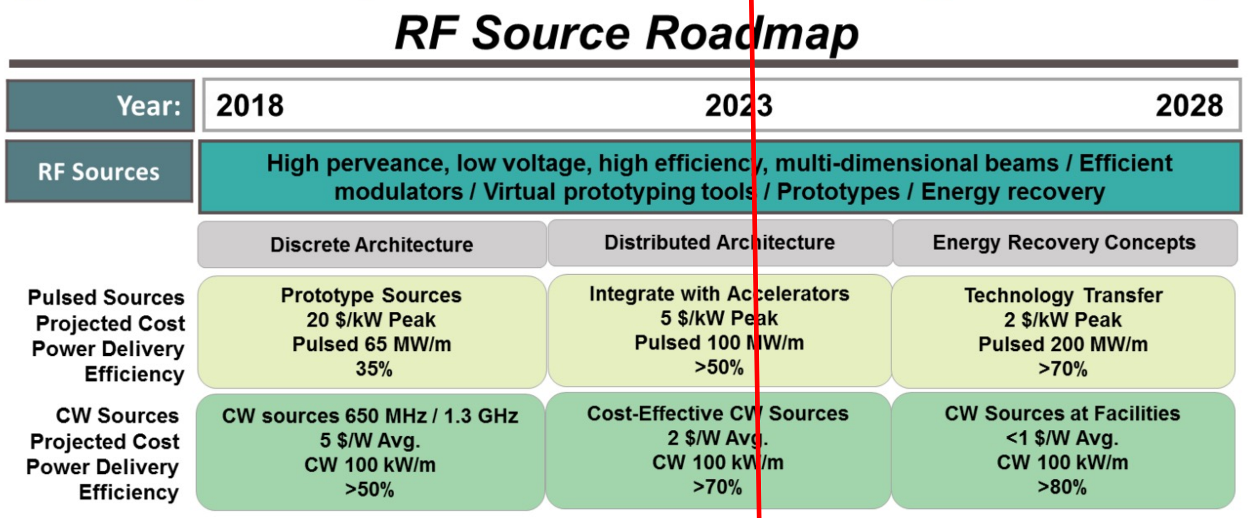
Figure 7: RF source cost including modulators in $ per peak kW vs. efficiency for mature source technologies.



Normal Conducting Structures Roadmap

Year:	2018	2023	2028
	Accelerator topologies / Advanced materials and manufacturing / New regimes of operation in temperature and frequency / Virtual prototyping		
	Develop Accelerators w/ Advanced Materials	Advances with Temperature and Frequency	Advances with Multi-Frequency
Goals: Gradient Impedance Efficiency	100 MV/m 120 MΩ/m >20%	150 MV/m 150 MΩ/m >30%	>300 MV/m >200 MΩ/m 60%

Figure 5: Ten-year roadmap and milestones for the normal conducting structures roadmap.



RF Source Roadmap

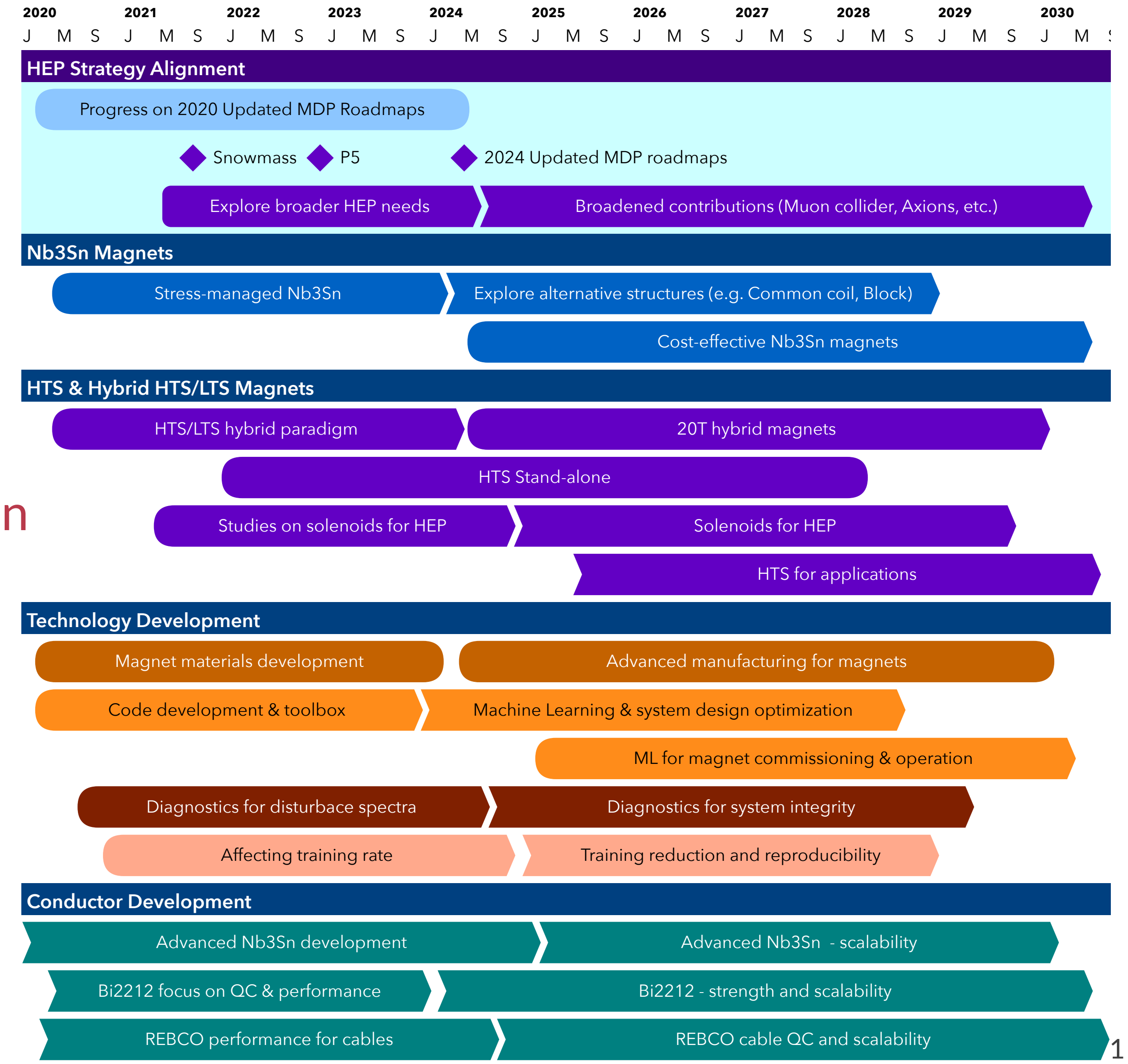
Year:	2018	2023	2028
RF Sources	High perveance, low voltage, high efficiency, multi-dimensional beams / Efficient modulators / Virtual prototyping tools / Prototypes / Energy recovery		
	Discrete Architecture	Distributed Architecture	Energy Recovery Concepts
Pulsed Sources Projected Cost Power Delivery Efficiency	Prototype Sources 20 $/kW Peak Pulsed 65 MW/m 35%	Integrate with Accelerators 5 $/kW Peak Pulsed 100 MW/m >50%	Technology Transfer 2 $/kW Peak Pulsed 200 MW/m >70%
CW Sources Projected Cost Power Delivery Efficiency	CW sources 650 MHz / 1.3 GHz 5 $/W Avg. CW 100 kW/m >50%	Cost-Effective CW Sources 2 $/W Avg. CW 100 kW/m >70%	CW Sources at Facilities <1 $/W Avg. CW 100 kW/m >80%

Figure 6: Ten-year roadmap and milestones for the RF source roadmap.

https://www.osti.gov/servlets/purl/1631119

Superconducting Magnet and materials R&D needs

See Magnets for Energy Frontier, S. Prestemon



HEP Strategy Alignment

Progress on 2020 Updated MDP Roadmaps

Snowmass

P5

2024 Updated MDP roadmaps

Explore broader HEP needs

Broadened contributions (Muon collider, Axions, etc.)

Nb3Sn Magnets

Stress-managed Nb3Sn

Explore alternative structures (e.g. Common coil, Block)

Cost-effective Nb3Sn magnets

HTS & Hybrid HTS/LTS Magnets

HTS/LTS hybrid paradigm

20T hybrid magnets

HTS Stand-alone

Studies on solenoids for HEP

Solenoids for HEP

HTS for applications

Technology Development

Magnet materials development

Advanced manufacturing for magnets

Code development & toolbox

Machine Learning & system design optimization

ML for magnet commissioning & operation

Diagnostics for disturbace spectra

Diagnostics for system integrity

Affecting training rate

Training reduction and reproducibility

Conductor Development

Advanced Nb3Sn development

Advanced Nb3Sn - scalability

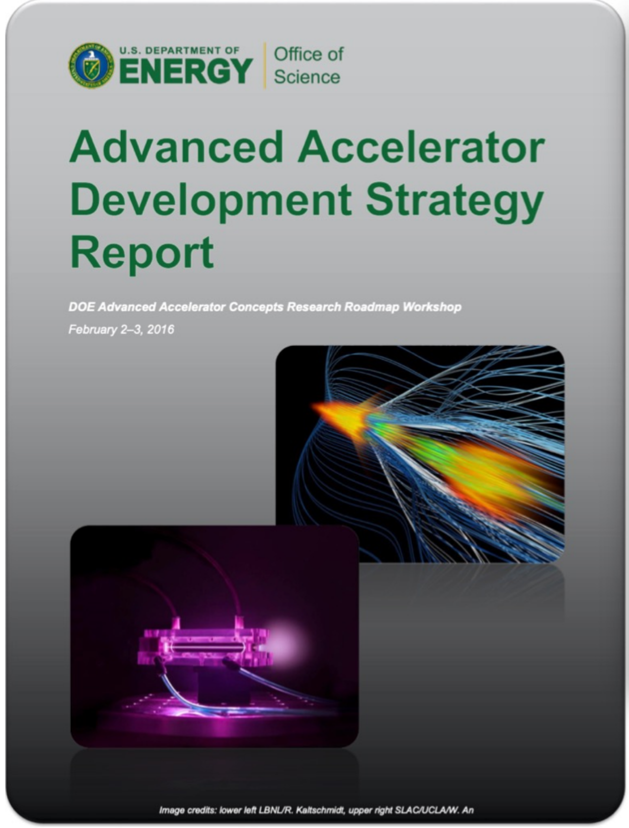
Bi2212 focus on QC & performance

Bi2212 - strength and scalability

REBCO performance for cables

REBCO cable QC and scalability

Advanced Acceleration Concepts: R&D needs



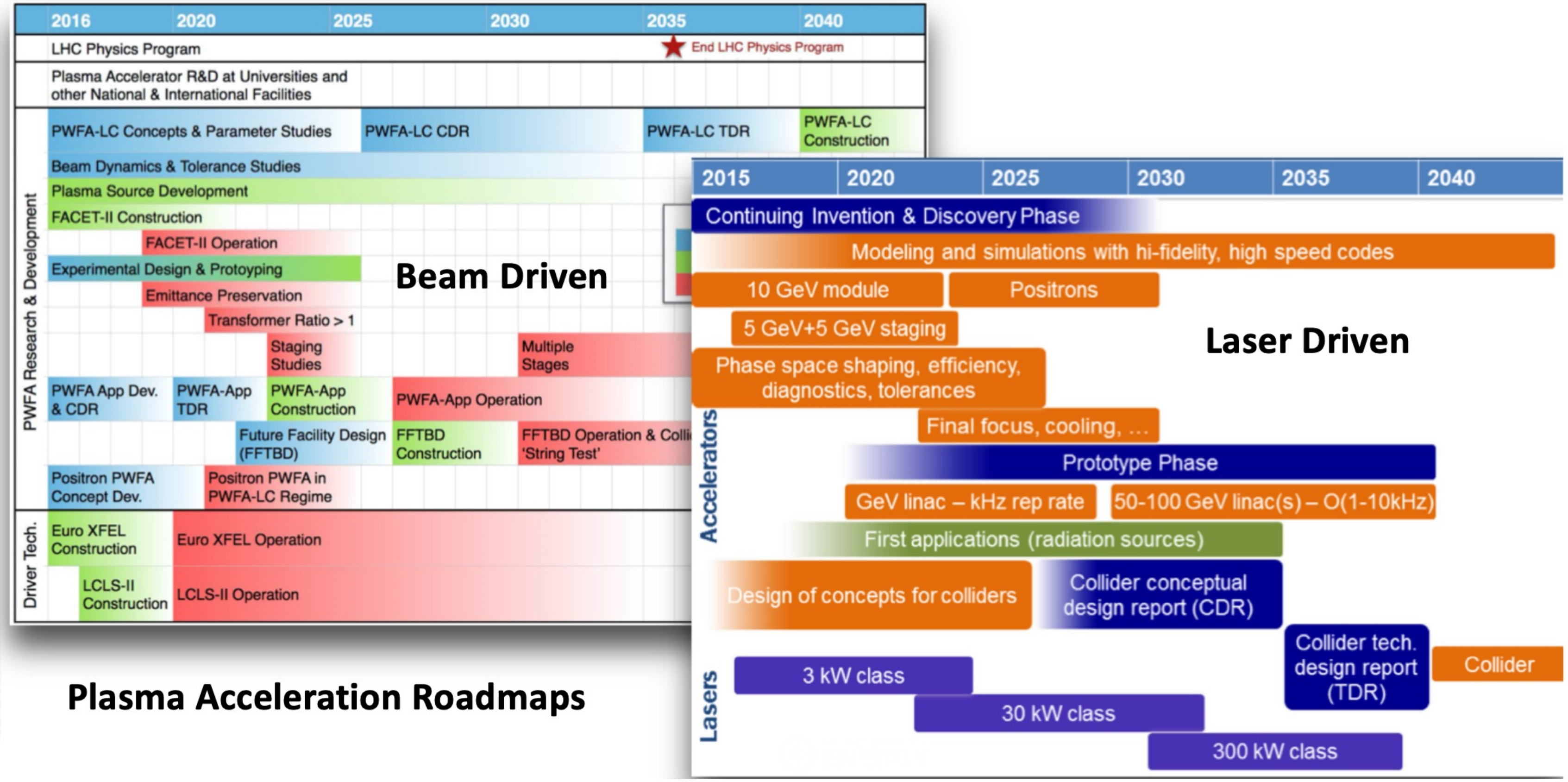
U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An

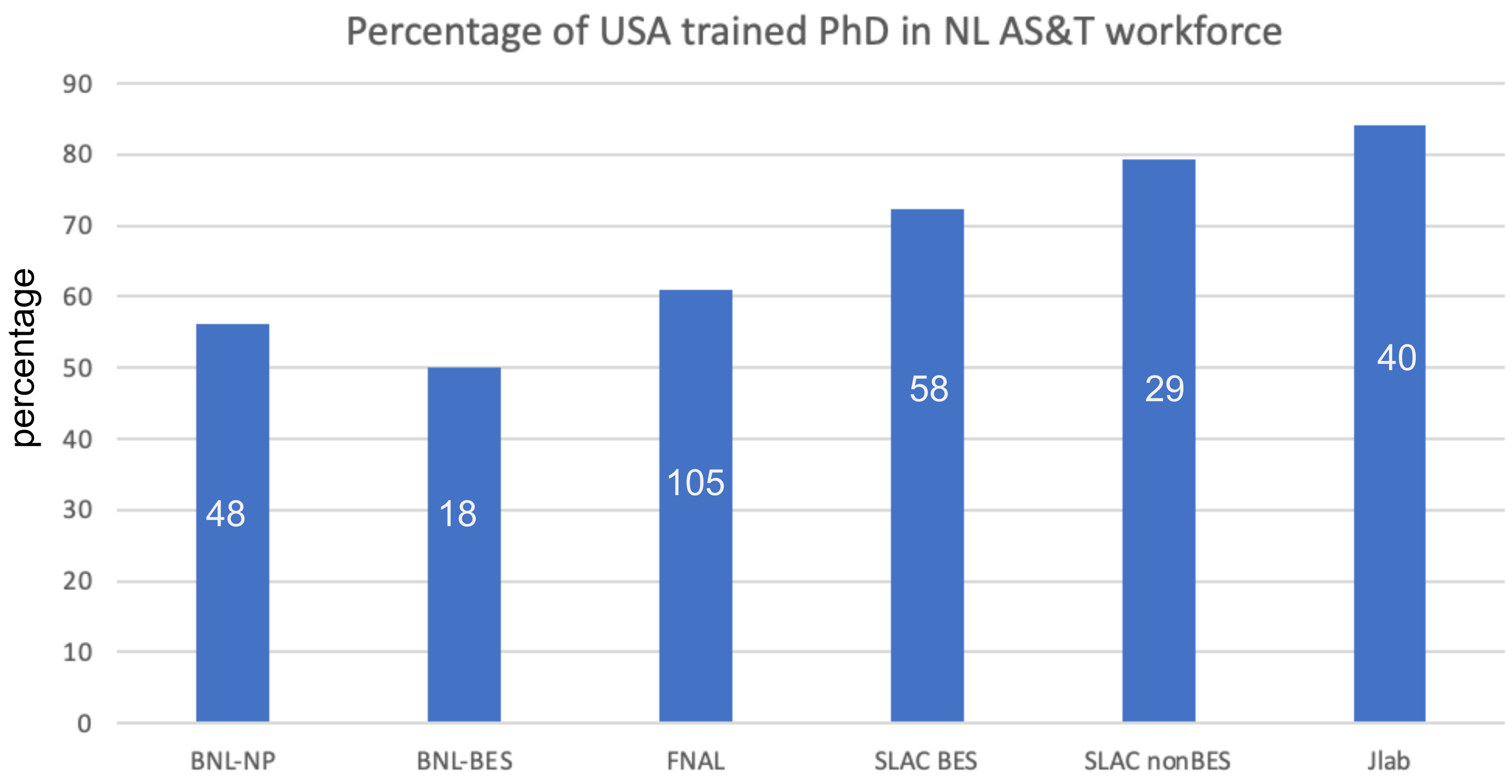


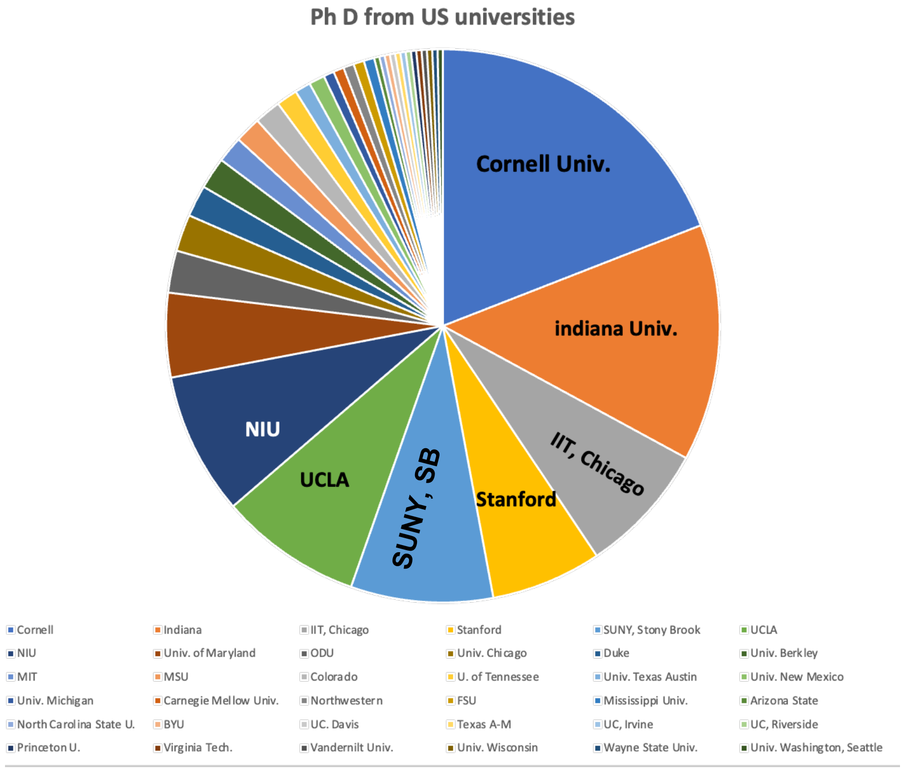
Plasma Acceleration Roadmaps

See Advanced Accelerator Concept, Spencer Gessner

Universities: an indispensable part of the US accelerator R&D

- US universities provide valuable research and a significant part of the accelerator workforce in the national labs

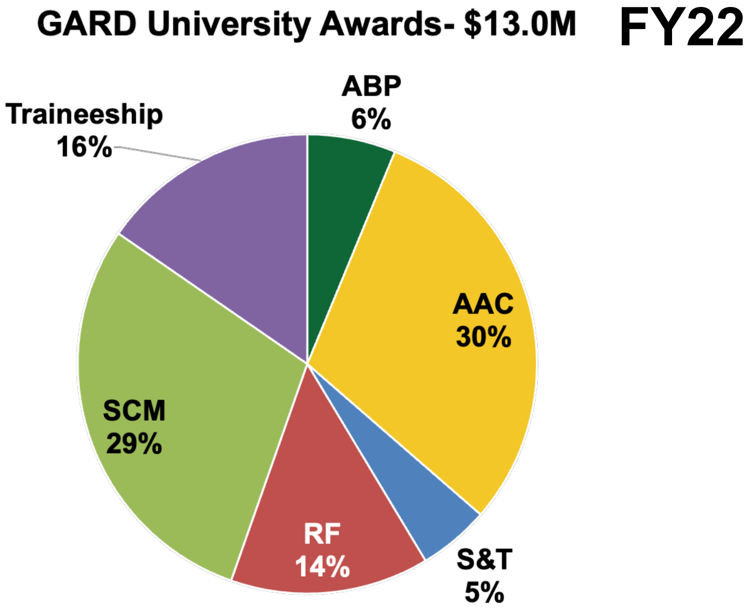




Based on data collected on ad hoc basis. Could be incomplete.

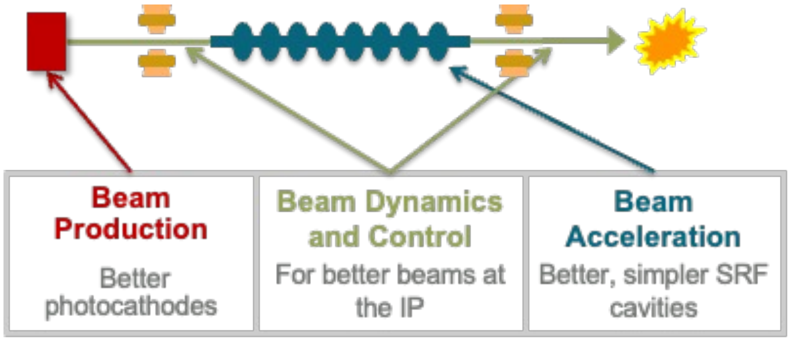
Universities: an indispensable part of the US accelerator R&D

GARD has been supporting ~35 universities



Currently, NSF Sci&Tech center supports the accelerator R&D program, Center of Bright Beams, led by Cornell

- A hub of strong faculty team with bright students to tackle challenging R&Ds to increase the intensity, or brightness, of beams of charged particles by a factor of 100 while decreasing the cost of key accelerator technologies



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

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

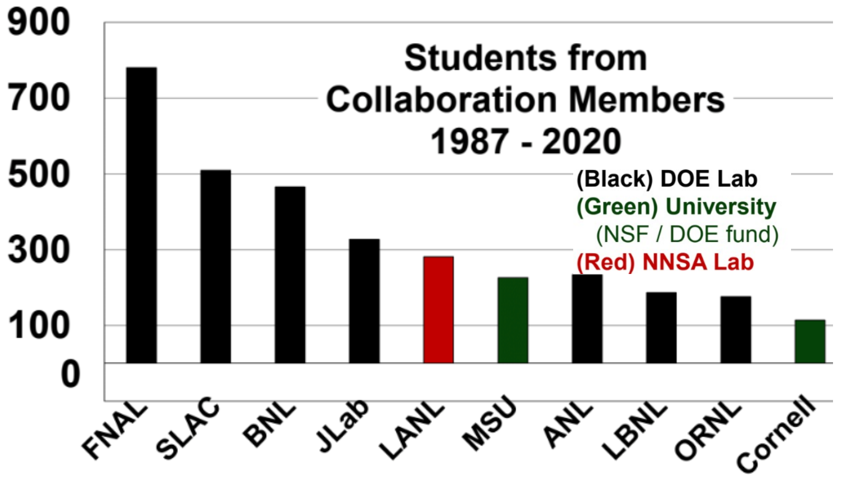
For details, please see Ritchie Patterson's talk on NSF funded accelerator projects/university work

NSF has also funded the proton source development IsoDAR, an isotope at rest experimental program at MIT, and CXFEL for Biology at ASU

- Both are accelerator-based projects which require novel accelerator design and technologies, also offer rich beam dynamics

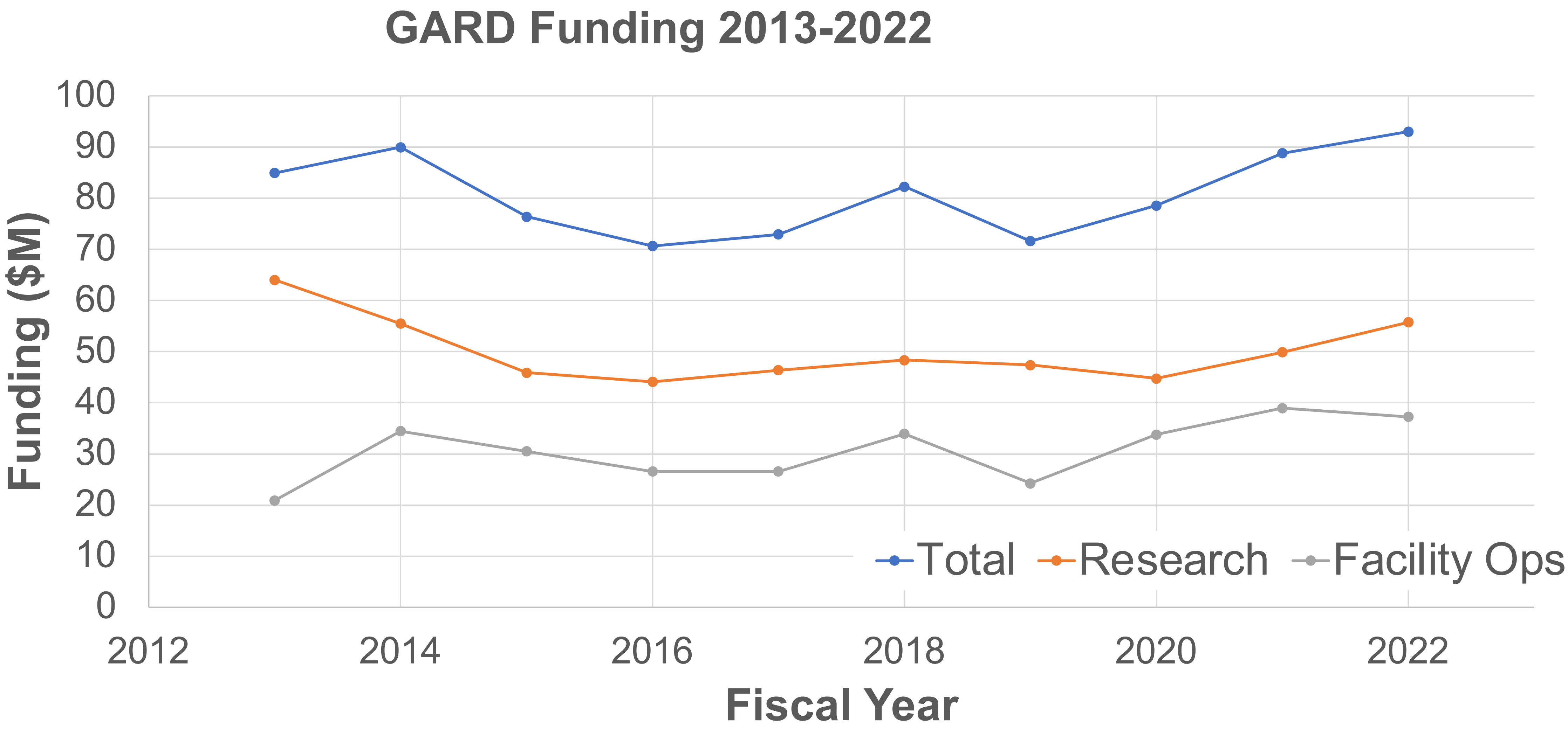
GARD funded US PAS and Accelerator Traineeships

- US Particle Accelerator School (USPAS) and accelerator traineeships are to fill the needs of many specialized courses that are rarely available in universities such as high-power RF engineering, high power pulsed power, accelerator cryogenic design, collective effective, etc
- USPAS was funded in 1987 as a national lab consortium and stewarded by Fermilab to provide high quality training for the accelerator community at large. It draws teaching resources from national labs
- In two intensive format sessions per year, the USPAS delivers typically 22 mostly grad-level academic-format courses reaching 280 students
- As part of the ABP roadmap, GARD currently funds four accelerator traineeships at ASET at MSU, Courant at SUNY, CAST at IIT/NIU, and VITA at ODU which all rely on USPAS courses for students



- The USPAS's annual budget has been flat (~$1M) over the past five years to cover 2.75 FTE (director + 2 admin experts), student supports, etc.
- **Modest increase** of current funding level **to add one FTE** will enable continued larger sessions and ensure continuity in administrative knowledge to continue success. **Further budget increase** can also help USPAS to **increase** its recruitment from **undergraduates and underrepresented groups**.
- The 2023 GARD ABP roadmap calls for closer coordination of all accelerator education and trainee efforts in the US

These R&D needs vs. current funding profile



Summary

- HEP has been the steward for accelerator R&D in the US. The outcomes have not only benefited for HEP missions but also the missions across the Office of Science as well as other funding agencies
- While current GARD funding portfolio has been well aligned with the 2014 P5 recommendation, its overall funding size for general research, facilities and education/training needs to be **significant increased** to keep the US accelerator R&D stay healthy and competitive for tomorrow's HEP missions.
- While US currently has a set of accelerator test facilities, some of them are dated and in urgent needs for addressing the long-deferred maintenance not only for safe operation, but also allow them to be competitive w.r.t. similar test facilities worldwide
- Universities make important contributions to the US accelerator R&D as well as workforce. Continue to have strong NSF and DOE supported accelerator programs in the universities can further augment HEP accelerator developments

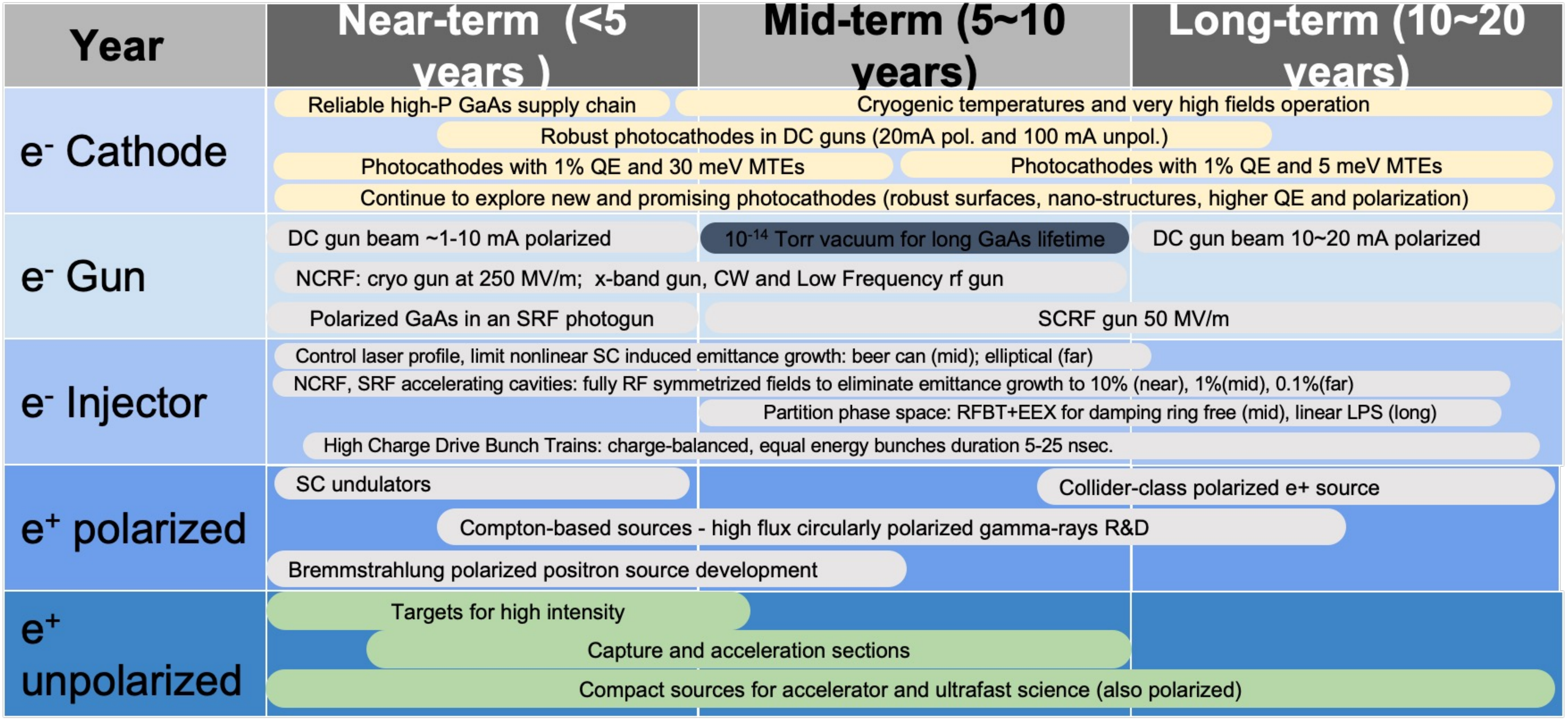
十年树木，百年树人

Acknowledgment

Many thanks to the colleagues who provided comprehensive inputs and invaluable discussions upon very short notice! In particular,
-- Ken Marken and Derun Li for providing GARD funding statistics
-- Frederique Pellemoine and Yine Sun for providing Particle sources and targets roadmaps and R&D needs
-- Sergey Belomestnykh and Emilio Nanni for providing SRF and NC-RF related materials
-- Vladimir Shiltsev, Steve Lund, Sergei Nagaitsev for helping ABP, USPAS and Traineeships
-- Sasha Valishev for very fruitful discussions on PIP-II,/ACE, IOTA and GARD
-- Jared Maxson for providing the high brightness photoinjector development details
-- Ritchie Patterson for providing CBB and university related information
-- Mark Hogan, Eric Esarey and John Power for providing AAC related materials

Particle source R&D needs

April 2023 e± Source Roadmap Working Group Report



Year	Near-term (<5 years)	Mid-term (5~10 years)	Long-term (10~20 years)
e- Cathode	Reliable high-P GaAs supply chain	Cryogenic temperatures and very high fields operation	
	Robust photocathodes in DC guns (20mA pol. and 100 mA unpol.)		
	Photocathodes with 1% QE and 30 meV MTEs	Photocathodes with 1% QE and 5 meV MTEs	
	Continue to explore new and promising photocathodes (robust surfaces, nano-structures, higher QE and polarization)		
e- Gun	DC gun beam ~1-10 mA polarized	10^{-14} Torr vacuum for long GaAs lifetime	DC gun beam 10~20 mA polarized
	NCRF: cryo gun at 250 MV/m; x-band gun, CW and Low Frequency rf gun		
	Polarized GaAs in an SRF photogun	SCRF gun 50 MV/m	
e- Injector	Control laser profile, limit nonlinear SC induced emittance growth: beer can (mid); elliptical (far)		
	NCRF, SRF accelerating cavities: fully RF symmetrized fields to eliminate emittance growth to 10% (near), 1%(mid), 0.1%(far)		
		Partition phase space: RFBT+EEX for damping ring free (mid), linear LPS (long)	
	High Charge Drive Bunch Trains: charge-balanced, equal energy bunches duration 5-25 nsec.		
e+ polarized	SC undulators	Collider-class polarized e+ source	
	Compton-based sources - high flux circularly polarized gamma-rays R&D		
	Bremmstrahlung polarized positron source development		
e+ unpolarized	Targets for high intensity		
	Capture and acceleration sections		
	Compact sources for accelerator and ultrafast science (also polarized)		