Office of High Energy Physics

Report of the DOE Program Review of HEP Laboratory General Accelerator R&D

August 5-9, 2024

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I. Introduction

The General Accelerator R&D (GARD) Program, under the stewardship of the DOE Office of High Energy Physics (HEP), plays an indispensable role in advancing accelerator science and technology. Although its primary mission is to advance research and development in accelerator science and technology for high-energy physics experiments, its impact profoundly reaches across a broad spectrum of scientific disciplines. The program not only advocates innovation in particle colliders but also supports the broader needs of other DOE Science Offices, such as Basic Energy Sciences (BES), Nuclear Physics (NP) and Fusion Energy Sciences (FES). These advancements enable transformative applications in areas such as materials science, energy research, nuclear physics, and medical technology. By supporting foundational research, GARD underpins the operation of DOE facilities such as Free Electron Lasers (FELs), neutron sources, and storage-ring based synchrotron light sources, which are essential for breakthroughs in atomic and molecular science, energy research, and biological imaging.

A notable example of GARD's interdisciplinary impact is the application of its advancements in Accelerator and Beam Physics (ABP). The multi-bend achromat (MBA) lattice design, originally developed for damping rings for linear colliders, has been successfully adapted for diffraction-limited light sources. These include the Advanced Photon Source Upgrade (APS-U) at Argonne National Laboratory and the Advanced Light Source Upgrade (ALS-U) at Lawrence Berkeley National Laboratory. These upgrades provide significantly improved beam quality, enabling groundbreaking research in condensed matter physics, chemistry, and biological imaging. This successful transfer of technology highlights GARD's ability to address both high-energy physics challenges and the broader DOE scientific mission.

The 2024 GARD Review, conducted from August 5–9, was a comprehensive evaluation of general accelerator R&D efforts across five GARD-supported national laboratories: BNL, Fermilab, ANL, LBNL, and SLAC National Accelerator Laboratory (SLAC). The review committee, co-chaired by Dr. Derun Li (DOE-OHEP) and Dr. Andrei Seryi (Thomas Jefferson Laboratory), consisted of 10 committee members with expertise representing five GARD thrusts:

1. Felicie Albert, Lawrence Livermore National Laboratory
2. Lance Cooley, Florida State University
3. Sarah Cousineau, Oak Ridge National Laboratory
4. Yue Hao, Michigan State University
5. Matthias Liepe, Cornell University
6. Michiko Minty, Brookhaven National Laboratory
7. Pietro Musumeci, University of California, Los Angeles
8. Robert Rimmer, Thomas Jefferson National Accelerator Facility
9. Andrei Seryi, Thomas Jefferson National Accelerator Facility
10. Yuhu Zhai, Princeton Plasma Physics Laboratory

The review was organized to avoid overly detailed technical presentations, instead favoring broader overviews of each lab's GARD thrust areas to foster high-level discussions. While this approach provided a comprehensive understanding of R&D progress, the committee noted insufficient time for Q&A sessions and internal deliberations to explore certain critical topics. To address these gaps, follow-up Zoom meetings were held after the review, allowing the committee to thoroughly discuss and evaluate each lab's performance, findings, workforce development efforts, and proposed recommendations.

The review also featured poster sessions at facilities at ATF (BNL), AWA (ANL), Fermilab, and LBNL, which offered direct engagement in-person with students, postdocs, and early-career scientists. The committee was highly impressed by the enthusiasm and quality of work displayed by early-career researchers, recognizing workforce development as a cornerstone of GARD's success. Tours of research facilities, including FAST/IOTA, BELLA, AWA, FACET-II, and NLCTA, provided firsthand exposure to the state of art technologies under development and the practical applications of GARD research across accelerator science and technology.

While the review format effectively showcased progress at each lab, the committee believes future reviews could benefit from extended Q&A sessions and additional time for internal committee discussions to allow a more detailed exploration of specific issues of concerns. However, given the time constraints of a single week, the current review format remains the most practical and efficient approach.

In the following sections, the report begins with an overview of the GARD thrusts, followed by detailed findings, comments, and recommendations organized by thrust area in Section II, and by individual facility in Section III. A summary of the review is provided in Section VI. The appendices include the charge letter for the review, a list of recommendations, the committee members, and the agendas of the review sessions at each institution.

II. Overall Program Evaluation

The GARD program plays a pivotal role in maintaining the U.S. leadership in particle accelerator technologies. The program shows solid overall health, with significant progress being made across all major thrusts. This review highlighted significant advances across various thrust areas. These advancements are crucial for supporting the long-term mission of high energy physics. Despite this progress, certain aspects of the program require improvement, particularly in terms of focus, resource allocation, and maintaining a balanced funding profile and development priorities.

Workforce development efforts have been particularly successful within the Advanced Accelerator Concepts (AAC) thrust, where a continuous pipeline of students, postdocs, and junior scientists are actively contributing to cutting-edge research. However, there is a recognized need to expand similar efforts to more traditional technology areas, including accelerator and beam physics, to ensure balanced progress across all thrusts. Enhancing workforce development in these areas is essential for maintaining the long-term vitality of the field. The GARD Program should further strengthen the collaboration between the AAC thrust and other areas to better support the long-term needs of traditional accelerator science and technology at national laboratories. By encouraging the integration of AAC innovations with conventional technologies, along with sharing workforce development efforts, the program will be well-positioned to address both immediate challenges and future needs of the workforce in accelerator science and technology.

One of the most critical observations from the review is the alignment of GARD's efforts with the previous and the 2023 P5 recommendations. The AAC and Accelerator and Beam Physics (ABP) thrust may need further adaptation to fully align with the evolving HEP mission. National laboratories continue to deliver world-class research, but they face challenges in workforce retention, resource limitations, and management issues. These challenges, if left unaddressed, could have a negative impact on the long-term sustainability of the GARD program and its contributions.

The importance of collaboration between national labs and universities cannot be overstated. While current collaborations have been fruitful, stronger mechanisms for knowledge transfer and workforce development are needed to ensure the future growth of the field. This includes fostering students and postdocs involvement in GARD activities and creating more structured pathways for academic engagement and career development.

Another key observation concerns the balance of funding profile and research thrusts within the GARD program. There is a need to ensure that funds are distributed strategically across various research areas, rather than being overly concentrated in facility operations or specific research directions.

The AAC community has made impressive academic progress, produced publications in high-impact journals and successfully attracted and developed young talent at universities and laboratories, contributing to workforce development in accelerator science. While near-term applications using AAC technology are still in development, it is recommended that the GARD Program should consider reassessing its funding allocation. Given AAC's long-term and high-reward potential for HEP, a balanced approach may be beneficial, ensuring continued investment for long-term R&D while carefully evaluating the immediate and mid-term benefits to HEP. The AAC support should be balanced with ABP and other technology thrusts, which are critical for mid- and long-term advancements. Furthermore, the imbalance between proton and electron research, noted in last GARD review in 2018, remains an issue, with electron research still receiving the bulk of funding. Given the critical role of proton research and high-power target development for the U.S. high-intensity neutrino program and future energy frontier colliders, these areas require greater focus and support. Ensuring a more balanced investment across all thrusts is essential to addressing both current and long-term challenges in GARD. The review noted that while test facilities are vital for advancing GARD's goals, their operational costs must be kept in check to ensure that adequate resources remain for broader research activities.

The Five GARD Thrusts

One of GARD's key strengths lies in its investment in foundational accelerator science which includes Accelerator and Beam Physics (ABP), Advanced Accelerator Concepts (AAC), RF Technology (superconducting and normal conducting RF), and Superconducting Magnets and Materials (SCM) and Particle Sources and Targetry (PST). The program has been instrumental in developing technologies for high-efficiency production of high energy and high intensity beams, compact accelerator structures, and advanced superconducting materials. These developments are not only critical for future high energy frontier colliders but also have broader applications in DOE research infrastructure, such as light sources, neutron sources, and FELs, which support critical research in materials science, chemistry and biology etc.

To provide a clear overview of the program across five GARD-supported national laboratories, the following table outlines each lab's research activities and facilities within the five GARD thrust areas: Accelerator and Beam Physics (ABP), Advanced Accelerator Concepts (AAC), RF Technology, Superconducting Magnets (SCM), and Particle Sources and Targets (PST). This comparison highlights the unique strengths, complementary efforts, and key facilities that support accelerator R&D under GARD.

Lab/Thrust	BNL	Fermilab	ANL	LBNL	SLAC
ABP	Yes* (NP)	IOTA/FAST exp.	Beam manipulation	AMP and BACI	Collider Physics
AAC	PWFA* (ARDAP)	AAC beam testing	High gradient NCRF	LPA-BELLA	PWFA-FACET-II
PST	Photocathode	High Power Target	Photocathode	No	No
RF	No	SRF	NCRF structures	NCRF RFQ etc.	NCRF & source
SCM	Yes	SC magnets and materials	No	SC magnets and materials	No
Facilities	ATF* and SCM Lab*	IOTA/FAST, ATF for SRF and SCM	AWA	BELLA, magnet cable & test lab	FACET-II and NLCTA

* Not supported by HEP GARD.

Accelerator and Beam Physics (ABP)

The ABP thrust is centered on advancing our understanding of beam dynamics, improving beam quality, and optimizing accelerator operations. The R&D programs are also guided by the ABP roadmap report, developed in 2022 and released in 2023[1]. Across national labs, ABP programs focus on developing new theoretical models, simulations, and experimental techniques that enhance the performance of both conventional and advanced accelerator systems. These efforts are critical for improving beam stability, reducing losses, and pushing the boundaries of beam intensity and energy. LBNL, SLAC and ANL are leaders in using AI/ML algorithms to predict and control beam behavior, paving the way for more efficient and stable accelerator operations.

Advanced Accelerator Concepts (AAC)

The AAC thrust is focused on developing next-generation ultra-high gradient and compact accelerator technologies, based on plasma wakefield acceleration in both beam- and laser-driven (PWFA), and structure wakefield acceleration (SWFA). Berkeley Lab (with its BELLA program) and SLAC (with FACET-II) are key players in pushing the frontiers of plasma-based acceleration, achieved milestone of a 10 GeV single-stage acceleration at BELLA and multi-GeV beam acceleration at FACET-II. These technologies have potential for future compact, cost-effective accelerators, light sources and colliders.

RF Technology (Superconducting and Normal Conducting RF)

In the RF thrust, both SRF and NCRF technologies are being advanced across national labs at Fermilab, LBNL and SLAC. Fermilab has achieved record-high gradients in Nb3Sn cavities and pioneered the mid-T baking process, which enhances cavity performance and is critical for projects like PIP-II, EIC, light sources and colliders. LBNL continues to innovate in NCRF design and

[1] HEP GARD Accelerator and Beam Physics Roadmap Report can be found at DOE website at https://science.osti.gov/hep/-/media/hep/pdf/2022/ABP_Roadmap_2023_final.pdf

fabrication, focusing on improving RF system efficiency and cavity development. SLAC has made significant progress with RF sources, copper and distributed coupling RF structures, aimed at achieving higher gradients through cryogenically cooled copper structures, and continues to advance the NCRF technology through experimental demonstration at the NLCTA facility. These efforts collectively push RF technology forward, supporting current and future accelerator designs and operations, and reinforcing the GARD Program's leadership in RF technology.

Superconducting Magnets (SCM)

The SCM thrust focuses on the development of high-field superconducting magnets. These magnets are central to next-generation particle colliders, such as the planned Future Circular Collider (FCC) and muon collider. Fermilab and LBNL are leaders in this area, working on the design, testing, and production of advanced superconducting magnets that can achieve higher magnetic fields with improved reliability. The SCM efforts are coordinated by the US Magnet Development Program (MDP) and support ongoing projects in high-energy physics, including upgrades to existing collider facilities.

Particle Sources and Targets (PST)

The particle sources and target thrust encompasses the development of reliable and efficient sources of charged particles and the design of robust targets that can withstand high-power beams. This area is crucial for maximizing the performance of existing and future accelerators. High power target R&D to improve particle production and minimize damage under extreme conditions is essential for current and future HEP's intensity neutrino program. This thrust directly impacts the efficiency and longevity of particle accelerator facilities.

Test facilities

Test facilities focus on maintaining and upgrading national laboratory infrastructure to support cutting-edge accelerator research, technology development, operations and projects. This includes the development and operation of experimental testbeds of AWA at ANL, FACET-II and Next Linear Collider Test Accelerator (NLCTA) at SLAC, Accelerator Test Facility (ATF) for testing of superconducting RF cavities and magnets, IOTA/FAST beam testbed at Fermilab, and BELLA at LBNL. These facilities provide critical platforms for testing new accelerator technologies and conducting advanced beam physics experiments. The ATF at Fermilab plays a key role in supporting SRF cavity and superconducting magnet testing and development, while BELLA is a world-leading facility for laser-plasma acceleration (LPA) research, having achieved a significant milestone recently for a 10 GeV electron beam acceleration in a single stage. These facilities also serve as hubs for collaboration, attracting researchers and students worldwide, and they play a pivotal role in training the next generation of accelerator scientists and engineers.

Evaluation of GARD Thrust at Each Laboratory

The review began on the East Coast and progressed to the West, starting at BNL on August 5, followed by Fermilab on August 6, ANL on August 7, Berkeley Lab on August 8, and concluding at SLAC on August 9. This strategic schedule leveraged time zone differences, allowing for a reasonable travel schedule and agenda at each lab, optimizing the in-person review process. There was no closeout presentation at each reviewed lab; instead, comprehensive close-out presentations were held for the review committee at the end of the review at SLAC, enabling the committee to consolidate findings and provide an integrated and comparative assessment of the GARD program. This approach, also used in the 2018 GARD review, maximized efficiency, ensured thorough evaluations at each lab, and provided the best possible format for conducting such a comprehensive review.

Accelerator and Beam Physics (ABP)

The committee conducted a review of Accelerator and Beam Physics research across ANL, FNAL, LBNL and SLAC, highlighting significant technical progresses since the 2018 review. Most noticeable accomplishments include advancements in Optical Stochastic Cooling (OSC) at FNAL, integration of AI/ML in beam diagnostics, structural wakefield acceleration at AWA of ANL, and advanced modeling tools for beam physics at LBNL. Nevertheless, challenges related to resource limitations, simulation discrepancies, and workforce retention were noted. The review emphasizes the need for continued collaboration between labs, increased focus on high-priority research, and the enhancement of workforce development initiatives.

Argonne National Laboratory

The Argonne Wakefield Accelerator (AWA) at ANL continues to lead research in Structural Wakefield Acceleration (SWFA), conducting innovative studies that align closely with the mission of High Energy Physics (HEP). AWA's contributions span four of the five GARD thrust areas, addressing critical challenges such as high-intensity bunch charge propagation and phase-space manipulation using its Emittance Exchange (EEX) beamline.

The EEX beamline serves as a versatile testbed, enabling precise control of beam phase space by exchanging emittance between horizontal and longitudinal planes. This capability is crucial for optimizing accelerator performance, especially for applications requiring sub-picosecond-level control over longitudinal beam distribution. Such precision is vital for next-generation accelerators, where even minor deviations in beam timing or energy can significantly impact overall system performance. By manipulating the transverse beam distribution to tailor longitudinal beam properties, the EEX beamline supports effective acceleration strategies that push the boundaries of modern accelerator science.

AWA has effectively integrated Artificial Intelligence and Machine Learning (AI/ML) techniques into its operations, greatly enhancing beam diagnostics and optimization capabilities. Bayesian optimization has been utilized to efficiently explore complex multi-dimensional parameter spaces, while generative models have enabled virtual diagnostics of 4D and 6D beam phase distributions. These advancements have reduced the number of measurements needed for accurate beam modeling, significantly improving tuning processes and overall facility efficiency. Further collaborative AI/ML efforts with other laboratories could amplify these successes and expand their application to more complex beam scenarios.

Current efforts to verify coherent synchrotron radiation (CSR) effects represent an important step in strengthening the theoretical underpinnings of AWA's beamline technologies. CSR effects, which become prominent at high beam intensities, are critical for improving theoretical models and ensuring beam stability. By rigorously benchmarking CSR behaviors, AWA aims to enhance both the reliability and stability of high-intensity beam systems, making valuable contributions to the development of next-generation accelerators.

AWA also stands out for its strong commitment to workforce development. The lab regularly produces Ph.D. graduates and early-career scientists, many of whom remain active in the accelerator field. Its integration of advanced and conventional accelerator concepts provides an ideal environment for training the next generation of researchers. Leveraging diverse funding sources, including the Argonne Accelerator Institute (AAI), LDRD programs, SBIR grants, and partnerships with academic institutions - AWA ensures a steady pipeline of skilled scientists and engineers equipped to tackle the most pressing challenges in accelerator science.

Recommendations:

1. Develop a concrete upgrade plan for AWA, including feasibility studies, design evaluations, and resource requirements before the next GARD review, to ensure the facility remains state-of-the-art.

Brookhaven National Laboratory

There is no GARD-funded ABP R&D at BNL at the time of this review. However, ATF does have a vigorous and diverse research schedule of user experiments, which includes accelerator and beam physics studies, many led by university researchers. The committee was offered a tour of the AFT and is impressed by the ongoing research programs and workforce development efforts.

Fermilab

Fermilab's Integrable Optics Test Accelerator (IOTA) facility has achieved significant technical milestones in beam physics, conducting 35 experiments since the last GARD review. Among its notable accomplishments is the demonstration of Optical Stochastic Cooling (OSC) without amplification, which was published in *Nature*. This groundbreaking experiment, conducted with electron beams, achieved unprecedented precision in measuring quantum fluctuations. By utilizing state-of-the-art diagnostic tools and single-electron beam studies, the IOTA team explored new regimes of beam behavior with remarkable sensitivity.

The OSC program is progressing further with innovative explorations into optical stochastic crystallization and steady-state microbunching, techniques that aim to enhance beam coherence and stability for applications in free-electron lasers (FELs). These novel approaches extend the scope of beam cooling technologies, offering the potential to significantly improve the performance of next-generation accelerators.

The IOTA team has also advanced the application of Nonlinear Integrable Optics (NIO), achieving a large tune spread (~ 0.05) using electron beams. This milestone represents a breakthrough in managing high-intensity beams, as NIO allows for resonance crossings with minimal particle losses. Experimental results confirmed that the tune shift caused by NIO closely matched theoretical predictions, validating its effectiveness in maintaining beam stability under extreme conditions. Furthermore, the team demonstrated the integral of motion for NIO using a pencil electron beam, adding critical experimental verification for theoretical models.

Despite these successes, progress in transitioning from electron to proton beam studies has been much slower than anticipated. Proton beam experiments, crucial for high-intensity beam applications, were intended to inform the design of Fermilab's ACE-BR accelerator complex upgrade. These studies are essential for evaluating whether NIO can enable a 3-4x increase in beam intensity, a critical factor for the future of Fermilab's accelerator complex. Without experimental data from these studies, key decisions regarding the upgrade path, such as whether to pursue a superconducting 8 GeV linac or a rapid cycling synchrotron remain uncertain. Additionally, discrepancies between simulation models for proton beam behavior, particularly regarding space charge effects and coherent instabilities, underscore the urgent need for experimental validation to resolve these critical challenges.

Fermilab's contributions to beam dynamics, particularly its pioneering work in OSC and advancements in NIO, are highly commendable. However, the delays in proton beam research pose significant risks to the lab's ability to deliver on high-intensity beam applications and inform future accelerator upgrade plans. A revitalized focus on leadership, collaboration, and strategic alignment within Fermilab's Accelerator and Beam Physics (ABP) program is essential to address these challenges.

To strengthen its position in the global accelerator community, Fermilab must also enhance its engagement through active participation in domestic and international conferences, workshops, and technical meetings (e.g., IPAC, NAPAC, ICFA events, and Muon Collider workshops etc.). These platforms provide critical opportunities to showcase Fermilab's innovations, foster collaborations, and align its R&D efforts with the broader accelerator science community. Moreover, expanding partnerships with universities and student programs is vital for maintaining a robust pipeline of skilled researchers, ensuring that the next generation of accelerator scientists is equipped to tackle the field's evolving challenges.

Recommendations:

1. Accelerate high-intensity proton beam studies in IOTA by implementing a structured timeline with clear milestones. Within one-year, complete key benchmarks to validate high-intensity beam models and resolve simulation discrepancies, with dedicated resources and clear accountability to prevent further delays.
2. Revitalize Fermilab's Accelerator and Beam Physics (ABP) program and research culture through organizational restructuring and strengthened leadership within one-year. Expand collaborations with national laboratories and universities to enhance research capabilities and workforce development. Ensure alignment with the 2023 P5 Recommendations, particularly PIP-II, Fermilab's accelerator complex upgrades and future collider R&D.
3. Reinforce Fermilab's leadership in accelerator R&D by immediately implementing a concrete strategy to increase participation in key community conferences, workshops, and collaborations (e.g., IPAC, NAPAC, ICFA, SRF, Superconducting Magnets, and future collider workshops).

Lawrence Berkeley National Laboratory

Berkeley Lab's Advanced Modeling Program has firmly established itself as a leader in accelerator simulations, providing critical tools like the Beam, Plasma & Accelerator Simulation Toolkit (BLAST) to the global accelerator community. AMP's simulation capabilities have reached new levels, particularly with the development of the WARPX[2] and IMPACTX[3] codes, which offer 10 -100 times performance improvement compared to previous versions. WARPX focuses on modeling and simulating plasma-based accelerators, such as laser-plasma accelerators, while IMPACTX is designed for simulating beam dynamics in conventional accelerators, including space-charge effects and advanced beam manipulation techniques. Both codes are part of the DOE's Exascale Computing Project and have been implemented in C++ with support for both CPU and GPU architectures, enabling large-scale, high-fidelity simulations. These significant

[2] WARPX stands for Wide Area Relativistic Particle-in-cell (PIC) eXtended.
[3] IMPACTS stands for Integrated Map and Particle Accelerator Tracking eXtended.

advancements have contributed to AMP's receipt of the 2022 Gordon Bell Prize for exascale applications, underscoring the impact of these tools on the accelerator science community.

AMP's BLAST toolkit is an open-source simulation framework that integrates various tools for simulating beam behavior, plasma interactions, and particle acceleration. It includes advanced particle-in-cell (PIC) algorithms and can run on the latest high-performance computing systems, enabling users to simulate complex beam dynamics with unprecedented accuracy. The toolkit's wide adoption within the accelerator community speaks to its versatility and robustness.

AMP has made important contributions to understanding beam breakup (BBU) and hosing instabilities, two critical challenges in high-energy accelerators. By demonstrating that head-to-tail variations in the beam, induced by ion motion, can suppress these instabilities, AMP has provided a valuable insight into how to manage these effects in practical accelerator designs. Their work on laser plasma wakefield accelerators continues to push the boundaries of what is possible in high-energy physics.

The review committee was impressed by AMP's achievements in exascale computing projects but expressed concerns about the future sustainability of these efforts, particularly as DOE Exascale funding comes to an end. Without continued support, BLAST toolkit development could lose momentum. The overlap between AMP's modeling efforts and those at Berkeley's BELLA Center also suggests a need for better coordination and resource allocation to avoid duplication of efforts.

AMP's contributions to training students, postdocs and early-career scientists, particularly in high-performance computing and accelerator simulation, are noteworthy. The lab has been a hub for computational physicists, but long-term sustainability of funding will be crucial to maintaining this momentum. AMP team should collaborate with a broader accelerator community to develop a sustainable model for supporting the BLAST toolkit, offering both basic and progressive levels of support for users.

Recommendations:

1. Prioritize AMP efforts to meet the most pressing needs of the HEP community, such as PIP-II, accelerator complex upgrade at Fermilab, offshore Higgs Factory and future collider R&D.
2. Strengthen collaboration with IOTA and other labs to validate models for proton beams.

SLAC National Accelerator Laboratory

SLAC's Accelerator Beam Physics program focuses heavily on beam physics, collider design, and the integration of machine learning (ML). SLAC's FACET-II facility remains a key platform for both traditional beam physics research and advanced accelerator techniques, particularly in beam-driven plasma wakefield acceleration. Comprehensive efforts have been dedicated to advancing fundamental physics underlying the design of future accelerators. This research spans charged-particle optics, nonlinear dynamics, and collective effects, with recent breakthroughs significantly enhancing accelerator performance. A key development is the nonlinear map method, which provides a powerful framework for systematically characterizing chromatic optics in particle accelerators. Using this approach, SLAC researchers are continuously optimizing the dynamic aperture of the Electron-Ion Collider (EIC) while laying the groundwork for next-generation high-energy colliders, such as the Future Circular Collider (FCC). Additionally, theoretical advancements in mitigating coherent synchrotron radiation (CSR) limitations have enabled the generation of ultra-short electron bunches (<0.1 μm) reaching the 1 MA peak current regime. This breakthrough opens the door to dramatically increasing luminosity in future linear colliders, marking a significant step forward in accelerator science.

Significant progress has also been made in integrating ML into SLAC's research. ML-based techniques are now embedded within beam parameter optimization, allowing researchers to control beam characteristics more precisely and efficiently.

SLAC's involvement in collider design is notable, with contributions to critical components of ongoing and future collider projects, including the EIC at BNL, SuperKEKB at KEK, and FCCee at CERN. The lab's application of normal form analysis techniques for dynamic aperture (DA) optimization has been instrumental in preserving beam polarization, which is essential for achieving high precision in HEP experiments. These efforts ensure that SLAC remains a vital contributor to high-energy collider physics.

However, SLAC faces significant challenges in retaining key personnel in the San Francisco Bay Area, where new startup and high-tech companies constantly pursue talented scientists with much higher salaries. Several experienced scientists and engineers have transitioned to the private sector, resulting in a notable drain of expertise in collider physics and machine design. The loss of such critical knowledge, especially in areas requiring deep expertise in beam dynamics and simulation, has impacted SLAC's ability to maintain its leadership in future energy frontier collider designs.

The review committee applauded SLAC for its pioneering work in ML integration and its contributions to CSR modeling and collider design. These advancements are critical for future accelerator and collider designs and operations. The loss of key personnel has created significant challenges for knowledge transfer in beam dynamics and collider design and simulations. SLAC must focus on retaining and transferring this expertise to the next generation of scientists and engineers to ensure the continuity of its contributions to future collider R&D.

While SLAC has been effective in attracting early-career scientists, particularly through its FACET-II facility, the lab must address the ongoing loss of senior staff. The lack of a structured knowledge transfer process has compounded the impact of these departures. As a result, SLAC needs to strengthen its retention efforts and enhance programs for early-career development to ensure that expertise is preserved and passed on to future generations of researchers.

Recommendations:

1. Strengthen national laboratories collaborations to accelerate collider design and beam physics study. Establish a formal partnership with Berkeley Lab's Accelerator Modeling Program to enhance simulation capabilities and develop next-generation accelerator designs. Expand joint efforts on Fermilab's Accelerator Complex Upgrade and future collider R&D to maximize available resources, drive innovation, and ensure a coordinated national strategy for advancing ABP research for high energy physics.
2. Preserve and develop collider physics expertise by systematically integrating senior scientists' knowledge into simulation frameworks, such as collaboration with AMP of Berkeley Lab, and expanding workforce development initiatives.

Advanced Accelerator Concepts (AAC)

The review focused on each lab's role in the AAC thrust for advancing particle acceleration science and technologies, as well as their contributions to the broader accelerator science community. This section summarizes the technical achievements, ongoing research, and strategic recommendations that aim to enhance future productivity and collaboration in the field.

The AAC program continues to demonstrate impressive progress across all reviewed facilities. Major milestones, such as the development of high-efficiency energy transfer systems, GeV-class accelerations, and the implementation of AI/ML assistance for accelerator operations, have been achieved. However, the reviewed labs also face challenges, including increased international competition, infrastructure constraints, and the retention of skilled workforce. The following sections provide detailed insights into each lab's performance, followed by recommendations tailored to address specific challenges and opportunities.

Argonne National Laboratory

The Argonne Wakefield Accelerator (AWA) operates with a highly efficient cost structure, partly due to the significant support it receives from the lab and its collaborative arrangements with institutions like Northern Illinois University (NIU), the University of Chicago, and UCLA. AWA has consistently contributed to workforce development, with an average of two PhDs awarded annually. The facility plays a key role in training the next generation of scientists and engineers, through its involvement in the design and operation of high-gradient accelerators.

AWA's technical achievements are notable. The facility has demonstrated the ability to produce 0.5-GW peak RF power in an 11.7 GHz metamaterial structure via Two-Beam Acceleration and has made significant progress in Collinear Wakefield Acceleration, achieving high-gradient acceleration exceeding 100 MV/m, in comparison with typical normal-conducting RF accelerating gradients at tens of MV/m, while superconducting RF structures typically operate well below 40 MV/m, making AWA's advancements a step beyond conventional acceleration limits. The facility also excels in controlling beam distributions with sub-picosecond precision, an essential feature for producing high-efficiency beam operations. Moreover, in collaboration with SLAC, the AWA facility integrates advanced AI/ML systems to enhance diagnostic capabilities and enable autonomous accelerator operations. These AI/ML systems, coupled with digital twins, provide a cutting-edge platform for testing and optimizing accelerator components.

Since the last GARD review in 2018, AWA has undergone several major upgrades. The drive beam energy has increased from 14 MeV to 65 MeV, and the witness beam energy from 4 MeV to 14 MeV. In collaboration with the BACI group at Berkeley Lab, AWA has successfully upgraded its LLRF system, which is crucial for enhancing the precision of AWA's high-gradient acceleration experiments. This partnership has improved synchronization between the drive and witness beams, optimizing the performance of both Two-Beam and Collinear Wakefield Acceleration. BACI's LLRF systems provide real-time adjustments, ensuring precision control of RF components, which is vital for maintaining beam quality. These upgrades, along with improvements to the laser system, RF gun, and LINAC, have resulted in significant operational stability and reliability. The facility has also cleared its backlog of deferred maintenance, further enhancing its efficiency. AWA has also expanded its research capabilities, evolving into a collaborative R&D facility rather than a traditional user facility. This shift allows AWA to pursue experimental research more flexibly, and it is now exploring participation in the BeamNetUS pilot program to foster further collaboration.

The committee commended AWA for its cost-effective operations, which run on an approximate $3 million annual budget under the GARD program. This efficiency is primarily due to the lab's unique overhead structure and its ability to attract students and postdocs who contribute to the research. AWA's success in fostering collaboration with other institutions is another highlight, providing the facility with a steady influx of skilled manpower and research opportunities. However, the committee noted that AWA's current approach to its future upgrade plans might benefit from a more innovative approach. While the proposed AWA-II upgrade involves adding more LINAC structures and klystrons to boost drive beam energy, exploring alternative technologies, such as cryogenically cooled copper technology and pulse compression scheme could offer a more forward-looking solution.

AWA should explore alternative approaches to increasing the drive beam energy, such as utilizing higher-gradient structures to avoid expanding the shielded bunker. As AWA transitions toward becoming a user facility under BeamNetUS, it is important to maintain a balanced approach that preserves R&D productivity. Additionally, the team should actively pursue early career research awards from HEP, which could strengthen workforce development and funding stability.

Recommendations:

None

Lawrence Berkeley National Laboratory

The Berkeley Lab's Accelerator Technology & Applied Physics (ATAP) division has made significant contributions to AAC research, with a particular focus on Laser-Plasma Acceleration (LPA) through its BELLA, AMP and BACI programs. As the leading US program in laser wakefield acceleration, BELLA has played a pivotal role in advancing LPA technology, which is an essential component of the AAC's long-term roadmap toward plasma-based colliders. One of the most significant achievements since the last GARD review has been the demonstration of 10 GeV acceleration in a single stage. This achievement was made possible by switching from capillary discharge-guided to optical field ionized plasma channels, a breakthrough innovation from the University of Maryland. The adoption of this new approach has allowed BELLA to remain competitive in the field of high energy LPA, although several other facilities globally are now achieving similar results.

The AMP program has also been highly productive, developing sophisticated simulation codes and modeling tools that extend beyond laser-plasma acceleration. These tools have broader applications in accelerator design and fusion energy research. The AMP has contributed significantly to the community-wide study of wakefield-based concepts for a 10 TeV pCM collider, providing essential insights into end-to-end accelerator design. The proposed kBELLA project is exciting, as it seeks to address the key R&D gap in developing high-average power, high-repetition-rate drivers that are necessary for future collider applications.

In addition to its core research, BELLA has fostered a productive collaboration with the BACI group, specifically in the development and application of fiber laser technology. This partnership focuses on utilizing fiber lasers for precision control and diagnostics within the BELLA facility, a crucial aspect for advancing the stability and scalability of laser-plasma acceleration systems. Fiber lasers, known for their reliability, compact size, and high repetition rates, are essential for the next generation of LPA experiments. The integration of BACI's fiber laser technology has enabled BELLA to enhance its beam diagnostics capabilities, improving real-time feedback mechanisms and ensuring tighter control over experimental conditions. This collaboration represents a key step toward achieving the high-repetition-rate drivers needed for future LPA-based collider designs and further demonstrates the value of interdisciplinary partnerships in advancing accelerator science.

To strengthen its research capabilities and its leadership role in LPA, BELLA should continue fostering strong collaborations within Berkeley Lab and with external institutions, leveraging collective expertise to drive innovation. Additionally, actively engaging in near-term applications, such as LPA-driven FEL applications, would provide valuable opportunities to validate system stability and beam quality — critical factors for future collider applications. Meanwhile, efforts to mitigate key risks associated with kBELLA should continue, with a comprehensive plan for securing co-sponsors and funding for its full-scale development. Given potential delays in positron studies at FACET-II, BELLA could also play a key role in investigating positron acceleration in PWFA, helping to address gaps in research and furthering the field's understanding of positron dynamics in plasma-based accelerators.

Despite its remarkable achievements, BELLA faces growing international competition. Other facilities, particularly in Europe and Asia, are now making similar advances in laser-plasma acceleration. The lab's 1 PW laser system, while still functional, is no longer considered state-of-the-art compared to newer, more powerful systems available elsewhere. However, the facility has been able to leverage its existing infrastructure to support a variety of scientific applications, including collaborations with external institutions like Ohio State University and DARPA[4]'s muon project.

The committee noted that while BELLA's near-term goals were somewhat unclear, the facility's long-term plans involve demonstrating 1+1 GeV and 7+7 GeV staged accelerations. These efforts will require additional funding and the construction of two additional beamlines for the guiding lasers. Furthermore, BELLA should continue to capitalize on its collaborations with institutions like the University of Maryland, which have proven crucial to recent BELLA's success.

Recommendations:

1. BELLA should develop a more concrete plan for its staging experiments while considering current funding constraints to ensure steady progress in advancing laser-plasma accelerator technology for colliders within six months.

SLAC National Accelerator Laboratory

FACET-II is the world leading facility for beam-driven Plasma Wakefield Acceleration (PWFA). The facility achieved full operations in 2024, following a successful commissioning process, and has already produced significant results, including the delivery of 10 GeV beams with a small energy spread. FACET-II's primary research goals focus on demonstrating efficient energy transfer and maintaining beam quality, both of which are critical for the future development of plasma-based colliders. The E300 collaboration, for instance, aims to achieve over 30% energy transfer efficiency, along with maintaining minimal emittance growth and small energy spread.

FACET-II supports a diverse range of experiments, including high-brightness beam generation, strong-field quantum electrodynamics (QED), and laboratory astrophysics studies. The facility has also integrated AI/ML research development to improve operational efficiency and diagnostic capabilities. FACET-II faces difficulty in producing the required beam spot size and charge delivery, both of which are currently below the promised parameters. However, no other beam test

[4] DARPA stands for Defense Advanced Research Projects Agency.

facility in the world can match FACET-II's capabilities, making it a unique facility for advancing PWFA research.

Another research area at FACET-II is to study the strong-field QED processes. These processes become significant at extremely high energy densities and can introduce new limitations on collider performance, particularly due to effects like nonlinear Bremsstrahlung radiation. Studying and understanding these processes are helpful in determining the potential performance limitations for future high-energy colliders. To enhance the impact of its research, FACET-II team should prioritize improving driver-to-witness beam efficiency, as optimizing this parameter will be critical for future Plasma Wakefield Acceleration (PWFA) applications.

Workforce retention is identified as one of the major issues by the committee, particularly in the highly competitive San Francisco Bay Area, where start-up companies in accelerator and beam physics are attracting skilled scientists. SLAC has made efforts to improve its work environment by offering more R&D opportunities, but additional measures, such as flexible working options, assistance to childcare and housing support, may be necessary to retain talent, ensuring long-term institutional stability and growth.

The committee also noted that future positron acceleration studies at FACET-II might be delayed or re-evaluated. The SLAC team's focus has shifted towards exploring alternative collider designs, such as the gamma-gamma option, which may be more feasible in the long term. However, SLAC should continue to explore opportunities for collaborating with other facilities like BELLA to conduct positron studies if necessary.

Recommendations:

1. Develop a plan to maintain SLAC's position as a leading training ground for young scientists in accelerator and plasma science, providing diverse opportunities for students and early-career researchers to develop expertise in the field.

In conclusion, the Advanced Accelerator Concepts program plays a crucial role in driving cutting-edge technologies across multiple laboratories, with significant contributions from Argonne National Laboratory (AWA), Berkeley Lab (BELLA), and SLAC (FACET-II). Each facility has made remarkable progress. However, the program faces several obstacles, including rising global competition, challenges in retention in the workforce, and the need for technological upgrades to maintain its leadership position. The committee emphasizes on the importance of near-term applications for AAC technology and strongly recommends the AAC community to significantly enhance its efforts to collaborate with the broader accelerator community, with a particular focus on future collider design studies and workforce development, which are imperative to the advancement of the field.

Particle Sources and Targetry (PST)

The committee evaluated the research and development activities at Brookhaven National Laboratory, Fermilab and Argonne National Laboratory. This review highlighted research advancements in photocathode development, material sciences for high-power targets, and electron source R&D. Each lab demonstrated leadership in its respective research thrust, with substantial contributions to the GARD, HEP, and NP missions.

The committee commended the efforts of BNL, Fermilab, and ANL for their leadership in their respective research areas. Each lab demonstrated substantial progress in the development of photocathodes, high-power targets, and advanced electron sources. The committee identified opportunities for future growth, including enhanced collaboration, infrastructure upgrades, and alignment with the broader DOE roadmap. The recommended actions will ensure continued U.S. leadership in particle sources and targetry.

Brookhaven National Laboratory

BNL is a leader in the U.S. in photocathode development, with research closely aligned with both the Nuclear Physics and High Energy Physics missions. Particle Source research at BNL is supported through collaborations with Arizona State University (ASU) and Cornell University, with additional funding from NP and ARDAP programs. These collaborations and funding streams provide strong synergies with HEP-related activities, particularly in advancing the development of multi-alkali cathodes (high QE) and III-V systems (polarization).

BNL possesses three production and two research growth systems, offering the highest density of such facilities in the U.S. This capability provides a critical advantage in advancing the nation's research infrastructure. Notably, one of BNL's research systems can be transported to beamlines at NSLS-II for X-ray characterization of photocathodes, a unique feature in the photocathode research community.

BNL has positioned itself as a hub for photocathode research, with world-class infrastructure supporting both production and testing. The ability to utilize X-rays for photocathode characterization offers a significant competitive edge, enhancing the potential for deeper investigations into material properties. However, expanding the integration of photocathode growth and characterization facilities into HEP-related activities remains an opportunity for growth. Additionally, there is a need to continue collaborations with universities to attract and train students and postdoctoral researchers in this field.

To maximize the impact of photocathode research on high energy physics (HEP), efforts should focus on leveraging existing photocathode growth and characterization facilities for more HEP-related studies. Strengthening collaborations with universities and enhancing accelerator traineeship programs will be essential for attracting and developing the next generation of researchers. Additionally, a strategic evaluation of how photocathode research can more directly contribute to HEP's long-term goals should be conducted to ensure alignment with future priorities and roadmap objectives.

Recommendations:

None.

Fermilab

High-power target research is crucial for Fermilab's high-intensity neutrino research program, Deep Underground Neutrino Experiment (DUNE) and Long-Baseline Neutrino Facility (LBNF). The ability to generate intense, reliable neutrino beams hinges on the performance of high-power targets that can withstand extreme conditions with high-energy and high-power proton impacts, high temperatures, and radiation-induced damage etc. Fermilab's efforts in developing advanced target materials and systems are essential to meeting the demanding requirements of these projects, ensuring that targets can support multi-MW beam power levels without failure.

For DUNE and LBNF, the proton beam power will reach up to 1.2 MW, and future upgrades may increase this to 2.4 MW or more. High-power targets must handle intense heat loads, thermal shock, and fatigue due to the repeated high-power beam impacts. Materials like high-entropy alloys and tungsten are being researched for their potential to endure these extreme environments. In addition, Fermilab's g-2 experiment, which focuses on muon beams, also requires high-power target systems, particularly in terms of thermal management and longevity under high beam intensity. The continuous improvement in radiation damage testing and molecular dynamics simulations for material selection will be vital to extending the operational life of these targets, reducing downtime, and increasing beam reliability for all experiments within Fermilab's neutrino research program.

Fermilab's current R&D efforts are focused on understanding and development of target and window material properties under extreme conditions. The program is supported at approximately $1.2M/year and 3.9 FTEs, small but a substantial increase since the last GARD Review in 2018. The GARD program aims to help enable the design, construction, and operation of multi-MW target facilities, developing technologies for targets that can withstand extreme environments, such as radiation, thermal shock and fatigue etc.

Fermilab has taken a leading role in the development of high-entropy alloys for beam windows and has begun testing nanofiber ceramic and tungsten as future target materials. Advanced molecular dynamics (MD) simulations and density functional theory (DFT) provide critical insights into atomic-level defects caused by radiation damage. These methods, coupled with AI/ML tools, offer new opportunities for predicting material behavior under extreme conditions.

Fermilab led the development of the latest GARD High Power Target (HPT) roadmap report in collaboration with domestic and international institutions: University of Wisconsin-Madison, UC Santa Barbra, MSU, CERN in Switzerland and J-PARC in Japan. The lab's leadership in the RaDIATE collaboration exemplifies its ability to bring together a broad community to tackle shared challenges in high-power targetry. Diagnostic developments, including live health monitoring tools for targets, are particularly promising and could benefit the entire targetry community. However, more emphasis on the prototyping of new materials and engineering are needed to validate laboratory findings in operational environments.

Expanding collaborations beyond the target community will be essential to leveraging expertise in material sciences and radiation damage studies from other fields and national labs, such as fusion research and LANL, to accelerate advancements in target material development. While improving radiation tolerance is a key objective, it is critical to ensure that particle yield remains a primary performance metric, balancing durability with the efficiency needed for high-intensity experiments.

Recommendations:

1. Provide a detailed analysis of prototype engineering challenges for top candidate materials identified in the High-Power Target Roadmap Report[5] within two years, assessing key limitations and potential solutions. This assessment should consider factors such as thermal stability, radiation resistance, and manufacturability to ensure that material selection aligns with long-term operational requirements.

Argonne National Laboratory

The AWA program focuses on generating bright electron beams (100 nm/100 pC) and intense bunch trains for wakefield drivers. The AWA team operates multiple electron sources, including

[5] [2502.03305] HEP High-Power Targetry Roadmap -- Workshop Report

the Argonne Cathode Test-stand (ACT), which has tested advanced photocathode materials and routinely generates 100 nC bunches, one of the highest charge-per-bunch levels globally.

The most remarkable achievement at ANL is the development of a 1.5-cell X-band photo-RF gun, which operates with the highest gradient recorded to date (over 350 MV/m). This RF gun, driven by the two-beam acceleration technique, has demonstrated stable beam production, making it a key component for future FEL and linear collider concepts. The collaboration with universities like NIU and MSU on photocathode research further strengthens the national capability in electron source R&D.

ANL has made significant strides in electron source R&D, setting world records for photocathode gradient performance. The lab's expertise in flat beam production should be leveraged further, particularly in addressing damping-ring-free collider designs. However, difficulties remain in achieving the expected improvements in beam brightness. The AWA team should focus on experimentally verifying the improvements associated with the high-gradient RF gun.

To enhance the impact of photocathode research, efforts should focus on increasing compatibility between cathode tests across various electron sources, ensuring a more streamlined and cohesive research approach. Additionally, experimentally demonstrating beam brightness improvements from high-gradient extraction will be crucial for advancing photocathode performance and validating theoretical models. As the new roadmap for high brightness sources is established, it will be important to realign research goals with the HEP mission, ensuring that ongoing efforts remain aligned with future priorities and high-energy physics priorities.

Recommendations:

None

RF Acceleration Technology (RF)

The committee reviewed the RF technology programs across GARD-supported labs, including Fermilab, BACI at Berkeley Lab, SLAC, and AWA at ANL. This report highlights significant technical advancements in Superconducting Radio Frequency (SRF) and Normal Conducting Radio Frequency (NCRF) technologies, such as high-Q and high-gradient SRF cavities, cryogenically cooled copper structures, FPGA-based Low-Level RF (LLRF) controls, and advancements in Two-Beam Acceleration (TBA) technology. Despite these advances, the committee raised concerns over research priorities, budget constraints, funding gaps, and facility maintenance. Additionally, workforce development remains critical as the labs aim to ensure continuity in technical expertise.

Fermilab

Fermilab's SRF R&D facilities are among the most advanced in the world, thanks to decades of investment from GARD and specific project funding. The facilities are in near-constant use, supporting large-scale projects such as LCLS-II, LCLS-II HE, and PIP-II, as well as research on superconducting materials and quantum systems.

Fermilab's SRF R&D program is particularly distinguished by its work on high-Q and high-gradient cavities, achieving record-breaking performance in both areas. Fermilab has pioneered a mid-temperature (mid-T) bake process for niobium cavities, which modifies the niobium pentoxide layer and creates a favorable impurity profile in the surface region. This process has resulted in remarkable performance improvements, such as a maximum accelerating gradient of over 50 MV/m at 1.3 GHz and 650 MHz cavities. The mid-T bake process is now standard for the LB650 cavities used in PIP-II, and it may also be applied to the FRIB energy upgrade and potentially the FCC-ee at CERN.

Fermilab has also made significant progress in the development of Nb3Sn SRF cavities, which are capable of operating at 2X higher gradient and higher temperatures (~ 4 K) compared to niobium cavities. The higher operating temperatures offer substantial reductions in the cryogenic load, lowering both the capital and operational costs of large accelerator systems. The program has achieved gradients up to 24 MV/m at 1.3 GHz and 650 MHz Nb3Sn cavities, a major milestone in SRF technology. While still below the 100 MV/m theoretical limit, it demonstrates significant progress and the potential for high-efficiency, cost-effective SRF cavities. With continued R&D in deposition techniques and surface engineering, further improvements in performance can be expected, reinforcing Nb3Sn's long-term promise for future accelerators. Another innovation is the development of a repair method that uses mechanical polishing and recoating to fix defects in Nb3Sn films, allowing performance recovery without removing the entire film.

In addition to Nb3Sn advancements, Fermilab has initiated the development of a fast-tuning low-frequency (~ 50 MHz) SRF cavity for high-intensity proton synchrotrons. This cavity could significantly benefit Fermilab's MI RF system as part of the ACE-BR upgrade, allowing greater flexibility in the synchrotron's operation.

The committee commended Fermilab's SRF program for its consistent delivery of high-impact results, both within HEP and in applications beyond accelerator physics. Fermilab's work in Nb3Sn SRF cavities represents a critical step toward more efficient accelerator systems, which could enable compact designs with reduced cryogenic demands. The integration of quantum science and materials science into the SRF R&D program has created a synergy that benefits both accelerator and quantum information science research.

However, the SRF program is facing budgetary challenges due to increasing cryogen costs at ATF, the superconducting RF cavity and magnet test facility, and a flat budget. This has led to reductions in staff and FTEs, which could limit future R&D efforts. While LCLS-II and PIP-II have utilized ATF for testing and assembly rather than R&D, LCLS-II HE is now ramping down. Additionally, the loss of direct ILC funding in past years has led to setbacks in high-gradient SRF cavity research and crab cavity development.

To strengthen the SRF program, updating the SRF roadmap to align with the latest P5 recommendations and resource allocation is essential. Continued R&D on Nb3Sn SRF cavities will help advance the technology for near-term and future accelerator applications. Prioritizing the development of fast-tuning low-frequency SRF cavities for Fermilab's MI RF system and resonant control for high-Q SRF cavities could enhance high-gradient operation in pulsed mode, benefiting from external collaborations where needed. Encouraging student and early-career researcher participation and reinforcing collaborations with U.S. institutions and universities will be critical to maintaining leadership in SRF technology.

Recommendations:

1. Reevaluate the business model for cost-recovery and non-GARD and non-HEP projects using Fermilab's ATF facilities to ensure fair contributions toward maintenance and operational costs within one year.

Lawrence Berkeley National Laboratory

BACI group is a world leader in Low-Level RF (LLRF) control, particularly in the development of FPGA-based ultra-high precision RF control systems. The *Marble board*, a significant contribution from BACI, has been widely adopted by major U.S. accelerator projects, including AWA at ANL and PIP-II at Fermilab. BACI's LLRF systems can deliver unprecedented field stability, achieving 0.01 degrees in phase stability and 0.01% amplitude stability.

BACI's LLRF efforts extend beyond RF control for accelerators. The team has adapted its FPGA-based systems to applications in fiber laser control and quantum qubit controls, demonstrating the broad applicability of these control systems. In collaboration with the BELLA Center, BACI has also developed customized and advanced controls for coherently combined fiber laser research program for the generation of high-repetition rate and high-energy laser pulses.

In addition to LLRF, BACI has made key contributions to RF cavity design and analysis, including the ALS-U RF cavity design, and ALS-U impedance analysis and impedance budget. Recent past contributions include CW RFQ for PIP-II, harmonic cavities for the ALS-U, and the development of NCRF cavities for muon ionization cooling channels and international MICE experiment.

The committee praised BACI's LLRF control innovations, which have had a significant impact on U.S. accelerator projects. Continued support from GARD will be critical to further advancing these developments. BACI has also played a crucial role in workforce development, actively involving students and early-career researchers in its cutting-edge LLRF projects.

HiRES[6] has been out of operation for a few years and is currently in the process of resuming its activities. However, the continued support from BES is still uncertain, which raises concerns about its long-term sustainability as a testbed for high power RF, AI/ML and LLRF controls within the GARD program. If significant support from BES or Berkeley Lab is not secured, HiRES may be repurposed as an injector test facility for SLAC's LCLS-II project. In this context, critical R&D areas such as LLRF controls and AI/ML development for HEP may be better pursued through collaborations with other HEP facilities. Given these uncertainties, it is important to carefully evaluate the role that HiRES will play in the future of GARD research.

The BACI has a highly experienced team with unique expertise in low-frequency NCRF cavity design and fabrication. Their recent major contributions include the CW RFQ injector for the PIP-II Project, the photocathode injector for LCLS-II, and RF cavities for muon cooling R&D and the international MICE experiment. Maintaining this capability is crucial, as BACI has been a trusted collaboration partner for a number of R&D projects in the past, consistently delivering successful outcomes. To sustain and expand NCRF expertise at Berkeley Lab, a strategic plan should be developed in coordination with RF R&D efforts at other DOE labs. Additionally, continued engagement in EIC and future collider R&D will help advance Berkeley Lab's role in NCRF cavity design and LLRF controls while fostering long-term collaborations.

The committee noted that NCRF expertise at Berkeley Lab is at risk due to recent retirements. Maintaining this competency will require renewed investment and engagement in upcoming RF projects, such as the EIC NCRF cavity design and future collider initiatives.

[6] HiRES is a High Repetition-rate Electron Scattering apparatus for ultrafast electron diffraction (UED) experiment at Berkeley Lab.

Recommendations:

1. Strengthen collaboration with Fermilab on PIP-II RF and ACORN developments to enhance Berkeley Lab's contributions to major accelerator projects. This includes formalizing joint R&D efforts, leveraging Berkeley Lab's expertise in RF cavity design and LLRF controls and FPGA programing, and establishing a clear roadmap for technical contributions and resource sharing over the next one to three years.

SLAC National Accelerator Laboratory

SLAC's Next Linear Collider Test Accelerator (NLCTA) resumed operations after a two-year hiatus and is now ready for high-gradient structure studies in S- and X-band. Recent research has demonstrated significant potential in cryogenically cooled copper structures, with gradients of up to 140 MV/m being achieved. Future development will explore the performance of these structures at cryogenic temperatures as low as 4K. Another important development is the distributed coupling structure, which has opened new possibilities for high-gradient operations at reduced RF power.

SLAC has been heavily involved in RF structure modeling and simulation through the ACE3P suite of codes. These tools have been enhanced to include non-linear material properties, beam dynamics integrations, and AI/ML techniques. ACE3P has proven invaluable for RF structure development, with applications in LCLS-II, EIC cavities, and HL-LHC (high luminosity upgrade to Large Hadron Collider). SLAC continues its tradition in the development of high-efficiency RF sources and has contributed to commercial applications, such as portable radiography and cargo scanning systems. The committee noted that SLAC's efforts in RF power source development, in improving efficiency and reducing costs, are crucial for the future of DOE accelerator facilities.

The cryogenically cooled copper structures may have the potential to revolutionize high-gradient acceleration technology. SLAC's ongoing R&D in this area, including the development of high-brightness RF guns and pulse compression, could lead to advancements in future collider designs. The ACE3P simulation tools continue to play a vital role in RF structure designs, and their integration with beam dynamics codes has further improved the accuracy of RF accelerator simulations. Advancing cold copper technology for high-gradient beam testing while exploring synergies with BES research will further enhance its impact.

Expanding the integration of the ACE3P code suite into collaborative frameworks like CAMPA and BLAST will enhance data exchange, streamline multi-institutional collaboration, and support more effective global optimization efforts in accelerator design and simulation.

Recommendations:

1. Prioritize the development of high-efficiency RF sources, aiming to demonstrate a prototype tube with increased power efficiency and reduced costs within the next few years.

Argonne National Laboratory

The Argonne Wakefield Accelerator at Argonne National Lab is a flexible and cost-effective facility for testing beam-driven high-gradient RF structures. AWA has achieved a record gradient of 300 MV/m in a copper accelerating structure during Two-Beam Acceleration operation with short pulses (~ 6 ns). The facility has also developed dielectric structures that have reached gradients of 100 MV/m in short-pulse operation.

Recent upgrades at AWA include improvements to the Low-Level RF control system, developed in collaboration with Berkeley Lab. The new system offers greater stability, reliability, and flexibility, and it has potential for adoption by other accelerator facilities.

AWA's TBA program continues to make significant progress in understanding RF breakdown physics, high-power RF generation, and high-gradient normal conducting cavity development. A recent development based on SLAC's distributed coupling cavity design has demonstrated promising results, and future work will focus on cryogenic operation, which could lead to record-high gradients.

The facility's flexible setup supports a wide range of experiments and is an important site for the training of graduate students and early-career researchers.

AWA's unique capacity for high-gradient structure testing, combined with its cost-effective operation, makes it an asset in advanced RF research. The facility's focus on Two-Beam Acceleration, short-pulse operation, and distributed coupling designs is critical for future HEP accelerators. The collaboration with Berkeley Lab on LLRF control has further enhanced the facility's capabilities, allowing for greater precision and stability in RF operations.

Long-term plans for AWA should be revisited in light of the latest P5 recommendations, particularly the call for a 10 TeV pCM collider. AWA should encourage young scientists to apply for HEP early-career research proposals in support of workforce development and drive innovation in high-gradient RF technology.

The committee emphasized the importance of refining the scope of AWA-II, a proposed upgrade to the facility that aims to develop more advanced staged structures with higher power drive beams. AWA-II could play a key role in advancing TBA technology and exploring applications such as compact free-electron lasers (FELs).

Recommendations:

1. Refine the scope and cost estimates for AWA-II in collaboration with GARD and other stakeholders, ensuring alignment with the HEP missions while exploring broader applications, such as compact FELs. A detailed assessment should be conducted within the next one to two years to establish feasibility and funding strategies.

Superconducting Magnets and Materials (SCM)

The Superconducting Magnet (SCM) research program was evaluated at Brookhaven National Laboratory (BNL), Fermilab, and Berkeley Lab, focusing on their significant technical contributions to the development of advanced superconducting magnet technology. These labs have made notable advancements in high-temperature superconductors (HTS) and low-temperature superconductors (LTS) integration, high-field magnet design, and robust quench protection systems. These efforts are key ingredients in the US Magnet Development Program (MDP), important to the success of the HL-LHC, and the Electron-Ion Collider. Additionally, the review emphasized the need for infrastructure upgrades, strategic alignment with the latest P5 report, and continued focus on workforce development to ensure future US leadership in this critical field.

Brookhaven National Laboratory

BNL's superconducting magnet program has been a vital contributor to the development of HTS technology, with a particular focus on REBCO conductor applications in high-field magnets. One of the lab's key strengths is its direct-wind (DW) technology, which has allowed the integration of REBCO cables into complex magnet geometries tailored to the requirements of next-generation colliders like the EIC. This direct-wind approach enables highly customizable magnet designs, providing precise control over field geometry and mechanical stability. Developing a plan to better integrate direct wind activities into and alignment with MDP goals, for example, utilizing them for high-field magnet correctors, essential for ensuring high field quality.

BNL has led the quench protection systems for REBCO magnets, addressing the unique challenges posed by the slow normal-zone propagation velocities (NZPV) typical of HTS materials. Quenches in HTS magnets propagate more slowly than in traditional LTS systems, requiring more sensitive detection methods. BNL has incorporated temperature sensors directly into the windings of their REBCO magnets, enabling early detection of quench zones. This system, combined with distributed quench protection circuits, ensures that localized quench events are rapidly identified and mitigated, preventing damage to the magnet.

BNL's work with CORC® cables has also been pioneering, particularly in understanding how these HTS cables respond to mechanical strain and thermal cycling. These studies have informed the development of quench protection systems that account for the mechanical stresses and quench dynamics unique to HTS conductors. Additionally, the successful test of the BigBOX[7] coil, which used a wax-potting technique for mechanical stress management, has demonstrated how improved stability can significantly reduce quench training and improve magnet performance. The common-coil platform used for these tests supports the evaluation of both REBCO and Nb3Sn conductors, offering a versatile testbed for high-field applications.

BNL has focused on workforce development as a core component of its magnet program, particularly following the departure of key personnel. The lab has made significant efforts to involve early-career researchers in critical projects, providing them with opportunities to work on cutting-edge HTS technology and quench protection systems. BNL's partnerships with universities have facilitated the training of postdoctoral researchers and graduate students, ensuring that knowledge transfer continues within the superconducting magnet group.

Recommendations:

1. Complete the revision to the MDP roadmap and re-balance BNL's program according to MDP's new priorities.

Fermilab

Fermilab has made significant contributions to superconducting magnet technology, mainly through its research development on advanced Nb3Sn conductors. The lab's development of artificial pinning centers (APC) has led to improvements in flux pinning, allowing Nb3Sn magnets to operate at higher fields with greater stability. This has enabled Fermilab to push the boundaries of high-field dipole magnets, as evidenced by their successful demonstration of a 4-layer dipole magnet, which set a world record for performance.

Another focus of Fermilab's work has been the integration of quench protection systems into these high-field magnets. The lab's stress-managed dipole magnet design incorporates quench heaters and energy extraction systems that ensure rapid dissipation of stored energy during a quench event,

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[7] A stress-managed racetrack Nb3Sn coil, called BigBOX, impregnated with paraffin wax for studying the training behavior.

protecting the magnet from damage. The stress-managed approach has been crucial in reducing quench-induced failures in large-bore magnets, intended for future muon collider applications.

Fermilab has also pioneered the use of wax impregnation and composite materials, Telene in Nb3Sn magnets, further enhancing their mechanical stability and reducing quench training times. Wax impregnation stabilizes the magnet coils, reducing the likelihood of quenches caused by mechanical stress. This technique has proven particularly effective in minimizing quench training and improving the overall operational reliability of high-field magnets.

In addition to their LTS research, Fermilab has made significant strides in the development of REBCO insert magnets. These hybrid systems, which combine HTS and LTS technologies, present unique challenges for quench protection, as the quench dynamics of REBCO conductors are significantly different from those of Nb3Sn. Fermilab has addressed these challenges by integrating temperature-based quench detection systems into their hybrid magnets, allowing for more responsive quench protection in the slower-propagating REBCO systems. This ensures that quenches are detected and managed before they can spread to other parts of the magnet, enhancing both safety and performance.

Fermilab's ATF, cryogenic testing infrastructure is a critical asset for their magnet development program. The lab is currently expanding its testing capabilities with the construction of a new large-bore test pit and cryostat, which will allow for the testing of high-field magnets in realistic operating conditions. This facility will be vital for the continued development of hybrid magnets and high-field Nb3Sn magnets, supporting both the MDP and future accelerator applications.

Upgrading the cryogenic testing infrastructure within the next few years is essential to support high-field and hybrid magnet development and maintain U.S. leadership in superconducting magnet technology. Expanding superconducting magnet activities beyond GARD funding will enhance program sustainability. A realistic plan should be developed to implement advanced Nb3Sn conductors, ensuring an effective balance with HTS and hybrid alternatives within MDP. Strengthening workforce development by increasing leadership opportunities for early-career researchers in projects like the 4-layer dipole and stress-managed magnet systems will be key to sustaining expertise in the field. The lab has provided opportunities for students and postdocs to work on major projects such as the Nb3Sn SMCT (Stress-Managed Cos-Theta) magnet and REBCO insert tests, offering them hands-on experience in advanced superconducting magnet technology.

Recommendations:

1. Bring the SMCT to completion by finishing the construction of the full magnet and preparing for the proposed testing to validate its performance within two years. This will provide critical insights into stress management techniques, support the development of high-field superconducting magnets, and inform future magnet designs for accelerator and fusion applications.

Lawrence Berkeley National Laboratory

Berkeley Lab has been a leader in the development of both LTS and HTS magnet systems, with a particular focus on REBCO and Bi-2212 conductors. The lab's work on the CCT-6 (canted-cosine-theta) outsert, a hybrid magnet combining LTS and HTS technologies, has pushed the limits of high-field magnet design. Berkeley Lab's expertise in elliptical bore magnet designs has enabled them to address the mechanical challenges posed by REBCO conductors, which are particularly sensitive to bending strain and small bend radii. These developments are critical for future accelerator applications where precise control over field geometry is essential.

Berkeley Lab's advancements in quench protection have been focused on the development of temperature-based detection systems for HTS magnets. Because HTS magnets have slower quench propagation than LTS magnets, traditional voltage-based quench detection methods are often insufficient. Berkeley Lab's solution has been to integrate temperature sensors directly into the coils of their REBCO and Bi-2212 magnets. These sensors provide real-time feedback on the temperature within the magnet, allowing for early detection of quench events and faster response times.

As a complementary effort to Fermilab's work on large-scale magnet wax impregnation, Berkeley Lab focuses on material optimization and hybrid insulation approaches. Their research explores various wax formulations, assessing thermal, mechanical, and electrical properties for broader superconducting applications, including hybrid and fusion magnets. Wax impregnation has proven effective in reducing quench training by enhancing mechanical stability, minimizing stress-induced quenches, and lowering training requirements. This technique has been integrated into Berkeley Lab's hybrid magnet designs, protecting both LTS and HTS components during high-field operation. By studying wax's interaction with other insulation methods, such as epoxy-wax hybrids, Berkeley Lab aims to improve coil fabrication, insulation performance, and long-term stability, informing future refinements in Fermilab's large-scale applications.

In addition to their magnet development efforts, Berkeley Lab has been a key player in the quench protection research for hybrid magnets, particularly those combining LTS and HTS systems. The lab's collaboration with Fermilab has led to significant advancements in understanding how different conductor types respond to quench events, allowing for the development of integrated protection systems that ensure the safe operation of complex coil systems in future collider applications.

Berkeley Lab has made workforce development a high priority, providing early-career researchers with opportunities to work on large-scale projects such as the CCT-6 outsert and hybrid magnet systems. The lab collaborates closely with universities and international research institutions, offering students and postdocs the chance to engage in cutting-edge magnet R&D. Berkeley Lab's strong focus on mentoring and leadership development ensures that young researchers are prepared to take on critical roles in future superconducting magnet projects.

Recommendations:

None

Comparison of R&D Programs at Each Laboratory

Brookhaven National Laboratory

BNL's GARD program primarily supports high-temperature superconducting (HTS) magnets and polarized electron sources. In addition to these capabilities, BNL has significant expertise in Accelerator and Beam Physics, which could be increasingly leveraged for high-energy physics (HEP) after the EIC enters the construction phase. As ABP scientists transition from EIC-related research, they are well-positioned to contribute to HEP's ABP needs, particularly by assisting Fermilab in its accelerator complex upgrades and future energy frontier collider R&D. BNL's long-standing strengths in magnet R&D and ABP research make it a valuable resource for future HEP projects despite the challenges of aging infrastructure and workforce retention.

Fermilab

Fermilab's GARD program plays a central and indispensable role in the U.S. high-energy physics community. Fermilab leads in Superconducting RF, magnet technology and Accelerator and Beam Physics, critical to developing high-power proton accelerators and colliders. Fermilab accelerator complex future performance and potential upgrades are key to the US's high-intensity neutrino program, supporting flagship projects DUNE and LBNF, which are essential for the future of U.S. particle physics. Fermilab is also poised to contribute significantly to the development of future Higgs Factory initiatives, FCC-ee at CERN. In collaboration with ABP scientists from other labs, including BNL after the EIC construction begins, there is strong potential for collaboration to support Fermilab's accelerator complex upgrades. These joint efforts will enhance the lab's capabilities in ABP research, ensuring continued U.S. leadership in high-intensity proton physics and future collider development. Fermilab remains crucial to advancing the U.S. HEP mission.

Argonne National Laboratory

ANL's GARD program focuses on the Argonne Wakefield Accelerator, with expertise in advanced accelerator concepts such as beam-driven wakefield acceleration, beam manipulations and high gradient RF structures. Despite its modest GARD funding compared to other national labs, ANL excels in efficiently leveraging collaborations and resources to maximize its impact. The lab plays a key role in Basic Energy Sciences, in supporting the Advanced Photon Source (APS) upgrade. ANL's combination of conventional and advanced accelerator technologies, along with strong ties to the APS, makes it an important player in both accelerator R&D and broader DOE research initiatives.

Lawrence Berkeley National Laboratory:

Berkeley Lab's GARD program plays a pivotal role in advancing accelerator technology through key contributions in several areas. The lab's BELLA program in Advanced Accelerator Concepts has achieved major breakthroughs, including 10 GeV single-stage laser-plasma acceleration, positioning Berkeley at the forefront of plasma wakefield research with implications for future high-energy colliders. Additionally, Berkeley Lab is a major player in Accelerator Modeling and Simulation through its Advanced Modeling Program (AMP), which includes advanced simulation codes like BLAST. These capabilities provide essential tools for HEP, BES and NP, enabling simulations critical for accelerator design and performance optimization. BACI has pioneered FPGA-based Low-Level RF control systems, widely adopted across U.S. accelerator projects, enhancing performance and control. Berkeley Lab also leads the US MDP and focuses on R&D in high-field magnets and superconducting materials, essential for future particle colliders. Together, these contributions drive the advancement in accelerator beam physics, technology innovations, enhance workforce development, and address key challenges in accelerator science, securing Berkeley Lab's leadership in the future of HEP GARD.

SLAC National Accelerator Laboratory:

SLAC's GARD program is centered on plasma wakefield acceleration (PWFA), supported by the FACET-II facility, alongside strong expertise in collider design and RF structure testing. SLAC remains a leader in advanced accelerator technologies, particularly in beam-driven plasma wakefield acceleration, but faces challenges in retaining talent due to Silicon Valley's competitive labor market. In addition to its work in HEP, SLAC plays a pivotal role in supporting Basic Energy Sciences programs, particularly in high-brightness beam development for the Linac Coherent Light Source (LCLS). SLAC's expertise in RF and collider design ensures it remains a key player in both accelerator research and applications beyond high-energy physics.

III. Test Facilities

The Review Committee visited each lab's facilities which include IOTA/FAST at FNAL, AWA at ANL, BELLA at Berkeley Lab, and NLCTA & FACET-II at SLAC. This section highlights each lab's contributions to GARD supported R&D activities and advancement. Despite ongoing challenges with resource limitations, deferred maintenance, and balancing expanding research scopes with operational capabilities and support of the ongoing projects, the facilities have made notable scientific progresses. The recommendations focus on ensuring that each facility adopts a strategic approach to resource management, funding allocation, and prioritization of GARD programs and impactful experiments while maintaining operational efficiency.

IOTA/FAST at Fermilab

IOTA/FAST is a critical testbed for intensity frontier accelerator physics, with its primary focus on studying beam dynamics under high space charge conditions. This facility is unique due to its highly flexible optics and innovative experimental setups, such as quasi-integrable optics and optical stochastic cooling (OSC). The research at IOTA/FAST is integrated into the Accelerator Research Directorate and supported by collaborations across 30 institutions, but it is not a formal user facility.

Resource availability has been a persistent issue, with the facility supported by only 4.5 FTEs spread among 8 staff members. This includes significant reliance on key personnel for critical areas, such as LLRF support, which raises operational risks. Furthermore, equipment like superconducting cavities has shown degradation, and some power supplies require replacement. The facility has broadened its research scope beyond its original goals, particularly with successful demonstrations such as the world's first OSC, but other core objectives, most notably, Nonlinear Integrable Optics (NIO) for proton beams are behind schedule. This delay is partially due to resource constraints and the impact of the COVID-19 pandemic.

In addition to the expanded research focus, IOTA's long-term value lies in its potential for future high-energy physics (HEP) machines. The successful demonstration of OSC, the use of an electron lens for space-charge compensation, and other advanced beam dynamics experiments position IOTA/FAST at the forefront of accelerator R&D. However, further development is needed to maintain this momentum, including improvements in resource allocation and technical upgrades.

A rigorous facility maintenance and upgrade strategy should be established, incorporating risk assessment metrics and benchmarking against similar facilities. Alternatives to the FAST linac for electron injection should be explored to ensure long-term operational flexibility. Balancing facility operations, upgrades, and the scientific program within budget constraints is essential, and an external advisory board could provide valuable guidance. While the demonstration of optical stochastic cooling remains an important academic achievement, its immediate impact on Fermilab's future accelerator upgrades is limited, and it should be pursued as part of broader exploratory research efforts in ABP.

The committee also noted that IOTA is highly valuable not only for research in beam physics but also as a training ground for future scientists. Strategic decisions, such as focusing on optical stochastic cooling during the pandemic, yielded significant scientific accomplishments, further expanding the facility's potential for high-impact research. However, there is concern about the number of projects being undertaken with the limited resources available, raising questions about whether the facility is overstretching its capacity. The original goal for studying the space charged dominated beam using protons has been delayed significantly. The committee did notice recent progress on the commissioning of the ion source for the 2.5 MeV RFQ injector.

Recommendations:

1. Accelerate the full implementation of the IOTA proton program, building on the successful commissioning of the ion source. Establish a clear timeline for beam studies, prioritize key experiments, and ensure optimal utilization of proton capabilities to advance high space charge beam physics research.

AWA at Argonne National Laboratory

The AWA operates with impressive efficiency and cost-effectiveness, thanks to strong collaboration with university-funded labor, external contributions from SBIRs, and material support from outside collaborators. The facility has made noteworthy advances in accelerator physics, such as surpassing previous breakdown levels in structure-based accelerators and achieving major milestones in beam diagnostics. The collaboration with SLAC on AI/ML techniques has proven to be particularly beneficial, enabling new developments in beam instrumentation and control.

Efforts to explore the short-pulse regime should continue to determine gradient limits and pulse-length dependence, providing valuable insights for future accelerator applications. At the same time, refining plans for facility upgrades with a clear distinction between GARD scope and other stakeholder interests will help ensure efficient resource allocation and program alignment. Additionally, maintaining and expanding education and outreach programs will be essential for fostering the next generation of accelerator scientists and strengthening community engagement.

The committee praised the facility's emphasis on collaboration, workforce development, and the strong engagement of students, many of whom have gone on to successful careers in the accelerator field. The leadership at AWA, including Director John Power, was also commended for its pivotal role in facilitating these achievements. Looking forward, the committee suggested that novel approaches, such as using high-gradient structures or Cold Copper technology, should be explored for the AWA-II upgrade to increase drive beam energy.

Recommendations:

None

BELLA at Lawrence Berkeley National Laboratory

The Berkeley Lab Laser Accelerator (BELLA) facility at Lawrence Berkeley National Laboratory is a flagship program for laser-driven plasma wakefield acceleration, which holds the potential to revolutionize particle accelerators by reducing their size and increasing efficiency. BELLA's primary goal is to demonstrate high-energy acceleration in a compact setup by using high-intensity laser pulses to create plasma waves that can accelerate charged particles to high energies over much shorter distances than traditional accelerators.

Since its inception, BELLA has achieved several groundbreaking milestones. One of its recent key successes is the formation of extended plasma channels, in collaboration with University of Maryland, which are essential for increasing the energy gain in LPA. These channels act as waveguides for laser pulses, allowing for efficient energy transfer to the particles being accelerated. BELLA has also demonstrated successful electron injection into these plasma waves, an essential step for staging multiple acceleration phases, which is necessary for achieving higher total energy gains.

Another critical area of development at BELLA is the kBELLA upgrade, proposed and designed to address the challenges of high repetition rate operation. This upgrade is crucial for advancing from single-shot experiments to practical applications where accelerators need to operate continuously. The goal of kBELLA is to demonstrate LPA at high repetition rates and higher efficiency, which are necessary steps toward a practical, collider-scale accelerator.

However, the technical challenges in LPA, combined with funding constraints, have slowed the pace of progress. The BELLA program initially aimed for a 10+10 GeV energy target for staging demonstrations (where two plasma stages would each accelerate particles by 10 GeV), but this goal has shifted over time to lower values, such as 5+5 GeV and 1+1 GeV recently. This fluctuation in energy targets has raised concerns about BELLA's ability to meet its initial long-term objectives. These energy shifts reflect both technical challenges, such as maintaining the quality of the plasma channel over longer distances, beam quality and limitations in available laser power.

Despite these challenges, BELLA remains at the forefront of laser-plasma acceleration research. The facility has benefited from strong simulation and modeling support from LBNL's Advanced Modeling Program group, which has been instrumental in optimizing experimental designs. Additionally, BELLA has demonstrated its utility beyond fundamental accelerator R&D by collaborating with other institutions on synergistic applications. For example, the collaboration with the Berkeley Accelerator Controls and Instrumentation (BACI) group has led to significant advancements in fiber laser combining and precision control technologies. These innovations are not only crucial for the future of LPA but also have broader applications in fields of basic energy sciences, and medical industry.

However, the committee noted that BELLA's current motivation within the High Energy Physics (HEP) framework needs to be more clearly articulated. While BELLA has made important strides in staging and plasma channel formation, the pathway toward achieving a collider-scale laser-plasma accelerator is still being defined. For example, the facility's expansion plans, such as building a kHz rep-rate laser system are motivated more by available laser technology than by meeting specific collider design needs. In this regard, BELLA's long-term goals should be more clearly aligned with practical accelerator applications, such as future high-energy colliders.

Efforts should continue to pursue GARD priorities within funding constraints, maintaining a competitive edge nationally and internationally. Collaboration with lab management and DOE is essential to balance facility operations, upgrades, and science/education programs, ensuring that resources are effectively distributed across these critical areas.

Furthermore, while BELLA's second beamline has been useful for experiments involving extended plasma channels, sharing laser power between multiple experiments limits the energy gain that can be achieved in any single stage. The committee also raised concerns about the facility's collaboration track record. Although BELLA has made important technical contributions, there have been fewer collaborative projects than expected for a facility of this caliber, particularly with respect to leveraging its LPA capabilities for broader accelerator applications.

Recommendations:

1. Develop a clear, prioritized cost and schedule for the staging options under consideration, establishing a well-defined implementation plan with key milestones within one year. This should include a detailed timeline outlining resource allocation, technical deliverables, and decision points to ensure efficient progress and accountability.

NLCTA & FACET-II at SLAC National Accelerator Laboratory

The SLAC National Accelerator Laboratory houses two key facilities for advanced accelerator R&D: The Next Linear Collider Test Accelerator (NLCTA) and the Facility for Advanced Accelerator Experimental Tests (FACET-II). Together, these facilities are pushing the frontiers of accelerator science, with a focus on novel techniques like beam-driven plasma wakefield acceleration (PWFA), high-gradient RF technologies, and advanced beam diagnostics that are critical for future HEP accelerators.

FACET-II is a flagship facility at SLAC, utilizing 10 GeV electron beams, the highest energy beam-driven for plasma wakefield acceleration in the world. FACET-II team has demonstrated one of the highest energy transfer efficiencies to date. Specifically, FACET-II achieved an impressive 41.8% drive energy transfer efficiency in its PWFA experiments. This high-efficiency energy transfer is crucial for developing next-generation accelerators that require less input energy to achieve the same output, potentially leading to more compact and cost-effective designs.

One of the core technical achievements of FACET-II is the development of two-bunch beam delivery, a method where a tightly focused beam of electrons is used to generate plasma waves that accelerate a trailing bunch. This process has proven highly effective in delivering the energy needed to accelerate particles within a short distance, addressing one of the key limitations of traditional RF accelerators, which require much longer acceleration paths. FACET-II has also been instrumental in developing and commissioning advanced diagnostics for plasma wakefield acceleration. Notably, it has pioneered the use of optical visualization techniques to observe plasma wakefield in real-time, allowing for more precise tuning and control of the acceleration process. Additional diagnostic tools, such as electro-optic sampling (EOS)-based timing and position measurements, have further enhanced FACET-II's ability to characterize beam properties with high precision.

FACET-II has also made substantial progress in incorporating artificial intelligence and machine learning (AI/ML) techniques into accelerator operations. One of the key successes has been the development of a virtual diagnostic tool that predicts beam behavior with the same level of detail as traditional, invasive transverse mode deflecting cavity measurements. This non-invasive diagnostic method significantly improves operational efficiency by reducing the need for physical measurements, which can interrupt experimental runs. Additionally, FACET-II has used Bayesian algorithms to optimize energy transfer efficiency in PWFA experiments, further increasing the facility's overall performance and reducing experimental downtime.

NLCTA focuses on high-gradient RF technology and compact accelerator systems, in addition to application for HEP accelerators, it has wide applications in medical, industrial processing, and national security. High-gradient RF structures are key to developing smaller and more affordable accelerators that can achieve high energies for a broad spectrum of practical applications. NLCTA has resumed operations after a period of safety-related shutdowns, with significant efforts dedicated to testing high-gradient RF structures and associated beam instrumentation.

One of the important areas of research at NLCTA involves streaking using THz radiation. This technique allows for extremely fine temporal resolution in measuring beam profiles. The development of such diagnostic tools is important for ensuring the precision and accuracy needed in future high-energy colliders.

The facility also supports the Laboratory for Experimental Sciences Applications (LESA) project, which uses high-energy beams to search for dark matter and perform detector R&D. LESA fully exploits the beam delivery capabilities of the adjacent LCLS-II, creating a powerful platform for advancing both fundamental physics research and technology development.

Looking to the future, SLAC is considering building a new Beam Test Facility that would allow for simultaneous operation of multiple R&D thrusts, such as photocathode gun development, novel acceleration techniques, and AI/ML integration into beam diagnostics and control. This facility would serve as a critical resource for both SLAC researchers and the broader scientific community, enabling a wide range of experiments to be conducted in parallel without interrupting ongoing user programs.

The committee praised SLAC for its strong lab-level support for NLCTA, particularly in areas like safety and experimental logistics, which have enabled the facility to return to full operational status. However, the committee also recommended the development of a formal business model for interlab testing at NLCTA. This model would allow other laboratories and institutions to use SLAC's infrastructure for their own experimental research, thus expanding the facility's utility and fostering greater collaboration between SLAC and the accelerator community. By providing access to external researchers, NLCTA could facilitate the development of new technologies and further cement its role as a leading testbed for RF technology and accelerator science.

Recommendations:

1. Establish clear timelines and milestones for future initiatives, including the LESA test accelerators, End Station A upgrades, and high-brightness injector developments. This roadmap should define key deliverables, funding strategies, and decision points to ensure timely execution and alignment with long-term research goals.
2. Implement a sustainable business model for interlab testing at NLCTA, ensuring broader accessibility and efficient resource utilization for other laboratories. This model should include cost-sharing mechanisms, operational priorities, and a structured framework for external collaborations to maximize impact and long-term viability.

In conclusion, the test facilities reviewed have demonstrated commendable scientific achievements despite facing common challenges such as resource constraints, deferred maintenance, and expanding research scopes. Strategic prioritization, resource management, and well-planned upgrades will be crucial to ensuring the sustained success of these programs. The recommendations provided for each facility should serve as a guide to maximizing the impact of the research while balancing operational efficiency and scientific productivity.

Comparison of R&D Programs by Thrust

This section offers a comparative assessment of the GARD thrusts by the committee, using the specific evaluation criteria outlined in the charge letter, such as scientific achievements, alignment with HEP's strategic goals, feasibility of proposed research, resource adequacy, and infrastructure quality. The tier ranking scheme used is Tier 1 (Excellent-Excellent), Tier 2 (Good-Excellent), Tier 3 (Good-Good), and Tier 4 (Poor-Fair).

	ABP	AAC	PST	RF Technology	SCM
Tier 1		BELLA & AWA			LBNL, FNAL
Tier 2	IOTA/FAST	FACET-II		SRF at FNAL	BNL
Tier 3			FNAL	NLCTA at SLAC	
Tier 4					

Accelerator and Beam Physics (ABP) is ranked as Tier 2: Good-Excellent. ABP is crucial for optimizing the performance of current and future accelerators, especially for high-intensity proton beams needed for key HEP experiments like DUNE, LBNF and future energy frontier collider. The development of advanced simulation tools, including BLAST, WARPX, and IMPACTX, has significantly contributed to accelerator science. However, the current funding resources and workforce limit ABP's ability to address mid-term goals effectively. With additional investment and strategic R&D prioritization, and alignment with the 2023 P5 recommendations, ABP would be better positioned to tackle challenges in complex beam physics for future accelerators.

Advanced Accelerator Concepts (AAC) earns a Tier 1 to 2. AAC leads the world in advanced accelerator technologies, with the BELLA program at Berkeley Lab, FACET-II at SLAC, and AWA at ANL driving groundbreaking research in laser-plasma acceleration, beam-driven plasma wakefield and structure acceleration. These programs position the AAC at the forefront of transformative accelerator concepts with long-term potential, even though near-term applications are still under development. AAC has made significant scientific advancements and developed a strong pipeline of talent, justifying its top-tier status. However, the primary challenge remains in its slow development of near-term applications, which limits its immediate impact on current and mid-term HEP programs despite their strong future prospects.

Particle Sources and Targetry (PST) is assigned Tier 3: Good-Good. PST is critical for developing high-power target technologies, particularly for the high-intensity neutrino program and future muon collider. Despite its importance, PST currently receives a very small portion of the GARD budget, limiting its ability to make a broader impact. The underfunding has constrained the thrust's potential to support the needs of future colliders and high-intensity experiments. Increased investment is necessary to enable PST to meet HEP's strategic objectives more effectively.

RF technology, particularly Superconducting RF, remains fundamental to the success of both current and future accelerator projects. Fermilab has made key advancements in mid-T techniques for high-Q SRF cavities. With the ongoing efforts on Nb3Sn SRF cavity, proposed fast tuning and resonant control R&D at Fermilab, it holds promise for enhancing SRF system adaptability in ACE-BR at Fermilab, FCCee and future colliders. Meanwhile, SLAC has significantly advanced NCRF technologies through its cryogenically cooled copper and high shunt impedance distributed RF coupling structures, contributing to the development of high-gradient RF systems crucial for future colliders and advanced applications.

Despite these achievements, RF technology faces critical challenges in workforce development. As a traditional technology field, RF lacks the appeal of emerging technologies, making it difficult to attract young talent. This is compounded by the fact that RF research often does not generate high-impact publications or offer the excitement associated with more cutting-edge R&D. To sustain and grow this essential skill set, the HEP Accelerator Traineeship program, which was established in FY2017 and has already supported workforce development in key areas, must see increased investment. The current level of support is insufficient to meet the growing needs of the field. Targeted investments in near-term, exciting R&D projects are urgently needed to attract and retain young researchers who are essential to ensuring the future of RF technology.

RF technology is indispensable for the operation of today's accelerators and will remain critical for future accelerators. Without a robust pipeline of skilled experts, the sustainability of current and future accelerator operations is at serious risk. Increasing the investment in workforce development and supporting high-impact, innovative R&D projects are essential to maintaining the field's relevance and capability. These combined factors place RF technology in Tier 2 to 3: Good-Excellent and Good-Good, acknowledging both its key achievements and the pressing need to address workforce challenges and invest in its future.

Superconducting Magnets (SCM) are crucial for the development of high-field magnets, which are essential for future collider designs, high-energy physics experiments, and other scientific applications. Berkeley Lab, through its leadership of the U.S. Magnet Development Program (MDP), has played a central role in advancing high-temperature superconductors, which are key to achieving the magnetic field strengths required for future energy frontier colliders. The MDP has been highly successful in coordinating the national SCM effort, fostering collaboration across U.S. laboratories, and driving innovation in magnet technology. Fermilab has contributed significantly to SCM R&D, focusing on high-field magnets for accelerators. Fermilab's ATF, its expertise in SRF cavities and large-scale magnet systems is critical for addressing the technical challenges of high-intensity beam applications and future colliders. At BNL, the focus on high-temperature superconducting magnets and direct-wind magnet technologies complements the broader U.S. SCM effort. BNL's work on magnets for the EIC will continue to be invaluable as EIC construction progresses, and the lab's talent and resources could further benefit HEP's future needs in superconducting magnets.

With the U.S. Magnet Development Program (MDP) at the helm, the U.S. effort in SCM remains robust and highly coordinated, ensuring that the nation maintains its leadership in this critical area of accelerator technology. SCM continues to be ranked as Tier 1-2: Excellent-Excellent and Good-Excellent, the GARD should continue supporting its strategic advancements. This thrust remains a vital component of the U.S. HEP program, ensuring that future collider projects and high-energy physics experiments can rely on cutting-edge magnet technologies.

In conclusion, the GARD thrusts are ranked based on their alignment with HEP priorities, scientific impact, and resource adequacy. AAC and SCM stand out for their groundbreaking research and strategic importance to the future of high-energy physics, earning them the highest ranking. ABP and RF technology are foundational thrusts that are critical to future collider projects but could benefit from additional resources to further enhance their contributions. PST, while essential, remains underfunded, limiting its ability to fully support high-intensity accelerator applications.

IV. Summary

The GARD review was a thorough five-day on-site evaluation of the General Accelerator R&D program by subject matter experts. The review focused on assessing the program's progress, impact, and alignment with the strategic goals, guided by thrust roadmap and P5 recommendation of the U.S. high-energy physics. Over the course of the review, the committee conducted in-depth examinations of the various R&D thrusts, test facilities, and workforce development efforts, with the objective of identifying both strengths and areas where enhancements may be warranted.

The review reaffirmed GARD's vital role in advancing accelerator technology and sustaining U.S. leadership in the field. However, it also highlighted the need for strategic adjustments to achieve a more balanced allocation of resources across the research thrusts, ensuring alignment with near- and mid-term objectives. While the Advanced Accelerator Concepts thrust has received significant attention and support due to its promising long-term potential, the review suggested that exploring a more balanced allocation of resources across all research thrusts could be beneficial. Notably, the committee emphasized the importance of increasing support for traditional Accelerator Beam Physics and high-power target research, which are critical for the U.S. high-intensity neutrino program and future collider R&D. Currently, funding is heavily weighted toward electron-based research, and a more balanced funding profile is recommended to address the needs of proton-based research and other high-priority areas in line with the 2023 P5 recommendations.

Additionally, the review emphasized the importance of strengthening workforce development and fostering collaboration between national labs and universities to ensure the continued pipeline of talent necessary for the future of accelerator research. With these adjustments, the GARD program will remain well-positioned to drive impactful research and innovation in accelerator technology and maintain U.S. leadership in high-energy physics.

V. Appendices

Charge Letter

Department of Energy
Office of Science
Washington, DC 20585

June 5, 2024

SUBJECT: Charge for the HEP GARD Lab Comparative Review

The mission of the High Energy Physics (HEP) program is to understand how our universe works at its most fundamental level. We do this by discovering the most elementary constituents of matter and energy, exploring the basic nature of space and time itself, and probing the interactions between them. The General Accelerator Research and Development (GARD) subprogram supports this mission by promoting fundamental research and development in particle accelerator science and technology. This subprogram fosters the research of accelerator science and technologies needed to design and build future accelerator facilities that will be used to conduct high-energy physics research programs that advance our science strategic goals.

This letter is to request that you conduct an onsite review of HEP-supported laboratory research efforts in the GARD subprogram on August 5-9, 2024. The purpose of this review is to assess the quality and impact of the recent scientific achievements by these research groups; the feasibility, relevance, and impact of the proposed research on achieving the scientific goals and milestones of the HEP mission; and the national deployment and balance of accelerator test facilities. The overall soundness of the GARD program, potential areas where consolidation or redirection will be beneficial and feasible. Your panel will also review the operation of accelerator R&D user/test facilities at each laboratory, including reliability, facility up-keep and improvement, effectiveness of the cost model and how well the users are being served. Considering the recent P5 report, assess each laboratory's workforce resources and future development plan, response, and alignment to the P5 recommendations in Accelerator Science and Technology.

For each laboratory's GARD research group, we request a specific evaluation and comment on

1) The quality and impact of the research accomplishments by the group since the last review in 2018.
2) The scientific significance, merit, and feasibility of the proposed research.
3) The competence and future promise of the group for carrying out the proposed research.
4) The adequacy of resources for conducting the proposed research, and cost-effectiveness of the research investment.
5) The quality of support and infrastructure provided by the laboratory.
6) For a laboratory where an experimental facility exists, provide an assessment of:
   - The reliability and cost containment of operation.

- The condition of the facility. What is the deferred maintenance backlog and its associated risk and cost?
- How impactful is the experimental portfolio of the facility to achieving the goals of the GARD roadmaps, and accelerator science in general?
- How to meet users research needs and feedback?
- Is the facility well suited to conduct these experiments?
- Could some or all the experimental work be conducted at other test facilities?

7) How does the group benefit the laboratory's experimental program (as applicable) and how well do the group's activities relate to the overall HEP mission?
8) The effectiveness of management in strategic planning, developing, and maintaining appropriate core competencies (including key workforce skills), implementing a prioritized and optimized program, and promoting and implementing a safe work environment.

The research efforts should be presented in terms of the laboratory group's contributions (as applicable) along the following programmatic thrust lines:

- Accelerator and Beam Physics (including modeling, beam instrumentation and controls).
- Particle Sources and Targetry.
- Advanced Accelerator Concepts.
- RF Acceleration Technology (including SRF, NCRF and RF Sources)
- Superconducting Magnets and Materials.
- Test Facility Operations.

Each laboratory should provide information in this format on both its accomplished and proposed research in advance of the review, including the level of effort for each thrust area (FTEs and funding), using the provided Excel template worksheet.

The final report should outline the laboratory-based accelerator R&D program in each of these thrusts and discuss the unique and important elements that the laboratory programs bring to bear in addressing these research topics. **In this context, we request a comparative assessment of each lab's overall performance in these areas relative to its peers, as well as an assessment versus comparable university groups.** The overall evaluation of the laboratory's research will be an important input to the process of optimizing resource allocations within the various research thrusts.

The HEP GARD subprogram supports a wide range of research thrust areas that are important to HEP needs, both in the mid- and long-term time scales. As part of this review, we are also requesting the reviewers to provide additional general findings and comments about the current status and future promise of the programmatic thrust areas listed above, for example:

- What are the expected deliverables and applications of this research thrust in the next 5-10 years?
- Are adequate resources in place to plausibly achieve these goals?
- Do the laboratories have sufficient technical and managemental infrastructure and workforce to reliably deliver the proposed R&D goals for this programmatic area in the next 5-10 years and respond to new developments?
- What is the benefit of additional investments in this particular thrust to HEP mission? What are the likely impacts of reduced investments?

I encourage you to interact with the laboratory groups at the review and provide them with whatever immediate feedback you find appropriate. Upon the completion of the review, reviewers should send a letter summarizing their findings and evaluations, which includes the overall findings on the GARD thrusts, an assessment of each laboratory's contributions to these thrusts. These letters will be confidential within OHEP.

Individual laboratory evaluations, along with the findings on each research thrust, and assessment of laboratory contributions therein, will be incorporated into a summary report. I would like to receive the draft individual laboratory evaluations and the summary report no later than October 15, 2024. Thank you for taking on this important task.

Regina Rameika

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Associate Director of the Office of Science for High Energy Physics
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A. Valishev and S. Posen, FNAL
J. Schmerge and Lisa Bonetti, SLAC

List of Recommendations

Argonne National Laboratory

1. Develop a concrete upgrade plan for AWA, including feasibility studies, design evaluations, and resource requirements before the next GARD review, to ensure the facility remains state-of-the-art.
2. Refine the scope and cost estimates for AWA-II in collaboration with GARD and other stakeholders, ensuring alignment with the HEP missions while exploring broader applications, such as compact FELs. A detailed assessment should be conducted within the next one to two years to establish feasibility and funding strategies.

Brookhaven National Laboratory

1. Complete the revision to the MDP roadmap and re-balance BNL's program according to MDP's new priorities.

Fermilab National Accelerator Laboratory

1. Accelerate high-intensity proton beam studies in IOTA by implementing a structured timeline with clear milestones. Within one-year, complete key benchmarks to validate high-intensity beam models and resolve simulation discrepancies, with dedicated resources and clear accountability to prevent further delays.
2. Revitalize Fermilab's Accelerator and Beam Physics (ABP) program and research culture through organizational restructuring and strengthened leadership within one-year. Expand collaborations with national laboratories and universities to enhance research capabilities and workforce development. Ensure alignment with the 2023 P5 Recommendations, particularly PIP-II, Fermilab's accelerator complex upgrades and future collider R&D.
3. Reinforce Fermilab's leadership in accelerator R&D by immediately implementing a concrete strategy to increase participation in key community conferences, workshops, and collaborations (e.g., IPAC, NAPAC, ICFA, SRF, Superconducting Magnets, and future collider workshops).
4. Provide a detailed analysis of prototype engineering challenges for top candidate materials identified in the High-Power Target Roadmap Report[8] within two years, assessing key limitations and potential solutions. This assessment should consider factors such as thermal stability, radiation resistance, and manufacturability to ensure that material selection aligns with long-term operational requirements.
5. Reevaluate the business model for cost-recovery and non-GARD and non-HEP projects using Fermilab's ATF facilities to ensure fair contributions toward maintenance and operational costs within one year.
6. Bring the SMCT to completion by finishing the construction of the full magnet and preparing for the proposed testing to validate its performance within two years. This will provide critical insights into stress management techniques, support the development of high-field superconducting magnets, and inform future magnet designs for accelerator and fusion applications.

[8] [2502.03305] HEP High-Power Targetry Roadmap -- Workshop Report

Lawrence Berkeley National Laboratory

1. Prioritize AMP efforts to meet the most pressing needs of the HEP community, such as PIP-II, accelerator complex upgrade at Fermilab, offshore Higgs Factory and future collider R&D.
2. Strengthen collaboration with IOTA and other labs to validate models for proton beams.
3. BELLA should develop a more concrete plan for its staging experiments while considering current funding constraints to ensure steady progress in advancing laser-plasma accelerator technology for colliders within six months.
4. Strengthen collaboration with Fermilab on PIP-II RF and ACORN developments to enhance Berkeley Lab's contributions to major accelerator projects. This includes formalizing joint R&D efforts, leveraging Berkeley Lab's expertise in RF cavity design and LLRF controls and FPGA programing, and establishing a clear roadmap for technical contributions and resource sharing over the next one to three years.

SLAC National Accelerator Laboratory

1. Strengthen national laboratories collaborations to accelerate collider design and beam physics study. Establish a formal partnership with Berkeley Lab's Accelerator Modeling Program to enhance simulation capabilities and develop next-generation accelerator designs. Expand joint efforts on Fermilab's Accelerator Complex Upgrade and future collider R&D to maximize available resources, drive innovation, and ensure a coordinated national strategy for advancing ABP research for high energy physics.
2. Preserve and develop collider physics expertise by systematically integrating senior scientists' knowledge into simulation frameworks, such as collaboration with AMP of Berkeley Lab, and expanding workforce development initiatives.
3. Develop a plan to maintain SLAC's position as a leading training ground for young scientists in accelerator and plasma science, providing diverse opportunities for students and early-career researchers to develop expertise in the field.
4. Prioritize the development of high-efficiency RF sources, aiming to demonstrate a prototype tube with increased power efficiency and reduced costs within the next few years.
5. Establish clear timelines and milestones for future initiatives, including the LESA test accelerators, End Station A upgrades, and high-brightness injector developments. This roadmap should define key deliverables, funding strategies, and decision points to ensure timely execution and alignment with long-term research goals.
6. Implement a sustainable business model for interlab testing at NLCTA, ensuring broader accessibility and efficient resource utilization for other laboratories. This model should include cost-sharing mechanisms, operational priorities, and a structured framework for external collaborations to maximize impact and long-term viability.

Committee Members and DOE Observers

Committee Members:

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Lawrence Livermore National Laboratory

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Meeting Agenda

Argonne National Laboratory

FY2024 DOE HEP GARD Laboratory Comparative Review Agenda at Argonne National Laboratory

August 7, 2024

Room F-108, Building 362

Time	Plenary Session Topics	Speaker
08:00 AM	Committee Executive Session	Committee
08:45 AM	Welcome & Introductory Remarks from ANL Leadership	Rik Yoshida K. HafidiL. Chapon
09:00 AM	AWA Program Overview	John Power
09:15 AM	AWA Research Overview	Philippe Piot
09:35 AM	AWA Operation Overview	Eric Wisniewski
09:45 AM	Q&A	John Power
10:00 AM	Coffee and AWA Facility Tour: Posters	All
	AWA Research	Phillippe Piot
11:00 AM	Developing technologies towards a 10-TeV class linear collide	Chunguang Jing
11:15 AM	High-Gradient High-Efficiency Acceleration in Collinear Wakefield Accelerators	Xueying Lu
11:30 AM	Beam Manipulation & Shaping	Rachel Margraf-O'Neal
11:45 AM	Bright Beams & Intense-Bunch Trains Generation	Gongxiaohui Chen
12:00 PM	Collaboration highlight: AWA as a platform for AI/ML development	Ryan Rousse (SLAC)
12:15 PM	Q&A	Phillippe Piot
12:30 PM	Working lunch: AWA Accelerator Science	All
01:15 PM	Collaborator Program	Scott Doran
01:30 PM	Recent and Ongoing Upgrades	Wanming Liu
01:45 PM	Collaboration highlight: AWA as a platform for LLRF development	Qing Ji (LBNL)
02:00 PM	Future Upgrades and AWA-II	Alexander Ody
02:15 PM	Q&A	John Power
02:30 PM	Report from the AWA Scientific Advisory Board	John Byrd
02:45 PM	Committee Executive Session	Committee members
03:45 PM	Adjourn	

FY2024 DOE HEP GARD Laboratory Comparative Review Agenda at Brookhaven National Laboratory

August 5, 2024

Building 902, Conference Room 63

Time	Presentation	Speaker
7:45 AM	Arrival at BNL	
8:15 AM	Executive Session	Committee
9:00 AM	Welcome	JoAnne Hewett
9:10 AM	Logistics	TBD
9:15 AM	Introduction to ATRO/ASTD & Interconnections/Crosscuts	David Asner
9:30 AM	Overview of GARD Magnet Activities Over Past 5 Years	Ramesh Gupta
9:50 AM	BNL Common Coil Magnet for Nb3Sn and CORC Insert Coil Testing	Mithlesh Kumar
10:00 AM	HTS/LTS Hybrid Magnet Technology (US-Japan)	Febin Kurian
10:10 AM	Direct Wind and Strech Wire Technology	Vikas Teotia / Brett Parker
10:20 AM	Cryo-electronics and Cryo-measurement System	Piyush Joshi
10:30 AM	Q&A	
10:40 AM	Photocathode R&D Program	Luca Cultrera
10:50 AM	Plans for Ongoing GARD Engagement	Mark Palmer
11:05 AM	Break/Q&A	All
11:15 AM	Magnet Division Tour	Mike Anerella
12:00 PM	Lunch & Executive Session	Committee
12:30 PM	DOE Tour of AFD Facilities	DOE Attendees
02:00 PM	Depart to Airport	

FY2024 DOE HEP GARD Laboratory Comparative Review Agenda at Fermi National Accelerator Laboratory

August 6, 2024

Wilson Hall, One West Conference Room

Time	Plenary Session Presentation	Speaker
07:30 AM	Executive Session	Committee
08:30 AM	Welcome	Bonnie Fleming
08:35 AM	Fermilab GARD Program Overview (25+5 Q&A)	Alexander Valishev
09:05 AM	Fermilab Accelerator Test Facilities (25+5 Q&A)	Sam Posen
09:35 AM	ABP (25+5 Q&A)	Aleksandr Romanov
10:05 AM	Coffee Break	
10:20 AM	SRF (25+5 Q&A)	Sergey Belomestnykh
10:50 AM	HFM (25+5 Q&A)	Steve Gourlay
11:20 AM	HPT	Frederique Pellemoine
11:50 AM	GARD Workforce (20+5 Q&A)	Jonathan Jarvis
12:15 PM	Lunch + Additional Discussion	All
01:05 PM	Tours: FAST/IOTA (Group 1) and RF&HFM (Group 2)	
02:30 PM	Coffee Break	
02:40 PM	**Breakout Sessions**	
05:15 PM	Coffee Break	
05:25 PM	Closing Comments	
05:35 PM	Executive Session	Committee
06:35 PM	Reception and Poster Session	All
08:30 PM	Adjourn	

Breakout Session A: SRF and HFM at Snake Pit (WH2NE)

Time	Breakout Session: SRF and HFM Topics	Speaker
02:40 PM	Cryogenic test facilities in support of GARD	Benjamin Hansen
03:00 PM	Nb3Sn Magnet Test Results	Maria Baldini
03:15 PM	FNAL Activities Toward Reduction of Training in Superconducting Magnets	Stoyan Stoynev
03:30 PM	Magnets: REBCO Program	Vadim Kashikhin
03:45 PM	Magnets: Conductor R&D	Xingchen Xu

04:00 PM	Break	
04:05 PM	Transformational SRF R&D using state-of-the-art facilities and future directions	Alexander Romanenko
04:25 PM	Advances in High Q and high gradient research	Daniel Bafia
04:35 PM	Progress in alternative superconductors for SRF	Grigory Eremeev
04:45 PM	SRF structures for future HEP accelerators	Kellen McGee
04:55 PM	Transformational SRF R&D for accelerator projects and applications outside of accelerators	Anna Grassellino

Breakout Session B: ABP and HPT at One West (WH1W)

Time	Breakout Session: SRF and HFM Topics	Speaker
02:40 PM	Facility and Operations at IOTA/FAST	Aleksandr Romanov
03:00 PM	Core Intensity Frontier Programs at IOTA/FAST	Nilanjan Banerjee
03:20 PM	General ABP Programs at IOTA/FAST	Michael Wallbank
03:40 PM	Break	
03:45 PM	Future, Strategy, and Workforce for ABP at IOTA/FAST	Jonathan Jarvis
04:00 PM	Break	
04:05 PM	Novel Materials for Next-Generation Accelerator Target Facilities	Kavin Ammigan
04:30 PM	Simulation Development in Support of HPT R&D Program	Gaurav Arora
04:50 PM	Advanced Tool Development in Support of HPT R&D Program	Grigory Eremeev
04:45 PM	SRF structures for future HEP accelerators	Sujit Bidhar
04:55 PM	Transformational SRF R&D for accelerator projects and applications outside of accelerators	Anna Grassellino

FY2024 DOE HEP GARD Laboratory Comparative Review Agenda at Lawrence Berkeley National Laboratory

August 8, 2024

Room 264, Building 71

Time	Plenary Session Topics	Speaker
09:30 AM	Committee Executive Session	Committee
10:20 AM	Photography Session	
10:30 AM	Welcome and Berkeley Lab Overview	Natalie Roe
10:40 AM	Accelerator Technology & Applied Physics Division Overview	Cameron Geddes
11:10 AM	High Field Magnet Development and Projects	Soren Prestemon
11:40 AM	BErkeley Lab Laser Accelerator (BELLA) program	Eric Esarey
12:10 PM	Break	All
12:30 PM	Berkeley Accelerator Controls and Instrumentation Program	Qing Ji
12:50 PM	Advanced Modeling Program	Jean-Luc Vay
01:10 PM	Working Lunch (with graduate students, postdoc and early career researchers)	
02:10 PM	US Magnet Development Program	Diego Arbelaez
02:30 PM	High Temperature Superconductor and Magnet Development	Tengming Shen
02:50 PM	High Temperature Superconductor Magnet Protection and Diagnostics	Maxim Martchevskii
03:10 PM	Electron Acceleration and Laser Guiding: BELLA Operations	Anthony Gonsalves, Lieselotte Obst-Huebl
03:45 PM	Tour of BELLA Facility, Fiber Laser Lab, Magnet Facility in 77A and Magnet Fabrication /TFD (organized in two groups)	
05:05 PM	Collider design and fiber laser drivers	Jens Osterhoff, Tong Zhou
05:30 PM	Advanced Controls for Complex Laser and Accelerator Systems	Dan Wang Qiang Du
05:50 PM	Simulations of Beams in the Exascale Era	Axel Huebl
06:10 PM	Workforce Development, IDEA and Safety Management	Asmita Patel
06:30 PM	Executive Session	Committee
07:30 PM	Refreshments and Poster Session (Room 150, Building 71)	All
08:30 PM	Adjourn	

SLAC National Laboratory

FY2024 DOE HEP GARD Laboratory Comparative Review Agenda at SLAC National Laboratory

August 9, 2024

Conference Room, Building 53

Time	Topics	Speaker
08:30 AM	Executive session	
09:00 AM	Welcome	Sarrao/Akerib
09:10 AM	SLAC Accelerator R&D Initiative	John Schmerge
09:30 AM	FACET-II Overview	Mark Hogan
09:45 AM	Question/ Discussion	
09:50 AM	PWFA Program	Doug Storey
10:05 AM	Question/ Discussion	
10:10 AM	Experiments Using Extreme Beams	Alexander Knetsch
10:25 AM	Question/ Discussion	
10:30 AM	Coffee Break	
10:45 AM	ML/AI overview at FACET-II: Recent successes and opportunities	Brendan O'Shea
11:00 AM	Question/ Discussion	
11:05 AM	ECA - Generating and diagnosing extreme beams for next-generation high energy physics and fundamental science experiments	Claudio Emma
11:20 AM	Question/ Discussion	
11:25 AM	Collider Directed R&D	Spencer Gessner
11:35 AM	Question/ Discussion	
11:40 AM	NLCTA restart and relation to GARD programs	Emma Snively
11:55 AM	Question/ Discussion	
12:00 PM	Lunch with students and early career	
01:00 PM	RF Accelerator Research Overview and Outlook	Emilio Nanni
01:30 PM	Question/ Discussion	
01:40 PM	Advanced Computation for RF Accelerator R&D	Cho-Kuen Ng
02:00 PM	Question/ Discussion	
02:05 PM	Highlights from Cold Copper R&D	Ankur Dhar
02:20 PM	Question/ Discussion	
02:25 PM	Broader Impact of RF Accelerator Research	Brandon Weatherford

02:40 PM	Question/ Discussion	
02:45 PM	Coffee Break	
02:55 PM	SLAC Accelerator and Beam Physics Thrust overview and its synergies with BES	Zhirong Huang
03:15 PM	Question/ Discussion	
03:20 PM	SLAC beam physics status, impact and outlook	Yunhai Cai
03:40 PM	Question/ Discussion	
03:45 PM	SLAC collider design and optimization status, impact and outlook	John Seeman
04:00 PM	Question/ Discussion	
04:05 PM	Presentation adjourns	
04:10 PM	Tour start	
05:15 PM	Tour end	
05:30 PM	Executive session	
06:30 PM	Adjourn and Reception/Dinner (optional)	

Acronyms and Glossary

ACE: Accelerator Complex Evolution. A proposed major upgrade to the accelerator complex at Fermilab.

ACE-BR: Accelerator Complex Evolution Booster Replacement. A proposed major upgrade to the accelerator complex at Fermilab, including a replacement of the booster synchrotron, as part of ACE.

ACE-MIRT: Main Injector Ramp and Target, a proposed upgrade to Fermilab accelerator complex to upgrade the beam power up to 2.1 MW; part of the re-envisioned DUNE Phase II. Included as a component of ACE.

ACORN: Accelerator Controls Operations Research Network (ACORN). A project to modernize accelerator controls and power supplies at Fermilab.

ATF: Accelerator Test Facility. A user facility at Brookhaven National Laboratory that supports experiments for advanced accelerator and laser research including research on technologies that could make future particle accelerators much smaller. Fermilab's ATF, a cryogenic test facility primarily focused on supporting SRF and superconducting magnet research.

AUP: High-Luminosity LHC Accelerator Upgrade Project. The accelerator portion of the US contribution to HL-LHC providing critical components such as high-field "triplet" magnets using the Nb3Sn technology.

AWA: Argonne Wakefield Accelerator Facility. A facility to demonstrate electron-beam-driven wakefield acceleration technologies that could make future particle accelerators much smaller.

BELLA: Berkeley Lab Laser Accelerator. A facility at Lawrence Berkeley National Accelerator Laboratory that uses intense lasers to drive wakefield in plasma for research on technologies that could make future particle accelerators 100 to 1,000 times smaller, including combination of successive acceleration stages.

EIC: Electron-Ion Collider. A new facility colliding electrons and protons, under construction at BNL in support of the DOE Nuclear Physics program.

FACET-II: Facility for Advanced Accelerator Experimental Tests. An accelerator facility at SLAC National Accelerator Laboratory that provides high-energy electron beams for researching particle accelerator technologies that could make future accelerators 100 to 1,000 times smaller.

FAST: Fermilab Accelerator Science and Technology. A facility including a fully equipped R&D accelerator chain to support research and development of accelerator technology for the next generation of particle accelerators.

FCC: Future Circular Collider. A future particle accelerator complex planned at CERN to support the FCC-ee and FCC-hh in a new underground tunnel with 91 km circumference.

FCC-ee: A proposed electron-positron Higgs factory in the FCC tunnel, possibly an intermediate step toward the FCC-hh collider.

FCC-hh: A proposed proton-proton collider in the FCC tunnel that will push the energy about seven times higher than that of the current LHC.

GARD: General Accelerator Research and Development program with the DOE Office of High Energy Physics. GARD develops advanced technologies for the acceleration of particles for HEP and other applications.

HEPAP: High Energy Physics Advisory Panel. A committee that reports to the Associate Director of DOE HEP and Assistant Director of NSF MPS.

HL-LHC: High-Luminosity LHC. The high luminosity upgrade to Large Hadron Collider

Higgs factory: A particle accelerator that collides beams of electrons and positrons, to

ICFA: International Committee for Future Accelerators. A body of the International Union of Pure and Applied Physics created to facilitate international collaboration in the construction and use of accelerators for particle physics.

ILC: International Linear Collider. A proposed future electron positron collider using superconducting radiofrequency technology.

ITN: ILC Technology Network. A network of international institutions set to advance ILC-related technology in selected areas toward engineering design and to explore opportunities for other accelerator applications.

IOTA: Integrable Optics Test Accelerator ring. The primary focus of the FAST accelerator R&D facility, IOTA is a circular accelerator testing nonlinear and other advanced approaches to high intensity particle beam technology.

J-PARC: The Japan Proton Accelerator Research Complex, jointly operated by KEK and the Japan Atomic Energy Association. J-PARC provides proton beams for T2K, COMET, and other particle physics experiments.

kBELLA: A proposed technology test facility of new plasma wakefield acceleration techniques that use high-power lasers to accelerate particles within very short distances.

LBNF: Long Baseline Neutrino Facility. A world-class facility hosting the DUNE experiment, and providing the long-baseline neutrino beam.

LCLS: Linac Coherent Light Source. The world's first hard X-ray free-electron laser located at SLAC National Accelerator Laboratory supported by DOE Basic Energy Sciences.

LCLS-II, LCLS-II-HE: Linac Coherent Light Source-II, and its upgrade. The world's first MHz rate hard X-ray free-electron laser located at SLAC National Accelerator Laboratory.

LHC: Large Hadron Collider. The world's largest and highest-energy accelerator, located at CERN, Switzerland.

Muon collider: A circular particle accelerator that steers and collides beams of muons and anti-muons.

Mu2e, Mu2e-II: Muon to electron conversion experiment and its proposed upgrade, stationed at Fermilab, set to search for physics Beyond Standard Model.

Muon g-2: An experiment at Fermilab that performed the most precise measurement of the muon anomalous magnetic moment.

Nb_3Sn: Niobium Three Tin. A superconducting material characterized by the ability to sustain high currents and magnetic fields; used in particle accelerators such as HL-LHC and nuclear magnetic resonance.

PIP, PIP-II: Proton Improvement Plan and its successor. An enhancement to the Fermilab accelerator complex, powering the world's most intense high-energy neutrino beam.

QIS: Quantum information science, technologies for computation, information processing, and detection that elude classical limitations through the use of quantum effects.

RF: Radio frequency, a portion of the electromagnetic spectrum ranging from kHz to GHz. In particle physics, RF is used to directly accelerate particles and as a detection technique.

RHIC: Relativistic Heavy Ion Collider, particle collider, currently operating at Brookhaven National Laboratory.

SRF: Superconducting radio-frequency, also SCRF, where the RF resonators are fashioned of superconducting materials, such that the energy dissipation is lowered.

SWFA: Structural Wakefield Acceleration.

SuperKEKB: An electron-positron collider located at KEK, Tsukuba Japan.

Synchrotron: A type of circular particle accelerator in which the resonant radio frequency is synchronized to the changing velocity of the particles.