General Accelerator R&D Program

Accelerator and Beam Physics Roadmap

DOE Accelerator Beam Physics Roadmap Workshop

September 6–8, 2022

U.S. DEPARTMENT OF ENERGY | Office of Science

Abstract

This document describes a roadmap for the Accelerator and Beam Physics (ABP) thrust of the General Accelerator Research and Development (GARD) program, sponsored by the Department of Energy Office of High Energy Physics (DOE OHEP). Accelerators are a key tool for enabling discoveries in many fields such as particle physics, nuclear physics, and materials sciences and for use-inspired research. The dramatic success of accelerator-based particle physics research has been the result of the development of ever-more powerful accelerators over the past eighty years. Future discoveries in particle physics will similarly require new accelerator capabilities and deeper understanding of beam physics. The roadmap offered here will guide ABP R&D programs and maintain world leadership of U.S. accelerator research for the next decade and beyond.

J. Blazey
Northern Illinois University, DeKalb, IL 60115

D.L. Bruhwiler
RadiaSoft LLC, Boulder, CO 80301

J. Byrd
Argonne National Laboratory, Argonne, IL 60439

S. Cousineau
Oak Ridge National Laboratory, Oak Ridge, TN 37830

Z. Huang
SLAC National Accelerator Laboratory, Menlo Park, CA 94025

S. Nagaitsev
Fermi National Accelerator Laboratory, Batavia, IL 60510
University of Chicago, Chicago, IL 60637

M. Palmer
Brookhaven National Laboratory, Upton, NY 11973

P. Piot
Northern Illinois University, DeKalb, IL 60115
Argonne National Laboratory, Argonne, IL 60439

J. Power
Argonne National Laboratory, Argonne, IL 60439

J.B. Rosenzweig
University of California, Los Angeles, Los Angeles, CA 9009

V. Shiltsev
Fermi National Accelerator Laboratory, Batavia, IL 60510

L. Spentzouris
Illinois Institute of Technology, Chicago, IL 60616

J.-L. Vay
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Contents

1 Introduction and Executive Summary

The April 2015 report of the Accelerator Research and Development Sub-panel of the High Energy Physics Advisory Panel (HEPAP) [1] recommended the development of a long-term vision and a research and development roadmap for accelerator science and technology to enable future DOE HEP capabilities. In response, this report is based on two community input-gathering workshops [2] as well as a GARD Accelerator and Beam Physics Roadmap Workshop held in September 2022. Over two and a half days, September 6–8, 2022, the DOE Office of High Energy Physics (DOE OHEP) held a hybrid workshop (those in-person gathered in Bethesda, MD) to develop an Accelerator Beam Physics (ABP) ten-year research roadmap to guide the General Accelerator Research and Development Program (GARD). The workshop charge, list of attendees and agenda can be found in Appendices A, B and C, respectively.

The first day of the workshop included presentations from OHEP and the Office of Accelerator Research and Development and Production (ARDAP), a discussion of the charge and agenda, reports on two previous workshops, and an overview of the most recent Snowmass'21 meeting. The afternoon of the first day featured presentations and discussion of the preliminary roadmaps for the four grand challenges identified at the preliminary workshops: Beam Intensity, Beam Quality, Beam Control, and Beam Prediction. The second day offered perspectives from abroad (CERN and Canada) and from other agencies (NSF and security agencies). Ample time was available for discussion within the grand challenge groups and with all attendees. Considerable emphasis was placed on charting the roadmap and community recommendations within the context of current and future facilities. The concluding day focused on integration of the individual roadmaps, organization of ABP, and integration with other programs. The agenda can be found in Appendix C.

Accelerator and beam physics is the science of the motion, generation, acceleration, manipulation, prediction, observation, and use of charged particle beams. Particle accelerators can be used to better understand our universe and to aid in solving societal challenges. As articulated at the previous workshops [2], ABP explores and develops the science of accelerators and beams to make future accelerators better, cheaper, safer, and more reliable by addressing four grand challenges:

1. **Grand Challenge #1: Beam Intensity**—"How do we increase beam intensities by orders of magnitude?" Beam intensities in existing accelerators are limited by collective effects and particle losses. A complete and robust understanding of these effects is necessary to help overcome the limits and increase beam intensities by orders of magnitude.
2. **Grand Challenge #2: Beam Quality**—"How do we increase the beam phase space density by orders of magnitude, towards the quantum-degeneracy limit?" Most applications of accelerators depend critically on the beam intensity and directionality (or beam emittance) in order to enable new capabilities or to optimize the signal-to-noise ratio. Addressing this grand challenge will yield unprecedented beam qualities that can revolutionize applications of particle accelerators.
3. **Grand Challenge #3: Beam Control**—"How do we measure and control the beam distribution down to the individual particle level?" An accelerator application benefits most when the beam distribution is specifically matched to that application. This challenge aims to replace traditional methods that use beams of limited shapes with new methods that generate tailored beams and also aims to provide new research opportunities, enabled by detecting and controlling individual particles in accelerators and storage rings.
4. **Grand Challenge #4: Beam Prediction**—"How do we develop predictive 'virtual particle accelerators'?" Developing virtual particle accelerators will provide predictive tools that enable fast computer modeling of particle beams and accelerators at unprecedented levels of accuracy and completeness. These tools will enable or speed up the realization of beams of extreme intensity and quality, as well as enabling much better control of the beam distribution, eventually reaching down to the level of individual particles.

These grand challenges must be considered in the context of important ABP missions associated with the overall DOE HEP mission:

1. Advance the physics of accelerators and beams to enable future accelerators.
2. Develop conventional and advanced accelerator concepts and tools to disrupt existing costly technology paradigms in coordination with other GARD thrusts.
3. Guide and help to fully exploit science at the HEP GARD beam facilities and operational accelerators.
4. Educate and train future accelerator scientists and engineers.

As explored in this document, current and future facilities in a wide set of disciplines depend on ABP methods, techniques, tools, and expertise. The requirements and challenges of specific facilities offer important guidance for the ABP roadmap. For all future facilities, there are a large number of inter-related research and development issues that must be addressed. A robust ABP program will be required for their success.

This document provides and justifies detailed R&D roadmaps for each of the four grand challenges as well as cross-cutting recommendations on ABP coordination, test facilities, and workforce development. The individual roadmaps offer a strategic plan that defines the time-sequenced steps and major milestones to accomplish the ABP mission. Fig. 1 collects the independent roadmaps with a single illustrative, example 20-year overview of current and possible HEP facility priorities. The figure also offers a high level overview of ABP experiments and tests over the next two decades, which features exploitation of FAST/IOTA and other test facilities [3], exploration of ultrabright sources, and development of advanced beam diagnostics. In terms of theory and modeling, the twenty-year program supports a variety of applications, design and implementation of virtual test stands, and exploitation and integration of both AI/ML and high performance computing into ABP.

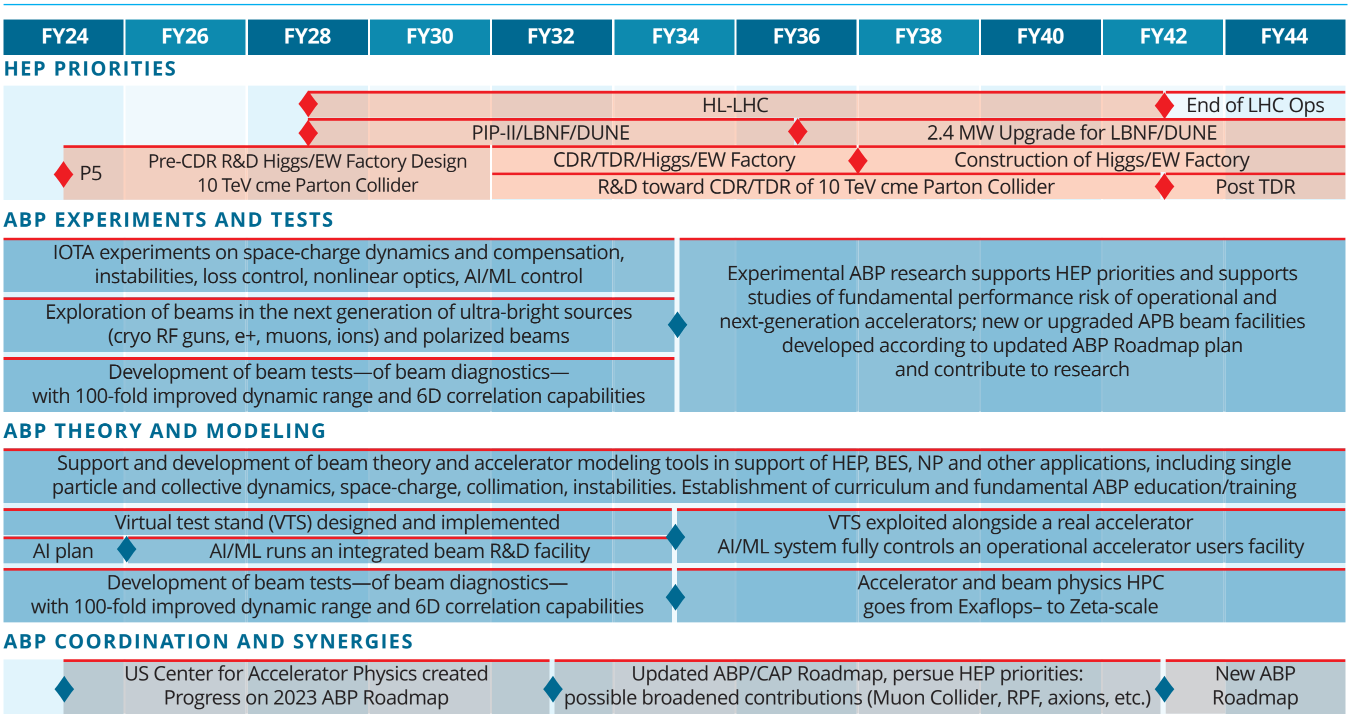

Figure 1: ABP roadmap for the next two decades reflecting HEP priorities, beam physics experiments and tests, theory and modeling developments, and coordination and synergies. *Grey shading of HEP Priorities indicates projects in progress. Red diamonds indicate anticipated start and end years of major HEP facilities and dates of Snowmass/P5 particle physics strategy updates. Blue diamonds show expected completion dates of various accelerator and beam physics activities and major ABP roadmap or organizational updates.*

The three cross-cutting ABP themes—a venue for coordination, support for test facilities, workforce development—emerged from the deliberations, which collectively serve as underpinning recommendations for supporting the roadmap. Although Fig. 1 illustrates one of many possible future scenarios, each with a set of specific ABP priorities, efforts to support these cross-cutting issues will be essential for all scenarios.

Fig. 1 explicitly carries the important recommendation, explored in Section 7, for a US Center for Accelerator Physics or an equivalent to serve as a venue for coordinating ABP research and education across the country. All efforts require sustained support for test facilities, discussed in Section 8. Workforce development, covered in Section 9, is both a critical requirement and a product of APB.

2 Accelerator Physics Drivers

The ABP missions include resolution of fundamental beam physics challenges and the design and commissioning of future particle physics facilities, as well as accelerators for BES, NP, ARDAP and various applications. Correspondingly, APB roadmap discussions have taken into account challenges and timelines of future facilities and address corresponding methods, techniques, and tools. In general, future particle accelerators will enable physics opportunities with a variety of particles (electrons, protons, ions, photons, muons, mesons, etc.) based on a spectrum of core accelerator technologies (RF, magnets, sources, targets, plasmas, etc.). Besides physics specifications (energy, power, luminosity, time structure, etc.), accelerator designs must address the issue of efficiency (in terms of performance, cost, and power consumption); take into account synergies and applications in basic energy sciences, nuclear physics, X-ray imaging for material physics and medical science; and consider compact particle accelerators for national security, advanced materials, and sustainable energy sources.

Fig. 1 explicitly carries the important recommendation, explored in Section 7, for a US Center for Accelerator Physics or an equivalent to serve as a venue for coordinating ABP research and education across the country. All efforts require sustained support for test facilities, discussed in Section 8. Workforce development, covered in Section 9, is both a critical requirement and a product of APB.

Fig. 2 summarizes the 2019 European Particle Physics Strategy Upgrade [4] plans and the Snowmass'21 discussions [5] and presents an approximate timeline for major current and future HEP accelerators. Among the approved programs, the LHC at CERN will be upgraded (HL-LHC) and operate until the early 2040s, and the PIP-II linac at Fermilab will be built by around 2028 and operate at 1.2 MW average 120 GeV proton power on a neutrino target for LBNF/DUNE in the 2030s. Both ILC and CLIC Higgs/EW factories are generally considered to be "shovel-ready" and their technically-limited timeline assumes decisions to proceed in the very near future. Three projects at Fermilab (a 2.4 MW power upgrade of PIP-II or PIP-III, Mu2e-II, and the PIP-II Accumulator Ring or PAR) are currently in conceptual stages, but their design work can start almost immediately after the 2023 P5 consideration and a decision to proceed.

One of the major outcomes of the Snowmass'21 planning exercise was a strong community interest in establishing a US national future collider accelerator R&D program [6] to address in an integrated fashion the technical challenges of promising future collider concepts, such as three Higgs factories—C3 [7] and HELEN [8] linear colliders, and FCCee—and an O(10) TeV center-of-mass (CM) energy Muon Collider. The goal of that program, awaiting P5 support, is to help move towards realization of the next collider as soon as possible and subsequently to advance towards a collider at a higher energy scale. Doing so will require significant efforts in APB to explore the the numerous collider concepts. The relevant timescales are the next European strategy update around 2026 and the next Snowmass and P5 around 2030. Of note, the CERN-led FCCee feasibility study in Europe may lead to a construction start in the early- to mid-2030s, while a similar CEPC collider proposal in China aspires to start

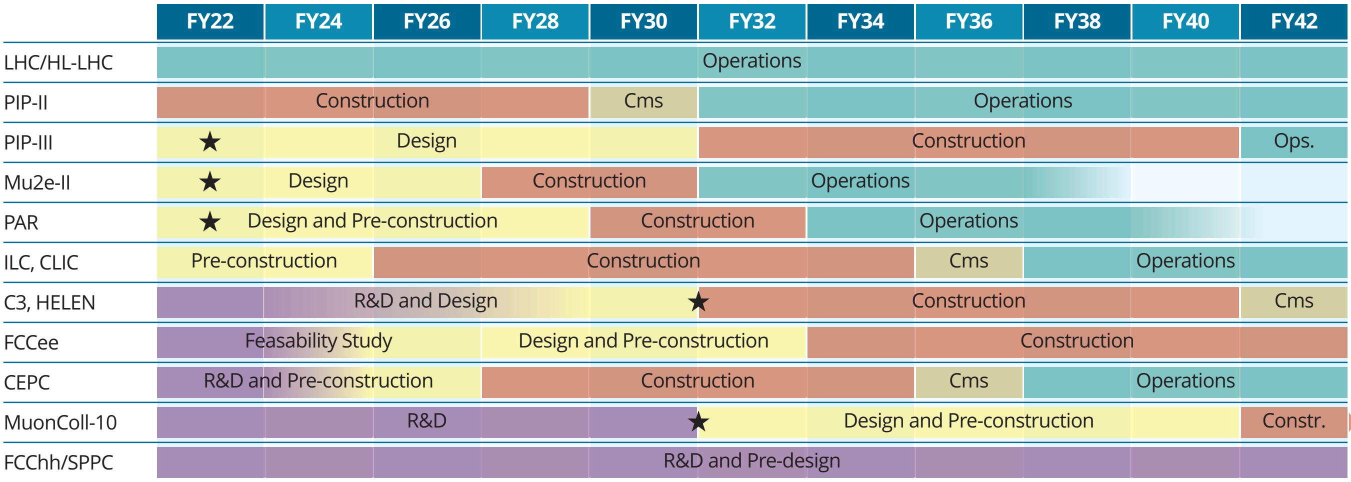

Figure 2: Approximate timeline of HEP accelerators according to the Snowmass'21 and EPPSU reports. *As described in the text, the star symbols indicate major decision points*

construction in late 2020s. Finally, on a much longer time scale, future hadron colliders FCChh and SPPC anticipate continuous R&D over the next 15–20 years.

Development and construction of many modern accelerators are supported by the DOE Offices of Basic Energy Sciences (BES) and Nuclear Phyiscs (NP). Most notable are large projects such as the LCLS-II and LCLS-II-HE free electron lasers (FELs) at SLAC, the ORNL Spallation Neutron Source (SNS) power upgrade and the Second Target Station, construction of the Electron Ion Collider (EIC) at BNL, and the planned upgrade of the Facility for Rare Isotope Beams (FRIB) at MSU. Under continuous development are high efficiency muon sources and μSR facilities and important beam applications, such as ultrafast electron diffraction and microscopy, low emittance beams, compact FELs with ultrashort pulses, CW H- and neutral particle beams, etc. Applications of these techniques and devices are of interest to the NNSA, DOD, DARPA, and the DOE Office of Accelerator R&D and Production (ARDAP).

Operational and future HEP facilities and facilities in other fields are critically dependent on the ABP methods, techniques, tools and integrated design expertise. The requirements and challenges of specific facilities offer important guidance for the ABP roadmap and are enumerated below. Of note, planning towards future high-intensity neutron and muon sources is mostly based on the ABP theory and modeling developments and experimental studies for the intensity frontier HEP machines (see listings below for PIP-II, PIP-III, Mu2e-II, and PAR). **The large number of items alone speaks for the need for a coordinated ABP effort.** The subsequent Table 1 offers a partial summary of the requirements and challenges with an indication of the importance of each. **The intensity of color offers a visual impression of high-priority subject areas and helps inform the priorities of the four grand challenges.** Note the strong emphasis on conceptual design integration and optimization for all potential facilities.

LHC and HL-LHC—*Theory and modeling:* e-cloud instability and nonlinearities; Landau damping e-lens, noise effects and control, beam collimation by crystals and hollow e-lenses, complex beam–beam dynamics (three beams with crab cavities, long-range beam–beam compensating wires and e-lenses); *Experimental studies/tests (at, e.g., LHC, RHIC, existing proton rings):* crystal collimation, electron lens Landau damping and collimation, intra-bunch feedback to control instabilities.

PIP-II, PIP-III, and possible Neutrino Factory—*Theory and modeling:* instabilities, e-cloud, impedances, transition crossing, injection and stripping, space-charge dynamics and losses, optics optimization and control, collimation and targetry physics (for a possible Neutrino Factory—beam interaction with materials and muon cooling physics); *Experimental studies/tests (e.g., in IOTA and existing proton rings):* verification on e-cloud, space-charge, non-linear integrable optics, losses and collimation, targets, electron lens space-charge compensation studies, control of instabilities, field tests and operation of virtual accelerators and AI/ML optimization of particle losses; *Integrated machine design (anticipated PIP-III request):* tools and expertise are needed to design rapid cycling machine optics and beam stability and RF controls, etc.

Mu2e-II and PAR—*Theory and modeling:* injection and stripping, large acceptance optics/FFAG optimization and control, collimation and targetry physics, muon emittance exchange, measurements and control; *Experimental studies/tests (in IOTA, existing proton rings, g-2/Mu2e beamlines):* optics channel acceptance optimizations for large dP/P ; Integrated machine design (PAR and Mu2e-II FFAG): tools to design machine optics/FFAGs, longitudinal manipulations, collective effects evaluations and control, losses and collimation, etc

Linear colliders (ILC, CLIC, C^3, HELEN, ERL-based, and AAC)—*Theory and modeling:* final focus optics (maximum dP/P , minimal length), emittance control and monitoring, jitters, noises, feedback systems and ML/AI tuning tools, efficient positron and electron production and acceleration schemes, drive beam dynamics for P- and S-WFA colliders, HOM effects in ERLs, polarization; *Experimental studies/tests (at FACET-II, AWA, FAST, CESR, PERLE/CBETA):* beam-based alignment techniques in the presence of external noises, high-current beam dynamics in ERLs, drive and main beam dynamics and power efficiency in the RF and AAC structures, positron production and acceleration, plasma lenses, advanced RF concepts beam demonstrations for C^3 and HELEN; *Integrated machine design:* C^3 and HELEN pre-CDRs are required by 2029 (part of the National Future Collider R&D Initiative), self-consistent parameter sets for WFA collider facilities by 2029, (possible) ERL-based collider design.

Circular colliders (FCCee, CEPC, CERC)—*Theory and modeling:* monochromatization, high-current beam dynamics in ERLs for LHeC and CERC concepts, combined beam–beam and impedance effects, IR collision optimization, polarimetry for energy calibration, possible plasma-wakefield based particle sources and linacs; *Experimental studies/tests (at Super-KEKB, DAFNE, etc):* monochromatization, lessons from the SuperKEKB commissioning experience; *Integrated machine design:* contribution to the FCCee Feasibility Study Report by 2025 (part of the National Future Collider R&D Initiative), (possible) CERC and ERLC pre-CDR.

Muon colliders—*Theory and modeling:* neutrino flux and beam-induced background, generation, accumulation, compression and dynamics of short very high intensity proton bunches, muon cooling and instabilities during the cooling, multi-physics effects, optics and dynamics challenges of the RCS- or RLA-based main accelerator/booster, neutrino radiation hazard mitigation; *Experimental studies/tests (LHC MC DemoFacility, FNAL, etc):* 6D cooling, physics of multi-MW targets and absorbers, laser stripping and high-intensity proton bunch compression studies; *Integrated machine design:* IMCC 10 TeV Feasibility Assessment Report and the Test Demonstration Facility TDR by 2026, the US Muon Collider pre-CDR by 2029 (part of the National Future Collider R&D Initiative).

Hadron supercolliders (FCChh, SppC)—*Theory and modeling:* scaling the LHC beam dynamics to larger rings, IR radiation environment, specifications for major accelerator components; *Experimental studies/tests (LHC, RHIC, FNAL, etc):* efficient synchrotron radiation control, luminosity leveling, electron cloud control; Integrated machine design: serious effort expected to start in the 2030s.

Future X-ray sources, UEM/UED instruments and compact X-FELs—*Theory and modeling:* for rings—transverse and longitudinal beam stability at the levels O(0.1) μm and frequencies up to O(1)kHz, advanced lattice designs, virtual machine AI/ML tuneup, ion effects, control of high beam power densities and energy deposition (collimators); for linacs—high repetition rate beams and CW beam dynamics, predictive, fast and accurate machine models, AI/Ml tuning, short high-current electron bunches, micro-bunching and heating; dechirpers and pre-bunchers, CSR effects, emittance exchange techniques; *Experimental studies/tests (LCLS-II, APS, etc):* beam physics lessons from the APS/U, ALS-U, and LCLS-II(HE) commissioning, studies of ion effects on beam dynamics with controlled leaks, XFELS—multiplexing and cavity-based/XFELO at LCLS; *Integrated machine design:* advanced ABP tools will be needed for designing the next generation rings, ERL-based and linac-based X-ray and gamma sources, including inverse Compton ones.

The **Electron-Ion Collider** design and construction requires many collider-related beam physics techniques and tools listed above, with specific interests—*Theory and modeling:* polarization production and control, orbit tuneup by AI/ML, electron-proton(ion) beam–beam effects in the presence of crossing angle, crab cavities, external noises, nonlinearities and dynamic aperture, collective effects in the electron storage ring (ESR), such as impedance and TMCI, strong hadron cooling poses a spectrum of issues depending on the scheme (microbunch cooling or e-cooling ring); *Experimental studies/tests (RHIC, SuperKEKB, elsewhere):* understanding the localized impedance effects due to collimators as in SuperKEKB, demonstration of the coherent electron cooling (CeC) using plasma cascade at RHIC, analysis of the potential application of the optical stochastic cooling (OSC), etc. One can also expect that shortly after (or even before) the end of the EIC construction integrated machine design studies will be started to understand possibilities for the collider luminosity upgrade.

Applications of accelerators, as envisioned by ARDAP, NNSA and DARPA, require a broad spectrum of "community-standard" modeling tools (codes to simulate and design sources, beam transport, space-charge, ion hose instabilities, etc). They will also greatly benefit from exploratory experimental beam studies/tests on a broad spectrum of topics from compact plasma-based FELs to cathode and transport beam physics, instabilities and aberrations at beam facilities like ATF, AWA, Neptune, FACET-II, BELLA, FAST/IOTA, etc.

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

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

3 Grand Challenge One

Beam Intensity: How do we increase beam intensities by orders of magnitude?

3.1 Roadmap

Future demands for beams will exceed present capabilities by at least an order of magnitude in several parameter regimes, such as average beam power and peak beam intensity. Ultimately, the beam intensities attainable in present accelerators are limited by collective effects and particle losses from various sources. The ten-year roadmap for GC1 research is graphically represented in Fig. 3.

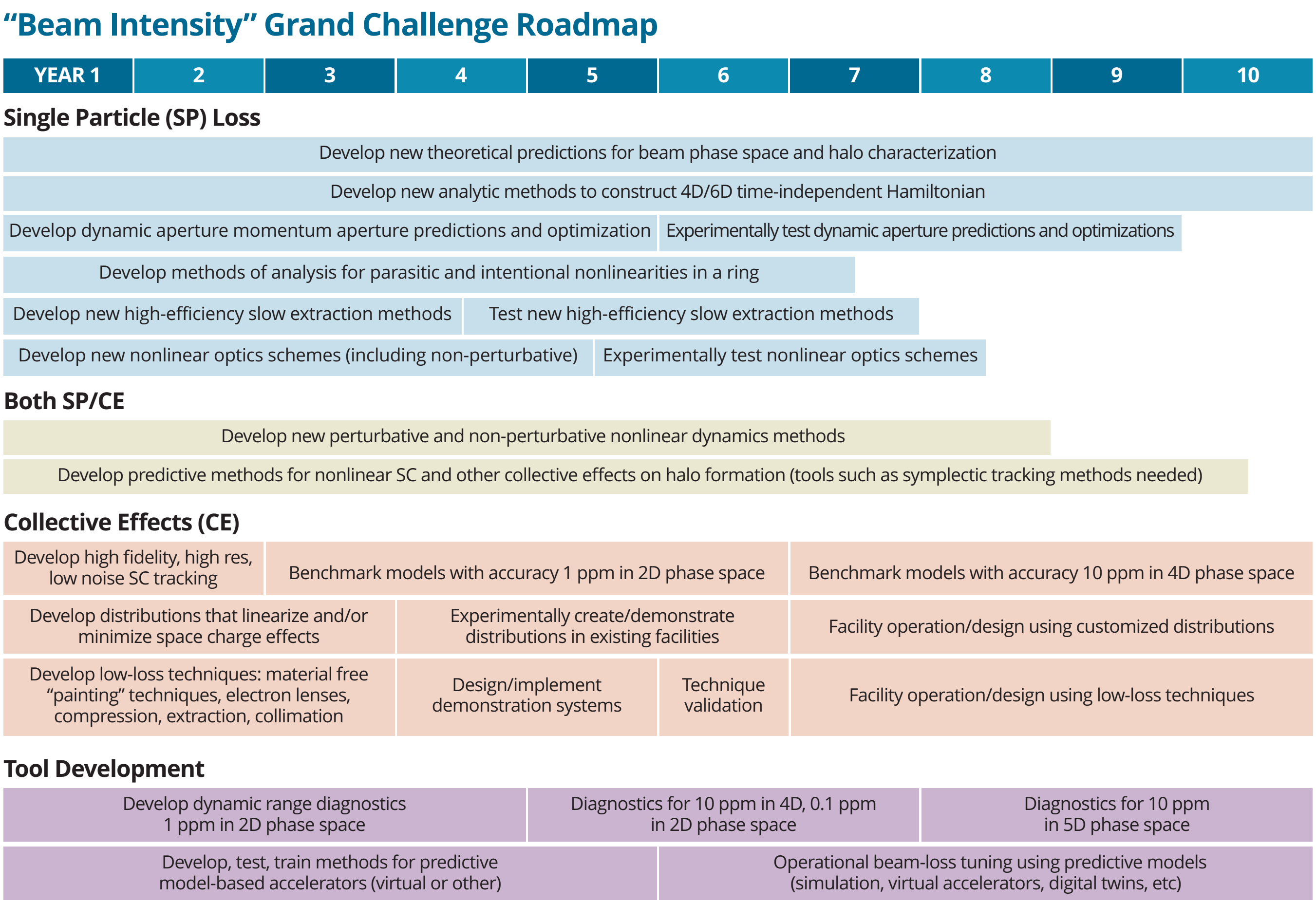

Figure 3: Approximate timeline of GC1 research topics *(see text).*

This section addresses how to overcome the collective forces in the beam that deteriorate beam properties and lead to beam losses and halo formation in the first place. If lost, even a part-per-million beam halo of a very intense beam can potentially damage equipment and cause radiation incidents. Collective effects include space-charge effects, beam interactions with impedances (causing, for example, beam break-up instabilities), electron cloud effects, and beam–beam effects in the presence of nonlinear dynamics. A robust understanding of these effects does not yet exist.

Theoretical, computational, and instrumentation tools to address this challenge are not yet fully developed at the precision level required by modern beam applications. Single particle dynamics must also be understood and controlled; a beam halo, created by single-particle (such as stripping foil scattering) and/or collective effects (such as space-charge effects), can cause particle loss through limitations of the dynamic aperture and momentum aperture. New analytic methods (4D/6D), and beam focusing schemes are needed in order to overcome these effects. Understanding of multi-physics processes such as halo formation at the interplay of single-particle dynamics and collective effects should be developed in the next decade. The advancement of beam manipulation methods (with minimal beam losses) is also needed to increase beam intensity. These methods include injection painting, compression, extraction (including slow extraction), beam distribution control, collimation, and RF manipulations.

The overall goal for research in proton rings is to enable a space charge tune shift in the medium term of greater than 0.5, and ideally in the long term of greater than 1.0. The space charge force in photoinjectors must not increase the beam mean transverse energy (MTE) above the intrinsic MTE of the photocathode.

Prioritization, organization, and implementation of the corresponding GC1 R&D efforts will require a venue for discussion and implementation such as within the framework of the proposed US Center of Accelerator Physics—see Section 7.

3.2 Single-particle dynamics

In the area of single-particle dynamics, increased theoretical understanding is needed on the prediction of beam phase-space and halo characterization, the role of nonlinear SC on halo formation, applying or developing nonlinear dynamics methods (perturbative and non-perturbative), and reducing numerical artifacts in long-term simulations. New analytic and theoretical methods to construct a 4D or 6D time-independent Hamiltonian are required in order to advance our understanding of single particle dynamics in future accelerators. These theoretical advances would help address all four Grand Challenges as they would form the underpinning of next generation beam dynamics. New beam dynamics methods would include the analysis of parasitic and intentional nonlinearities in a ring, dynamic aperture predictions and optimization, new high-efficiency slow extraction methods, and investigation of non-perturbative nonlinear optics schemes. For example, currently reliable tracking of dynamic aperture in storage rings, such as the Large Hadron Collider, spans about 10 million turns. However, it is highly desirable to track up to 108–109 turns. Another example concerns our understanding of dynamic aperture—it is mostly based on nonlinear resonances, tune shifts, and chromaticity as derived from conventional perturbation theory. A more detailed non-perturbative predictive knowledge of how these affect the dynamic aperture in storage rings is needed.

Prior research into strong transverse focusing (small average beta-functions) in storage rings and colliders indicates that it could mitigate intrabeam scattering and other undesirable dynamical effects. However, strong focusing also produces strong chromatic effects. Combining strong focusing with chromatic corrections is a very promising area of research to address Grand Challenges 1 and 2. This advancement would require increased precision in measurement capability and in control of optics (≈ 1% for beta-functions) to achieve the needed tunability of accelerators. In addition, all advanced linear collider schemes should be adaptable to beams with higher than normal momentum spreads. Large momentum spreads may arise from beam loading, but may also be needed for damping of transverse oscillations and to mitigate the beam-break-up instability. Transporting and focusing of beams with large momentum spread would open up many opportunities in advanced accelerator schemes.

Nonlinear optics (transverse focusing) schemes in high-intensity circular accelerators would enhance a beam's immunity to instabilities and losses. Such schemes with reduced chaos hold great promise for enhanced Landau damping and instability suppression by amplitude-dependent tune spread.

3.3 Collective effects and impedances

Understanding and control of collective effects, whether in linacs or rings, relies heavily on multiparticle simulations that give a complete picture of the underlying beam dynamics; such simulations can also aid the development of improved single particle dynamics models. However, prediction of beam dynamics under the influence of strong space charge with simulations has thus far been successful only at the RMS level, well short of the level required for true understanding, prediction, and control of beam loss caused by beam halo. In linear accelerators, models that incorporate the space-charge effect are developed and have been successfully benchmarked against theoretical predictions. However, for applications to real accelerators these models are limited by other practical unknowns about the beam and the accelerator, particularly the input distribution (initial condition of beam). Achieving prediction and control of beam halo under the influence of space charge requires precise knowledge of the full six-dimensional input distribution and all of the lattice details, along with diagnostic tools capable of measuring beam distributions at the level of beam loss, e.g., below 1 ppm, as detailed below. Milestones in development of high dynamics range diagnostics for two-dimensional and high-dimensional phase space are noted in Fig. 3. The ability to measure in all six dimensions was recently achieved [9], but was low resolutions and required impractically long scan times. An important goal is to achieve high resolution (>1000 points per dimension), high dimensional phase scan meausurements in 5D or 6D within one or two hours of scan time. The capability to accurately predict beam halo and beam loss with simulations will inform the development of theoretical single particle dynamics for halo generation and will lead to better methods of beam halo control either through optics manipulations or strategically placed scraping and collimation.

For high-intensity proton rings, beam loss resulting from foil scattering during charge exchange injection is a major limitation on scaling up intensity in future machines; even now, injection regions typically exhibit the highest levels of radiation in a proton ring due to beam scatering in the injection foil. Material-free methods of charge exchange can be envisioned that would drastically reduce beam loss in high-intensity rings. For example, the technique of laser-assisted stripping injection could be employed as a method to overcome limitations associated with foil-based charge exchange techniques and enable high-intensity proton beams, but must produce stripping efficiency with equivalent effectiveness as foils at a level of 95% or greater. Along with other technologies for mitigating losses, the method must undergo a technological readiness path with a demonstration system, technique validation, and operational readiness, as shown in yellow in Fig. 3.

In the case of rings, an extra degree of freedom is given through control over the painted beam distribution. Customized distributions that linearize and/or minimize space-charge effects can play a major role in reducing the space-charge tune shift and subsequent halo growth of the beam. Self-consistent beams are one such candidate that hold significant potential in this area, but other analogous distributions could be considered. Such distributions have been designed but need to follow a development and demonstration path as noted in the collective events section in 3. However, these distributions that require customized injection painting may be limited in rings that utilize foils for charge-exchange injection, where the injection painting scheme must consider the number of beam foil traversals. Complete freedom to optimize the injection scheme cannot be achieved until an alternative foil-free charge exchange injection scheme is designed.

The interplay of collective effects with nonlinearities and impedances (static and dynamic fields) will need to be understood even as novel space charge mitigation techniques are deployed. To achieve this, increased theoretical understanding is required on many related fronts, including (1) the prediction of beam phase space and halo characterization, (2) the determination of the role of nonlinear SC on halo formation, (3) the application or development of nonlinear dynamics methods (perturbative and non-perturbative), (4) understanding numerical artifacts in long-term simulations, (5) the development of novel space charge mitigation techniques (distributions, optics etc.), and (6) the determination of the interplay of collective effects, nonlinearities, and impedances (static and dynamic fields) with space charge.

Further understanding is also needed about the interplay between space charge and instabilities on both the simulation side and the experimental side. Of particular concern is the ability to mitigate these instabilities when traditional techniques, such as dampers, are not effective. Continued development of mitigation techniques is required, whether improved high-bandwidth dampers or other novel methods. Electron cloud instabilities also pose a significant risk. These instabilities are challenging to model as they require multi-particle simulations that include accurate modeling of interaction with a material surface. While progress has been made, it is still not possible to accurately predict when these instabilities will appear in operating machines.

Electron lenses can provide mitigation with a broad range of applications. While electron lenses have previously been tested in the Tevatron and at RHIC, evolution of their capabilities is required to address the needs of next-generation facilities. A particularly promising application is to use electron lenses for compensation of space-charge effects and reduced tune depression in, e.g., IOTA. Other promising electron lens compensation schemes include hollow electron beam collimation, Landau damping of proton instabilities, and compensation for beam–beam effects.

3.4 Tools and techniques

The development of tools and techniques must occur in order to make progress in the control and mitigation of particle loss and collective effects. These tools include analytical and computational methods, beam diagnostics, and beam control systems. As an example, high dynamic range diagnostics must be developed, where for the case of linacs a resolution of 1 part per million two dimensional phase space is needed to avoid damage, and for the case of rings better than 100 parts per million is needed. Milestones along the path to this accomplishment are noted in figure 3. Simulations and hardware are needed to achieve desired particle distributions in beams to control or exploit space charge. Symplectic tracking methods, including space charge, should be developed and applied to study halo formation. Numerical methods should be improved to accurately predict long-term behavior of beams. Advanced SC tracking algorithms at high fidelity and high resolution are needed, and need successful benchmark with experiments to a high accuracy of 1 ppm in 2D, at least, as noted in 3. Another more hardware-oriented example concerns the development of advanced phase-space painting techniques to produce a beam with linearized or integrable space-charge forces (e.g. KV-like distribution) in rings. Milestones along this path are noted in figure 3.

Controlling a beam might be done using the field produced by another co-propagating or counter-propagating beam. One method is the use of an electron lens to collimate the halo associated with a proton beam. A variant of the electron-lens concept could possibly be expanded to enable more precise control over the distribution of a hadron beam. Some of the other research topics related to the electron lens include mitigation of space-charge effects, control of tune shift, and "enhanced" Landau damping.

Finally, it is worth noting that R&D facilities, such as FAST-IOTA, AWA, etc. (see Section 8), as well as experiments at operational accelerators play an essential role in the successful development of better tools and techniques.4

4 Grand Challenge Two

Beam Quality: How do we increase beam phase-space density by orders of magnitude, towards the quantum degeneracy limit?

4.1 Roadmap

Beam phase-space density is a determining factor for the luminosity of high-energy colliders [10], for the brightness of photon sources [11], and the utility of direct imaging using particle beams. Research topics span a notably wide range, such as frontier schemes for generating high-brightness electron and proton/hadron beams; controlling space charge and coherent radiation effects and other collective instabilities; preserving beam brightness during beam generation and acceleration, compression and manipulation; and developing novel techniques for beam cooling to increase phase-space density and exploration of crystalline beams for quantum information science.

The ten-year roadmap for GC2 research is graphically represented in Fig. 4. As the figure illustrates, the four main emphases are high-brightness beam generation and preservation, collective effects, spin and storage ring dynamics, and beam cooling techniques, including crystalline beams. The roadmap includes quantitative goals for each emphasis. Details for each research topic follow.

Prioritization, organization, and implementation of the corresponding GC2 R&D efforts will require a venue for discussion and implementation such as within the framework of the proposed US Center of Accelerator Physics —see Section 7.

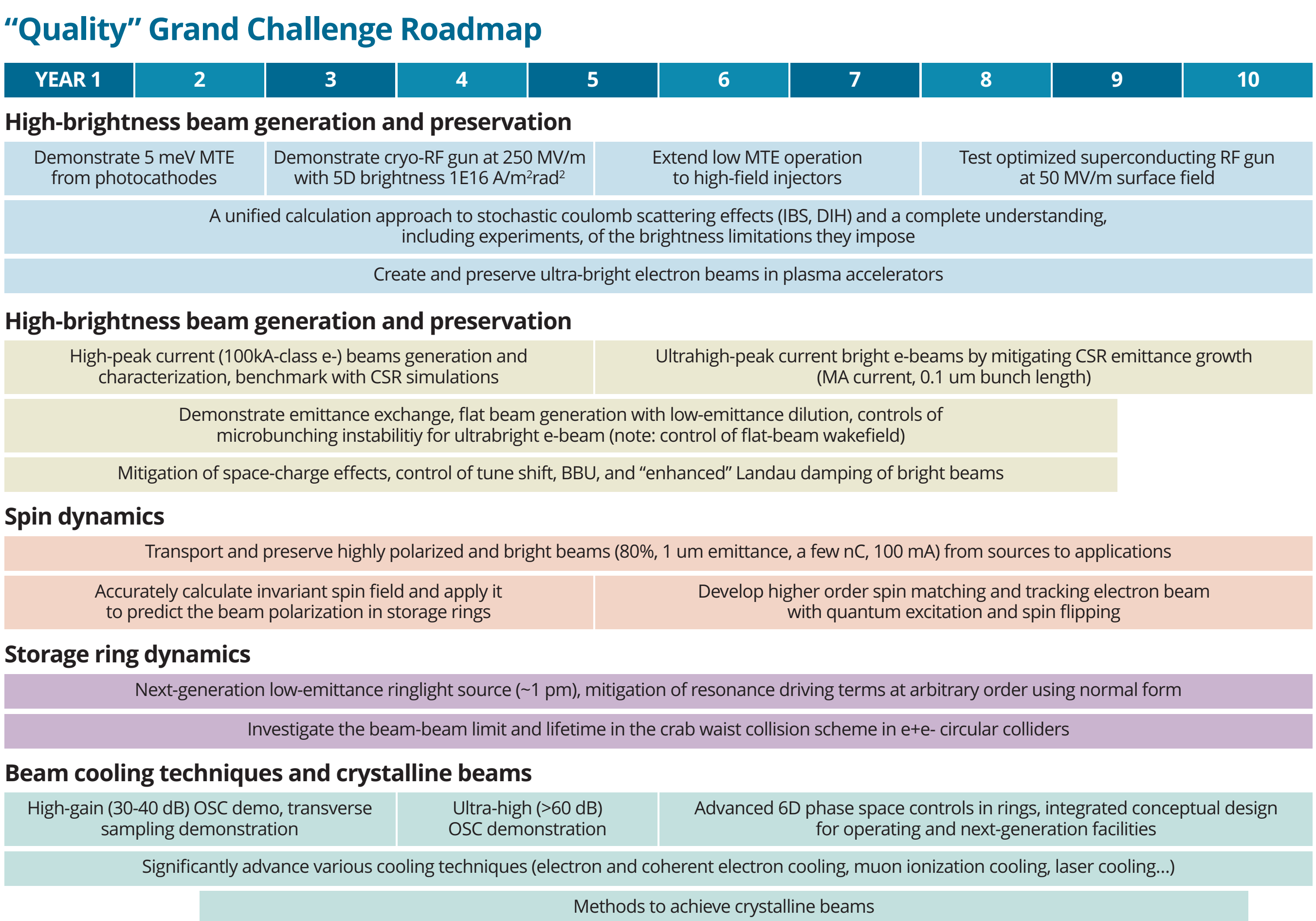

Figure 4: Approximate timeline of GC2 research topics *(see text).*

4.2 High-brightness beam generation and preservation

Milestones for beam creation and high brightness beam physics, including collective effects, are tightly linked to each other. Indeed, without overcoming space-charge limits on brightness utilizing very high field injectors (e.g. SRF or cryo-RF-based), the drive to push the mean thermal energy of cathodes has much less impact. Thus the development of very high field injectors is a primary consideration, and the operation of a photocathode RF gun at 250 MV/m field, with attendant measurement of 5D brightness at a level of two orders of magnitude of the original LCLS design is an essential milestone. The milestone to demonstrate a photocathode with 5 meV mean transverse energy (MTE), while initially likely to be performed at low cathode field, will need to be extended to high field operation. This provides another reference milestone, which completes the brightness development program as envisioned in the roadmap.

The combination of high field acceleration and low MTE will permit synergy in design and production of yet brighter beams through re-optimization of operating regimes. The emergence of such bright electron sources will permit exploration of novel physics effects, such as disorder-induced heating (DIH) and intra-beam scattering (IBS). IBS experiments are still in their early stages, and should be extended to explore effects on compression and coherent synchrotron radiation and longitudinal space-charge instabilities. The goal of such campaigns will be to understand 6D brightness limits, as they play a key role in applications such as XFELs.

Disorder-induced heating (DIH) may provide a strong barrier to the stated goal of achieving beams at the quantum degeneracy limit. However, DIH measurements are not yet possible, as the cold, dense beams needed to explore such effects are not in hand. Improvements in 6D brightness as discussed above may permit this barrier to be overcome. In the intervening time, studies of randomly-patterned beam emission to give DIH effects in the mesoscopic regime may be considered. All of these studies of stochastic phenomena are connected to GC4 – benchmarking in an integrated computational model.

The burgeoning field of plasma-based electron sources provides another frontier for high brightness beam production. The extremely high fields, to many 10s of GV/m in current scenarios, give the possibility of pushing brightness limits by further orders of magnitude. However, due to the very high longitudinal and transverse fields in plasma, in combination with short wave periods (100 micron-level), challenges must be overcome. Emission processes must be controlled at the sub-femtosecond time scale. Beam dynamics, including beam-loading effects which are much more important in plasma accelerators, present new problems, including explosive emittance growth upon exiting plasma section, and new types of beam breakup. These phenomena may be addressed effectively in national facilities such as the AWA and FACET-II.

4.3 Collective effects in beam compression, manipulation, and controls

Ultrashort bunches (< 1 μm) enable qualitatively new physics for a number of facilities, from future HEP colliders to high-intensity gamma-rays, as discussed in various Snowmass'21 whitepapers [12]. The FACET-II accelerator is expected to provide the possibility for > 100kA pulses with < 1 μm rms bunch length in the next four to five years [13]. The coherent synchrotron radiation (CSR) effects are expected to lead to significant emittance degradation that is beyond the current 1D CSR models implemented in Elegant and other codes. Various 2D and 3D CSR models and simulation tools have been developed [14] and will be used to benchmark with FACET-II compression studies. ML surrogate-modeling opportunity also exists for improved simulation speed. Taking the next logical step and compressing electron bunches into the < 0.1 μm, >1MA regime would support the development of revolutionary new applications across a range of physics disciplines. The next steps are developing fast and efficient 3D CSR simulation tools and designing novel bunch compressors to reach this extreme beam physics regime while preserving emittance. This is synergetic with GC4's goals on high-performance computing and AI/ML controls 6. In addition, a facility/experiment will be required to validate simulation and advance techniques (see more in Section 8).

In many applications, manipulation of beam properties through emittance exchange and flat beam generation techniques are required and are topics of GC3 [15]. Nevertheless, collective effects such as space charge and CSR will dilute emittance. Studying phase space manipulations while preserving phase space density with low-emittance dilution is an important GC2 topic. In a similar fashion, mitigation of microbunching instability for ultrabright e-beam without diluting the phase space density is another important example [16]. Intense charged-particle beams are used for applications in high-energy physics, spallation neutron sources, and nuclear energy, and space charge is the dominate collective effects for these intense beams. Long-term goals in this research area are prediction and experimental validation of beam phase space distribution (emittance and halo characterization at levels << 10−4 in linacs and rings under increasingly extreme conditions. Alternative strategies for controlling space charge and "enhanced" Landau damping of bright beams will also be explored.

4.4 Storage ring and spin dynamics

Electron storage rings provide the foundation for future circular colliders, damping rings in linear colliders, and synchrotron light sources, all essential instruments to study high-energy physics, nuclear physics, and medical science. To increase the luminosity of colliders or the brightness of light sources, the beam emittance has been continually reduced, recently to the 10 picometer region [17]. In the next decade, 1 pm emittance is expected. This requirement of extremely low emittance presents many design challenges in single-particle dynamics, including better analysis of maps and improvement of dynamic apertures. To meet these challenges, further refinement of methods to compute the accumulating resonance driving terms using the normal form technique are required. Discovery of new mitigation methods [18] of very high-order resonances within an achromat is envisioned.

The use of polarized electron beams in high-energy colliders provides an important opportunity to investigate the fundamental forces of nature. Polarized electron beams can also be used to calibrate the beam energy by a precession measurement of the resonance width in the event rate. Hence, it is extremely important to accurately predict the achievable polarization in electron storage rings. Currently, the estimate is mostly provided by a linear formalism and therefore not quite complete, especially at high energy, when the synchrotron sidebands become important. A general formalism based on the invariant spin field, extending the calculation to highly nonlinear region and including the degradation from the synchrotron sidebands, must be developed. The formalism will enable higher order spin matching and tracking electron beam with quantum excitation and spin flipping. Moreover, the high-order matching will ensure the transport and preservation of highly polarized and bright beams (80% polarization, 1 mm normalized emittance, a few nC bunch charge, 100 mA current) from sources to applications.

4.5 Advanced beam cooling

Beam cooling is a fundamental and essential element in the design, construction, and operation of modern accelerator facilities. Cooling is principally used to produce and maintain the bright particle beams that support the accelerator-based sciences. Relevant facilities are cross cutting and range from storage-ring-based light sources and particle colliders to R&D facilities and ion rings.

At present, the primary frontier in beam cooling is the extension of stochastic cooling (SC) [19] to optical frequencies and bandwidths. The recent demonstration of non-amplified Optical Stochastic Cooling (OSC)[20] with electrons at Fermilab's IOTA ring constitutes the first such realization [21]. This proof-of-principle result opens the way to the development of OSC systems with high-gain optical amplification, an essential step towards operational systems for future accelerators. Amplified OSC should first be demonstrated with 30–40 dB of power gain, which will increase damping rates by approximately two orders of magnitude. As system performance approaches the optimal-gain condition, further increases in the cooling rate require an increase in effective system bandwidth using transverse optical sampling (TOS) [22]. Subsequent demonstrations of OSC with TOS and ultrahigh gain (>60 dB) would establish OSC as a mature, flexible cooling technology that can be deployed in a variety of possible applications, such as in, e.g., future electron-ion, ion-ion, and muon colliders. Ultimately, OSC may be combined with specialized diagnostics and reinforcement-learning algorithms to enable on-demand, 6D phase-space control in storage rings. Initial experiments are possible during the high-gain OSC demonstration, and robust control capabilities are envisioned in the second half of the roadmap timeframe. Finally, the experience and understanding from the amplified-OSC experiments should be leveraged to develop mature, integrated conceptual designs for existing and next-generation accelerator facilities (both lepton and hadron).

Coherent Electron Cooling (CEC), another promising SC method for intense hadron beams, is currently under development by SC/NP for use in the planned Electron-Ion Collider at Brookhaven National Laboratory. The development of synergistic elements that benefit both OSC and CEC should be pursued; these include beam and optical diagnostics, enhanced synchronization and feedback capabilities, and high-stability bypass systems. Additional development programs in conventional electron cooling (e.g. high-energy, high-current ring coolers) and muon-ionization cooling should be considered.

Finally, ABP has a unique opportunity to support and diversify Office of Science and HEP efforts in Quantum Information Sciences (QIS) by exploring the key technologies necessary to scale cold-ion QIS architectures in storage rings [23, 24]. An essential R&D target is the advancement of laser cooling in storage rings to achieve ion temperatures below 100 μK. The current state-of-the-art temperatures are approximately 1 mK for the longitudinal dimension and 1 K for the transverse dimensions. Novel methods or implementations of laser cooling and phase-space coupling will likely be required to meet this ambitious goal. The resulting ultracold crystalline beams, consisting of linear chains of 105–106 ions, are of both fundamental and applied interest. Initial experiments could be conducted at an existing R&D storage ring (e.g. IOTA), or a dedicated small-scale demonstrator (e.g. a circular radio-frequency quadrupole trap) could be developed. Additional R&D could focus on the understanding and mitigation of thermal and RF noise in storage rings; the development of accurate diagnostics and control systems for the ion crystal's orbit; and the development of simulation codes that account for the radiation and absorption of photons, the finite temperature of the surrounding chambers, and the vacuum conditions.

5 Grand Challenge Three

Beam Control: How do we control and diagnose the beam distribution at all scales—from its macroscopic properties down to the level of individual particles?

5.1 Roadmap

Controlling beam phase-space distributions with extreme precision will enable more efficient accelerator-based light sources, mitigate instabilities and suppress halo-formation in intense-beam accelerators, and enable applications of beams in quantum information science (QIS). In current accelerators, beam control often refers to producing a beam with specific ensemble-averaged parameters—the beam statistical moments. Examples of such control include RMS beam matching and emittance compensation in photoinjectors. A first step toward achieving these goals requires control of first-order beam moments, as positioning and stabilizing the beam in space and time is critical to a number of particle accelerator applications. Improved control goes hand-in-hand with improved diagnostics: increasingly precise beam shaping methods will require increasingly precise beam diagnostics.

The ultimate goal of GC3 is the development of methods to control and diagnose a beam at single particle levels. An intermediate step will be to develop techniques capable of impressing specific beam correlations (within or between the phase-space plane) and possibly shaping the beam phase-space distribution at a "mesoscopic" scale, defined as scales at least one order of magnitude smaller than the characteristic size of the beam bunch.

Fig. 5 shows a ten-year roadmap for GC3. On the figure's horizontal dimension, research is organized in terms of targeted precision in structuring and diagnosing phase-space distributions. For the vertical dimension, research topics start with control within an axis or phase-space plane with control complexity gradually increasing to control of the full 6D phase-space distribution at a mesoscopic level. Ultimately, being able to locate the individual particle position would enable the generation of organized beams with applications to, e.g., QIS, coherent radiation emission, or high-luminosity colliders.

Prioritization, organization, and implementation of the corresponding GC3 R&D efforts will require a venue for discussion and implementation such as within the framework of the proposed US Center of Accelerator Physics—see Section 7.

Roadmap specifics are discussed in the following section. We categorize the GC3 challenges at three scales. The macroscopic scale focuses on the beam's statistical moments. The microscopic scale seeks to control and diagnose the beam at the microscopic level. Finally, the mesoscopic scale addresses a scale larger than the inter-particle distance, but smaller than the beam characteristic size (e.g. the beam's distribution standard deviations). Generally, control should be accurate, stable, and easy to implement, while the diagnostic features should include high accuracy, low-latency, non-invasive, and single-shot abilities.

GC3 is intertwined with GC1 and GC2 as they generally relate to improving beam properties characterized by the moments of the beam distribution. Likewise, given the complexity of the beam distribution and the associated collective effects, the use of machine learning and artificial intelligence (ML/AI) to control the beam distribution (in simulations or during accelerator operation) also implies a strong connection with GC4.

5.2 Macroscopic scale: controlling ensemble-averaged quantities

The most established level of beam control and diagnostics is at the macroscopic scale where the beam properties are defined in terms of ensemble-averaged quantities. These include root-mean-square (RMS) beam size, emittance, brightness, and luminosity (for interacting beams) or peak values, such as peak current. Despite the maturity of the systems at this scale, efforts to improve these systems remain an active area of research.

The zeroth moment of the beam—the bunch charge—is generally set by the particle source and/or injection scheme. Controlling the beam charge and its stability does not present significant challenge at the percent level. In addition to controlling the single bunch charge, bunch trains, as used in beam-driven wakefield accelerators, are additionally constrained by maintaining charge balance along the train. Large dynamical range charge diagnostics down to the single particle counting have been demonstrated in electron storage rings [25].

There are six first moments of the beam that describe the beam barycenter in the phase space. Traditional methods to control and measure the transverse spatial position are based on conventional kickers and beam position monitors (BPMs). Diagnostic challenges related to the shortness of the electron beam and noisy chamber environment have frustrated conventional BPMs. Improvements to BPMs or development of novel technologies, such as fiber-integrated electro-optic sampling components, near-field imaging of aperture-based coherent diffraction, or beam-based alignment using wakefield, have been under investigation. Time of flight and energy

“Control” Grand Challenge Roadmap

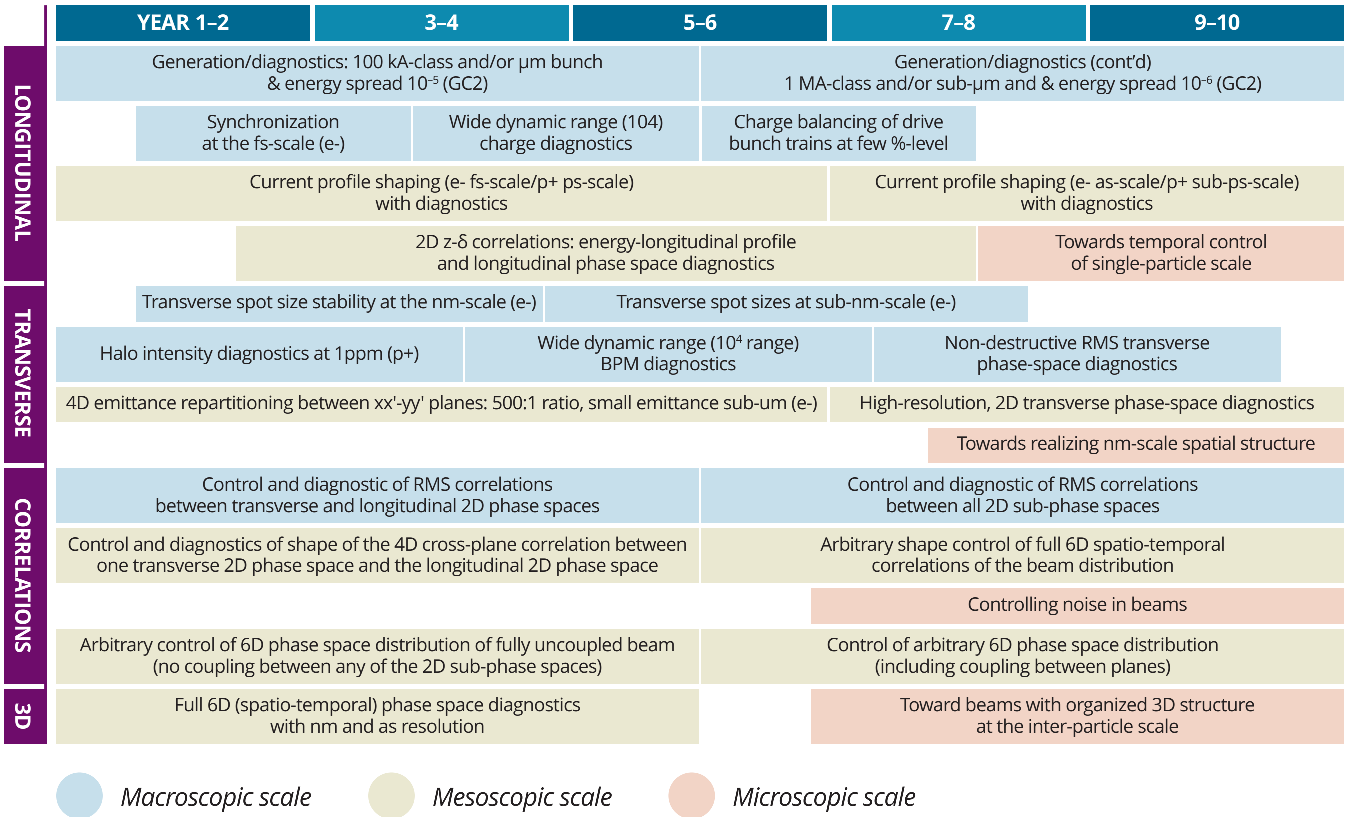

Figure 5: Timeline of GC3 research topics *(see text).*

measurement and control is critical to many applications and often relies on precise feedback systems for the acceleration system.

Nominally, there are 21 second moments associated with the 6D phase-space distributions often characterized by the beam covariance matrix. Often the beam motion is fully decoupled so that only moments in the sub-2D phase space are considered. Derived macroscopic kinematic-moment invariants [26], e.g. emittances, play a critical role in understanding the beam phase-space evolution. Coupled beams are finding an increasing number of applications. For instance, beams with significant angular momentum leading to a fully-coupled 4D transverse phase space have been considered for electron-cooling applications, and as an intermediate state for the generation of flat beams for linear-collider applications. Likewise, coupling between one of the transverse phase spaces and the longitudinal one has applications in muon cooling and light sources. These emittance-partitioning and emittance-exchange methods also have applications to improve injection in storage rings for light sources. Finally, higher-order moments have been proposed to quantify beam distortion and, e.g., halo formation in intense beams [27].

5.3 Mesoscopic scale: shaping the continuous distribution

The goal of generating specific beam distributions at the mesoscopic scale represents a paradigm shift from traditional approaches based on beam moments. For instance, producing electron beams with temporal modulations enable coherent-radiation emission and could enhance the performances of free electron lasers. Yet, forming microbunches at the sub-optical wavelength remains challenging and complex. Similarly, advanced beam-driven wakefield acceleration techniques could be more efficient if the drive beam’s longitudinal phase space and associated current distribution are tailored to produce an asymmetric current profile with specific longitudinal-phase-space correlation [28]. Additionally, beams with tailored 3D spatial distributions provide a path toward mitigating instabilities, e.g., linearizing space-charge forces. Finally, transversely shaping the beam distribution can alleviate stressed in target employed for secondary-beam production. The last decade has witnessed significant R&D efforts on mesoscopic-scale shaping methods for controlling the beam distributions utilizing external or self fields [15, 29], or using multi-pass techniques in storage rings, e.g. "phase-space" painting injection techniques [30]. These efforts have demonstrated new beam-manipulation techniques. Further developments of these methods toward higher-resolution shaping as well as of the beam-diagnostics methods capable of precisely resolving phase-space structures present significant challenges of conceptual and technical character.

5.4 Microscopic scale: toward individual particle control

Controlling the location of individual particles within the beam's six-dimensional phase space represents the ultimate goal of GC3. Such a precise control will enable the generation of crystalline beams [31] combining inter-particle ordering with mesoscopically-shaped distributions. This class of beam would have revolutionary applications: they would provide unprecedented luminosity in colliders, and they could radiate coherently copious amounts of radiation at wavelengths comparable to the inter-particle spacing. Likewise, ordered particles, e.g. ions, systems in traps [32] (storage rings or table-top traps), are possible contenders in QIS, especially for quantum computing applications [24].

So far there has been little work on attempting to control the beam at the microscopic scale. The free-electron laser and optical stochastic cooling [20] processes could be viewed as examples, albeit at larger scales, of possible techniques. The latter technique uses self-fields to detect information on the beam and apply a corrective kick. Generally, controlling the beam at the individual particle level will most likely rely on first controlling and understanding the source of noise in beams. Possible research directions include developing OSC-like methods for storage rings toward recording individual-particle information and applying the associated corrective kick. Beam ordering is somewhat similar to optical stochastic cooling. Likewise, methods to form ordered beams, e.g. combining traps with rapid acceleration, could provide a path to crystalline beams.

The beam diagnostics will be critical and present unprecedented challenges. However, fluctuation methods [33] and spectral analysis of beam-induced signal could provide information on the inter-particle spacing. Yet, expanding these techniques to yield a complete picture of the 6D phase-space distribution is an aspirational goal that will most likely be challenging to achieve within the suggested ten-year roadmap.

6 Grand Challenge Four

Beam Prediction: How do we develop predictive 'virtual particle accelerators'?

6.1 Roadmap

Computer modeling is essential to advances in beam physics, as well as particle accelerator design and operation. As particle accelerator science, technology, and applications increase dramatically in sophistication and complexity, simulations and the underlying algorithms must keep pace. As noted in the Snowmass'21 Computational Frontier (CompF) report: "The size and complexity of [High Energy Physics] Software and Computing are now commensurate with that of experimental instruments" [34]. In the next ten years, the modeling tools will incorporate enough physics and engineering details to enable virtual realizations of particle accelerators.

Developing the next generation of ABP computational tools that enable the realization of virtual accelerators calls for coordinated efforts among several sets of activities, as laid out in the 'Beam Prediction' roadmap (Fig. 6). The lead activity centers on the infrastructure to enable the assembly of 'Virtual Test Stands', which offer concrete realizations of building blocks, or stepping stones, toward end-to-end virtual accelerators. The purpose of activities laid out in this roadmap is to enable scientific discovery via computation—both new ABP science, as well as new work regarding computational science and associated efforts in AI/ML and applied mathematics. The roadmap also addresses the needs to push the frontier of ABP theory and modeling itself with better mathematical and computational methods and tools, the inclusion of AI/ML methods, and the exploration of quantum algorithms. It is also motivated by the need to improve computational support of existing facilities, planned upgrades, and new concepts. In particular, we call out the need to fundamentally improve controls with fast, high-fidelity online models.

Beam Prediction – Grand Challenge Roadmap – GC4

YEARS 1–2	3–4	5–6	7-8	9–10	GOALS
Virtual Test Stand (VTS)					
HEP community report: specify data & I/O standards	**HEP community report:** specify workflow technologies	Implement ABP **Virtual Test Stand (VTS)** subsystems, with an emphasis on automated workflow, easy access via supercomputers and cloud computing. Simulate new concepts relevant to an HEP experimental test facility.			Production-ready VTS for new ABP science
HEP community report: initial definition of all VTS subsystems					
AI/ML - Controls					
HEP community report: specify AI/ML standards/tools	Develop AI/ML representations of codes and subsystems for test facilities				Realtime model-driven controls for operating facilities
	Validate surrogates via comparison with a test facility		Use VTS subsystem(s) to optimize controls algorithms		
	Batch 1	Batch 2	Batch 3	Batch 4	
High Performance Computing					
Transition ABP codes to hardware-independent programming models, including deployment to serial and parallel platforms via standard tools.					2x to 1000x speedup of >10 codes
Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	
Algorithm R&D					
Advances into advanced mathematical, computational & theoretical methods, including new algorithms, new physics & quantum computing					New science
Review report 1	Review report 2	Review report 3	Review report 4	Review report 5	
V&V and Training					
Software documentation and testing; support and training for both users and developers; workforce development.					Reduce technical risk; increase efficiency
Test Suite v1	Test Suite v2	Test Suite v3	Test Suite v4	Test Suite v5	

Figure 6: Approximate timeline of GC4 research topics *(see text).*

The ten-year activities are organized along five tracks: one overarching track with a goal to develop the infrastructure for and the realization of virtual accelerator test stands, a second track to leverage AI/ML and integrate it into accelerator simulations and control systems, a third track to leverage high-performance computing, a fourth track to focus on advancing the underlying mathematical models and algorithms (including the exploration of algorithms on future quantum computers), and a fifth track to reduce technical risk and increase efficiency via documentation, validation, and verification ('V&V') and training.

The GC4 activities are cross-cutting, and the GC4 roadmap is thus relevant by construction to the three other ABP GC roadmaps, the other GARD thrusts roadmaps, and future facilities. It is consistent with the findings and recommendations from the Snowmass'21 white paper from the Beam and Accelerator Modeling Interest Group [35], which forms the basis of the recommendations on ABP modeling from the Snowmass'21 Computation Frontier draft report [34]. One finding reported in the white paper is that "Despite accelerator physics being a field with extreme levels of coordination and long-range planning for the research, design, construction, and operation of its largest accelerator complexes, e.g., at CERN or at Fermilab, the development of beam and accelerator physics codes has often been largely uncoordinated." [35] It is also consistent with the finding that, in accelerator and beam physics, as in other areas of science, "Software needs to transition from a set of individual research projects to a production infrastructure" [36]. Such transition to a coordinated infrastructure is essential if the community is to realize virtual accelerators and test stands for future ABP research and facilities, and is at the core of this roadmap.

Prioritization, organization, and implementation of the corresponding GC4 R&D efforts will require a venue for discussion and implementation such as within the framework of the proposed US Center of Accelerator Physics—see Section 7.

6.2 Virtual accelerators and virtual test stands

The ability to develop virtual realizations of particle accelerator components offers the opportunity to develop 'virtual test stands' (VTS) that can serve an analogous, and complementary, role to experimental test facilities. It is envisioned that the community would develop virtual test stands for generic particle accelerator subcomponents, such as, e.g., injector VTS for RF photocathode gun, DC thermionic gun, H-LEBT and RFQ, LINAC VTS, synchrotrons VTS, plasma accelerators VTS, etc. The VTS development will be an extension of the ASCR-supported "digital twins" approach – defined as (physical and/or virtual) machines or computer-based models that are simulating, emulating, mirroring, or "twinning" the life of a physical entity, which may be an object, a process, a human, or a human-related feature [37]—into the realm of particle accelerators.

For the virtual accelerators and test stands to be accessible across the community, it is essential that they do not depend on any particular beam or particle accelerator simulation tool specificities for control, data, and modeling. This means that they will instead be built upon an ecosystem of workflows that isolate underlying simulation codes via the use of standardized input controls and data handling. These standards and workflows, which already exist in part, need to be sufficiently developed and adopted by the HEP community early in the process, and documented in community reports. Concurrently, the community should establish a selection of VTS to be implemented. Once the standards and workflows are in place, the community can then proceed to the implementation of the VTS that will have been selected. In addition to the functionalities of a real-world test stand (e.g., for a particle beam source test stand, testing both the beam emission, acceleration and focusing, and the characteristics of the source itself, i.e., materials, shapes of emitters, etc), a virtual test stand is also a testing facility for new models, algorithms and surrogates (including from AI/ML), developed respectively by the activities of the tracks on "Algorithm R&D" and on "AI-ML—Surrogates & Controls".

6.3 AI/ML surrogates & controls

The exponential progress in AI/ML tools and methodologies must also be leveraged and incorporated into the ABP modeling codes and methods. Following the recommendations of the Beam and Accelerator Mod-eling Interest Group Snowmass'21 white paper, the community should "support the development of AI/ML modeling techniques and their integration into accelerator simulation and control systems, with an emphasis on fast-executing (up to real-time) and differentiable models, continual learning and adaptive ML for time-varying systems and distribution shifts, uncertainty quantification to assess confidence of model predictions, and physics-informed methods to enable broader model generalization to new conditions and reduced reliance on large training data sets" [35]. This requires first the specification of AI/ML standards and tools. The community can then proceed to develop AI/ML representations of codes and subsystems for test facilities. New surrogate representations must be validated via comparison with experimental data or other validated codes. Once validated, they would be integrated into VTS subsystems to optimize controls algorithms.

6.4 High-Performance Computing

Because particle accelerator modeling can be very computationally intensive, it is also essential to enable the simulation codes to take advantage of the most efficient hardware. The first "true exascale" supercomputer Frontier, hosted at ORNL in the U.S., has recently taken the #1 spot in the top 500 list of supercomputers [38], primarily due to over 37,000 AMD Instinct MI250X GPU accelerators. Many of the simulation tools that are used for accelerator modeling were conceived at a time that did not involve the type of specialized programming that is needed to run efficiently on these types of platforms. Hence, very few ABP practitioners are in a position to use the latest hardware efficiently. Yet, it is worth noting that a section of the particle accelerator community is at the leading edge of supercomputing, as illustrated by its involvement in DOE's Exascale Computing Project (ECP) and SciDAC projects, and by the attribution of the 2022 ACM Gordon Bell Prize to the work of an international team on "Pushing the Frontier in the Design of Laser-Based Electron Accelerators With Groundbreaking Mesh-Refined Particle-In-Cell Simulations on Exascale-Class Supercomputers" [39,40]. The community should leverage these capabilities by selecting batches of codes to be ported to the latest computer architectures, using recommended programming practices that have been elaborated and validated as part of the ECP and SciDAC projects.

6.5 Mathematics and algorithms

In addition to the development of virtual components and of a set of codes that run on the most efficient computer hardware and leverage AI/ML, the community needs to pursue the development of advanced mathematical, computational & theoretical methods, including new algorithms and new physics. Theoretical and computational beam and accelerator physics has spurred the development of mathematical and algorithmic advances that have boosted the predictive or computational capabilities tremendously, in some instances by orders of magnitude at a time. Continuous support to these activities will ensure the development of predictive tools that can reach a very high level of fidelity at increasingly high speed, up to being able to provide feedback in real time (in conjunction with AI/ML activities). Looking forward, it is also important to prepare for the possibility of using quantum computers for accelerator and beam physics and explore algorithms that could be used efficiently on such computers. The community can help spur innovation with sustained, dedicated funding and by periodically reviewing progress in community reports.

6.6 Validation & verification and training

The development of fast, high-fidelity virtual accelerators that exploit the latest hardware and AI/ML capabilities will require the use of modern software practices to ensure correctness and robustness, easy installation and deployment, and detailed, up-to-date documentation. This community effort also calls for multidisciplinary teams of accelerator physicists, applied mathematicians, computer scientists, and software engineers. Training of the workforce that will be needed is an important activity that also requires sustained care from the community. Support of the codes with detailed, up-to-date documentation, mailing lists, and training workshops will also be needed.

A community test suite could be developed, building on VTS to deliver validation and verification tools that will work as is with the codes supported by the community. The test suite will grow as an increasing number of ABP problems are supported and as the number of tests increases for a given problem. New versions of the test suite will be released periodically, with major releases on a periodicity of two years, for tracking by—and reporting to—the community.

7 ABP Coordination

Despite the modest total annual budget, the ABP thrust supports over 100 researchers at several DOE national labs (Fermilab, SLAC, LBNL, ANL, ORNL, etc.) and many leading US universities (Cornell, NIU, UCLA, SUNY, ODU, MSU, Stanford, UChicago, etc.). The ABP is distinct from other GARD thrusts, and is critically important for HEP and other related fields of research, because of the essential need for **integration** of all available or potential future technologies, methods, developed by all GARD thrusts, test facilities, and techniques and approaches into the most feasible and optimized designs of future accelerator facilities or facilities upgrades. The ABP roadmap must therefore emphasize coordination and prioritization across the accelerator R&D discipline in many critical areas:

- Theory, modeling, and experimental studies within individual ABP scientific priorities as described in the four grand challenges;
- Strategic guidance for other GARD thrusts;
- Conceptual integration, optimization and maturity evaluation of accelerators for US HEP (neutrino physics, colliders, rare processes physics, etc);
- Design efforts and contributions to accelerators for BES, NP, FES, ARDAP, NNSA and other applications;
- Effective involvement of other agencies (NSF/Universities, DOD, etc) in ABP research;
- International cooperation in ABP, first of all with Europe and Japan;
- Test facilities;
- Accelerator workforce education and training.

There is a strong need for a coordinating structure to organize and integrate new accelerator concepts and technologies to help address national HEP needs. With the current portfolio of accelerator-based projects, a significant share of ABP expertise is now project- and operations-focused and quite dispersed. A proposed **US Center for Accelerator Physics (US CAP), either physical or virtual, could provide a venue for discussing, prioritizing, coordinating, and addressing ABP challenges requiring collective attention.** US CAP would also offer a mechanism for coordinating ABP with the proposed National Future Collider R&D program [41]; other HEP GARD programs, DOE SC offices, and agencies; and international efforts.

There are many past and current examples of ABP centers sponsored by OHEP, all of them with significant roles in strategic planning and addressing operational challenges. Past examples are the Center for Beam Physics at LBNL (Berkeley), ARDA at SLAC, the Los Alamos Code Group (LANL), and the Accelerator Physics Center at Fermilab. The APC at FNAL (2007–2018) coordinated and carried out R&D and design work on several strategic HEP initiatives (ILC, HL-LHC/LARP, muon collider and neutrino factory, Project-X, education), which laid foundations for the 2014 P5 priority discussions and recommendations [42]. The Center for Advanced Studies of Accelerators (CASA) [43] now in operation at the Thomas Jefferson National Accelerator Facility pursues a broad program of theoretical and experimental research in Accelerator and Beam Physics.

Other instructive examples can be found outside of HEP or in other scientific or technical areas. The currently operational *Center for Bright Beams*, and the erstwhile NSF program supporting university research all offer lessons for coordinating ABP efforts. The *US Magnet Development Program*, which combines the expertise from several institutions, and the US QCD program [44] also offer instructive examples.

As with these examples, the structure of US CAP could similarly integrate the expertise and facilities from the collaborating institutions to address the ABP grand challenges. The program could be led by one of the leading HEP labs with partner DOE Laboratories and university programs. The scope, the mission statement and organizational structure of US CAP should be developed in consultation with the major stakeholders and the ABP community.

8 Beam Test Facilities

Demonstrating the viability of emerging accelerator science ultimately relies on experimental validation. A portfolio of beam test facilities at US National Laboratories and universities [3], as well as international facilities in Europe and Asia, are employed to carry out research critical to advancing accelerator science and technology (AS&T) and to validating ABP models and theories. These facilities have already enabled the pioneering accelerator research necessary to develop the next generation of energy-frontier and intensity-frontier user facilities across the nation.

8.1 Mission

Beam test and user facilities provide experimental test beds where fundamental accelerator research can be explored and novel accelerator technology can be developed and tested. These facilities are essential for exploring and developing novel accelerator science, as they are dedicated to advancing the science of accelerators and beams to enable future accelerators. However, user facilities dedicated to non-accelerator science (e.g. LHC) typically have a dedicated user base that cannot tolerate interruption and have limited beam availability, making them unsuitable for exploring and developing novel accelerator science.

The core aims of beam test facilities are to:

1. Provide experimental test beds where exploratory accelerator research can be conducted, emerging accelerator research can be validated, and promising accelerator technology can be programmatically developed and tested. (ABP)

2. Develop accelerator science and technology needed to enable the next generation of HEP user facilities for the energy and intensity frontiers, as well as other scientific facilities, such as light sources. (AS&T)

3. Educate and train future accelerator scientists and engineers. (AS&E)

The mission of test facilities is carried out by a broad community of accelerator scientists from universities, industry, and national laboratories. They also provide ideal platforms for engaging university faculty and their students in projects that can attract more talent to the field.

8.2 Facility capabilities

The US DOE Office of Science supports a portfolio of several beam test facilities for enabling the research necessary to develop the next generation of energy-frontier and intensity-frontier User Facilities:

1. The Accelerator Test Facility (ATF) at Brookhaven National Laboratory [45],

2. The Argonne Wakefield Accelerator (AWA) at Argonne National Laboratory [46],

3. The Berkeley Lab Laser Accelerator (BELLA) Center at Lawrence Berkeley National Laboratory [47],

4. The Facility for Advanced Accelerator Experimental Tests II (FACET-II) at SLAC National Accelerator Laboratory [48],

5. The Fermilab Accelerator Science and Technology facility (FAST/IOTA) at Fermi National Accelerator Laboratory [49],

6. The SNS Beam Test Facility (BTF) at Oak Ridge National Laboratory [50].

The beam test facilities support many of the GARD roadmaps. The FAST/IOTA facility is primarily dedicated to the ABP research [1, 51], while BELLA and FACET-II are focused on the AAC research [52], and the AWA supports the AAC, RF, and ABP R&D. The ATF and the BTF are focused on the missions of their sponsoring agencies, DOE ARDAP and DOE BES, respectively. Taken together, the portfolio capabilities include electron and proton beams, SRF and NCRF accelerators, O(100) MeV energy drive beams, O(10) Petawatt drive lasers, O(1) Gigawatt RF power sources, high-quality charged particle sources (e.g. low emittance electron beams), advanced beam manipulation systems (e.g. nonlinear integrable optics, optical stochastic cooling, emittance exchange), high dimension and high dynamic range beam diagnostics, and capabilities to develop AI/ML for accelerator science.

8.3 Synergy: Facilities and ABP

Test facilities support accelerator science and engineering in a number of synergistic and interconnected ways. Specifically to ABP, the advancement of experimental research along all four of the Grand Challenges strongly relies on the beam test facilities. For GC1, key areas include the development of nonlinear optics schemes, mitigation of space-charge effects, injection-painting scheme, and the research on halo formation. Test facilities also play an important role in enabling the development of instrumentation for high dynamic range diagnostics. Relevant GC2 R&D topics described in 4, such as preservation of high-brightness and polarized particle sources, mitigation of CSR and other collective effects, and advanced beam cooling techniques, can be tested at the existing and future ABP facilities. GC3 requires ABP facilities to test and develop new methods of bunch control and novel diagnostics as described in 5. A diverse set of facilities will be essential to validate the virtual test stands or accelerators recommended by GC4.

Facilites are also essential for workforce development both at the DOE labs and the universities. Staff can formally and informally extend their education. Undergraduates are recruited by participation in facility-based research. Graduate students can pursue their degrees while advancing the missions of the laboratories and OHEP.

The beam test facilities support other GARD efforts, such as the AAC roadmap [52]. Conversely, executing the roadmaps at the beam test facilities helps to add new capabilities and ensures the facilities remain internationally competitive. This is crucial since all beam test facilities have near-term upgrades underway [3] in addition to proposals for mid-term upgrades, which are needed to continue progress on the previously developed GARD roadmaps.

The centrality of test facilities to ABP will require thoughtful and sustained support and coordination over the next decade and beyond. These facilities are invaluable for advancing novel accelerator concepts and technologies, but a significant fraction of them are aging, underfunded, or share infrastructure with user facilities, which significantly reduces their potential to stimulate advances and draw in more talent. The US accelerator program depends critically on robust funding to operate, maintain, and upgrade these beam test facilities so that they remain productive for ABP. Likewise, a green-field national facility should be considered to remain competitive with the significant infrastructure development starting in international facilities, e.g., in Europe [53, 54]. Just as with ABP research projects, oversight of these facilities will require coordination which provides further justification for development of the USCAP or the equivalent as discussed in Section 7.

9 ABP and AS&E Workforce

Accelerator-based discovery science, technology, medicine, and commerce are enabled by a highly trained workforce, expert in the physics and engineering of particle beams and their associated instruments, methods, and technologies. The workforce includes physicists, specialized technicians, machine operators, hardware designers, and production experts. Both initial and specialized continuing education in accelerator science and engineering—inherently an integrative discipline that combines aspects of physics, computational science, and electrical and mechanical engineering—are crucial to maintain the long-term health of the US Accelerator Science and Engineering (AS&E) workforce [55].

As few US universities offer formal graduate education in accelerator science and its core technologies, the training and education of accelerator physicists and engineers for the future has primarily relied on on-the-job training—most notably, in leading national accelerator laboratories—supplemented with intensive courses at regional accelerator schools [56]. The nearly 1400 people in Europe and Russia receiving some training in accelerator science annually is a factor of about five higher than in the US. The scale of AS&E training in Asia exceeds that of the US, as well. Strengthening and expanding domestic workforce training programs in accelerators and beams will restore US leadership in ABP; draw in international accelerator talent, women, and underrepresented minorities; and ensure expertise is available to build large future facilities.

Traditionally, HEP has played a leading role in education and workforce training for particle accelerators, and the greatest support for stewardship of AS&E education and training comes (and is anticipated to come) from the OHEP [57]. Other SC offices planning to build new or upgrade existing facilities in the next decade need trained and talented accelerator personnel. Examples are NP and BES, which will need a significant workforce for the EIC and for operational and future X-ray and spallation sources, respectively. Naturally, one would expect that the EIC and other SC accelerator projects will, in return, provide an excellent training ground for personnel that would, in the future, be needed for HEP machines, such as high-intensity proton sources and high-energy colliders. All that requires a shared vision on accelerator workforce development and R&D across SC. The DOE OHEP should take a lead role in organizing corresponding discussions within the accelerator community and in the formulation of an integrated vision across the Office of Science and NSF.

Hence, **the proposed US Center for Accelerator Physics (US CAP, see Sec.7) should have in its mission coordination, guidance, and leadership of accelerator workforce education and training, with an overarching goal of strengthening the domestic AS&E workforce for existing and future accelerator-based research facilities.** The US CAP could coordinate current elements of the existing AS&E education and training system:

- US Particle Accelerator School: The USPAS focuses primarily on graduate workforce training in AS&E and will benefit from further improvements and augmentations in recruitment of a national undergraduate class; responsibility for gathering community statistics on jobs, workforce needs, diversity (ethnicity, gender, etc.); enhancements of cloud computing, videos and tutorials, interactive software tools for classes, class web sites and shared materials to deliver more effective classes; and better dissemination of course materials that are valuable to R&D efforts.

- DOE-sponsored university traineeships: The support of the four DOE-funded traineeship programs (ASET at MSU, Courant at SUNY, CAST at IIT/NIU, and VITA at ODU) is essential to building the future competency of the US AS&E field. Each program places an MS and/or PhD student recruited from physics, mechanical and electrical engineering, or a related field in a laboratory research project. Clear expectations should be set for the DOE labs to support placement of traineeship students. International students should be allowed to participate to preserve the strong historic benefits the US has derived by drawing in the best talent possible.

- Lab-based internships and training programs: These programs should emphasize diverse participation and be more welcoming to under-served communities. The programs should, for example, strengthen connections to professional societies such as the National Society of Black Physicists (NSBP) and the National Society of Hispanic Physicists (NSHP), improve outreach and inclusion efforts, and diversify hires.

- Educational access to ABP, AAC, and HPT programs and beam facilities, which should serve as an effective ground for hands-on training and student research.

- University programs: While the number of universities with faculty in accelerator physics and engineering is small (Cornell, Indiana, IIT, MIT, MSU, NIU, Old Dominion, Stanford, Stony Brook, UC Davis, UCLA, Maryland, and other institutions), they provide excellent training, produce leaders in the field, and increase the visibility of AS&E among a diverse population of undergraduate and graduate students.

- RENEW: Reaching a New Energy Sciences Workforce (RENEW) aims to build foundations for Office of Science (SC) research at institutions historically underrepresented in the SC research portfolio. In the OHEP, RENEW programmatic goals include: a) supporting investigators and building research infrastructure at institutions which have not traditionally been part of the particle physics HEP portfolio; b) encouraging underrepresented populations to pursue STEM careers by providing traineeships and/or support for undergraduate and graduate students, postdoctoral researchers, and faculty at academic institutions not well represented in the HEP research portfolio, including accelerators and beam physics.

10 Appendix A: Charge to the 2022 ABP Roadmap Workshop

Charge to the GARD Accelerator and Beam Physics Roadmap Workshop (September 6–8, 2022; Bethesda, MD)

This workshop is organized by DOE HEP General Accelerator Research and Development (GARD) Program in response to the 2015 HEPAP Accelerator R&D Subpanel Report and recent Snowmass community study. The workshop will focus on Accelerator Beam Physics and Instrumentation challenges and needs for maintaining and advancing the US's core capability for enabling discoveries in Particle Physics, Nuclear Physics, and Basic Energy Science, thereby addressing key elements of the research mission for multiple programs in the Office of Science.

While acknowledging the past successes of accelerator-based particle physics research, we face many physics and technology challenges for future accelerators. This workshop will address four grand challenges identified from previous Accelerator and Beam Physics (ABP) workshops to develop a long-term vision and a roadmap for basic research in accelerator science and technology development that can enable future world-leading DOE capabilities.

The goal of the workshop is to develop a roadmap addressing the four key Accelerator and Beam Physics *Grand Challenges* identified for the successful realization of future particle accelerators:

1. Beam Intensity: increase beam intensities by orders of magnitude;
2. Beam Quality: increase beam phase space density towards the quantum degeneracy limit;
3. Beam Control: measure/control the beam distribution at the level of individual particles;
4. Beam Prediction: develop predictive virtual particle accelerators.

The workshop will develop an R&D roadmap plan for the above research areas, primarily as input to strategic planning for the Office of High Energy Physics General Accelerator Research and Development (GARD) subprogram, and related SC programs as appropriate. While these research areas have potentially broad applicability for developing new scientific capabilities across the SC complex, the fundamental physics of accelerators and particle beams has historically been in the GARD subprogram.

The roadmap report should also acknowledge other ABP thrusts associated with the overall DOE research missions, such as: advancing the physics of accelerators and beams to enable future accelerator facilities; developing conventional and advanced accelerator concepts; developing AI/ML tools to enable cost-effective solutions and optimization of accelerator facilities; guiding the full fruition and participation in science at SC beam facilities; and the efficacy of current workforce development programs such as SCGSR, HEP traineeships, and RENEW to educate and train future accelerator scientists and engineers in beam physics.

The workshop is not a review of each research area, but rather a strategic undertaking to formulate a set of milestones that drive a research roadmap to guide the GARD-APB activities over the next 5–10 years with an eye towards possible long-term applications. These milestones should be accompanied by appropriate performance targets for the applications. In particular, as you construct the roadmap, please identify and align milestones addressing the Grand Challenges that must be addressed to move HEP forward toward future collider applications.

11 Appendix B: List of Attendees of the 2022 ABP Roadmap

Attendees of the GARD Accelerator and Beam Physics Roadmap Workshop (September 6–8, 2022; Bethesda, MD):

Rob Ainsworth
Fermilab

Michael Blaskiewicz
Brookhaven National Laboratory

Jerry Blazey
Northern Illinois University

David Bruhwiler
RadiaSoft LLC

John Byrd
Argonne National Laboratory

Younghai Cai
SLAC National Laboratory

Sarah Cousineau
Oak Ridge National Laboratory

Bruce Dunham
Nevada National Security Site

Auralee Edelen
SLAC National Laboratory

Nick Evans
Oak Ridge National Laboratory

Jonathan Jarvis
Fermilab

Yue Hao
Michigan State University

Zhirong Huang
SLAC National Laboratory

Siddharth Karkare
Arizona State University

Oliver Kester
TRIUMF

Andrew Lankford
University of California, Irvine

L.K. Len
DOE SC, OHEP (ret.)

Themis Mastoridis
California Polytechnic State University, San Louis Obispo

Jared Maxson
Cornell University

Michiko Minty
Brookhaven National Laboratory

Chad Mitchell
Lawrence Berkeley National Laboratory

Sergei Nagaitsev
Fermilab and the University of Chicago

Mark Palmer
Brookhaven National Laboratory

Ritchie Patterson
Cornell University

Philippe Piot
Northern Illinois University and Argonne National Laboratory

John Power
Argonne National Laboratory

Soren Prestemon
Lawrence Berkeley National Laboratory

James Rosenzweig
University of California, Los Angeles

Andrei Seryi
Thomas Jefferson National Accelerator Laboratory

Vladimir Shiltsev
Fermilab

Linda Spentzouris
Illinois Institute of Technology

Jean-Luc Vay
Lawrence Berkeley National Laboratory

Christie Ashton
DOE SC, OHEP

Craig Burkhart
DOE SC, OHEP

Bruce Carlsten
DOE SC, ARDAP

Eric Colby
DOE SC, ARDAP

Glen Crawford
DOE SC, OHEP

Manouchehr Farkhondeh
DOE SC, NP

Elaine Lessner
DOE SC, BES

Derun Li
DOE SC, OHEP

Jeremy Love
DOE SC, OHEP

Ken Marken
DOE SC, OHEP

12 Appendix C: Agenda of the 2022 ABP Roadmap Workshop

Hyatt Regency Bethesda, MD 20814
September 6–8, 2022

Day 1—Tuesday, September 6, 2022

TIME *(EST)*	SPEAKER	TITLE	DURATION
9:00 AM	Glen Crawford	Welcome and opening remarks	5
9:05 AM	Ken Marken	GARD Overview	30
9:35 AM	Jerry Blazey	APB Roadmap Workshop Charge and Objectives	15
9:50 AM	All	Discussion, questions and adoption of the agenda, topical leads	10
10:00 AM	Eric Colby	ARDAP Overivew and Objectives	25
10:25 AM	***Coffee Break***		20
ABP Program Overview and Snowmass 2022			
10:45 AM	Sergei Nagaitsev	Reports on previous ABP Workshops	30
11:15 AM	Vladimir Shiltsev	Snowmass 2022 reports and perspectives	30
11:45 AM	Sergei Nagaitsev / Linda S.	Beam Intensity	10
11:55 AM	Zhrong Huang / Jamie R.	Beam Quality	10
12:05 PM	John Power / Philippe P.	Beam Control	10
12:15 PM	Jean–Luc Vay / David B.	Beam Prediction	10
12:25 PM	***Lunch*** *(provided)*		65
Topical Group Discussions			
1:30 PM	Sergei Nagaitsev / All	Discussions and presentations led by Beam Intensity group	60
2:30 PM	Zhirong Huang / All	Discussions and presentations led by Beam Quality group	60
3:30 PM	***Coffee Break***		30
Topical Group Discussions *(continued)*			
4:00 PM	John Power / All	Discussions and presentations led by Beam Control group	60
5:00 PM	Jean–Luc Vay / All	Discussions and presentations led by Beam Prediction group	60
6:00 PM	Adjourn		
6:30 PM	***No host dinner*** *(TBD)*		

Day 2—Wednesday, September 7, 2022

TIME	SPEAKER	TITLE	DURATION
International and domestic perspectives			
9:00 AM	Elias Metral	ABP perspectives from Europe (CERN)	35
9:35 AM	Ritchie Patterson	NSF and Center for Bright Beams	35
10:10 AM	Oliver Kester	ABP Perspectives from Canada (TRIUMF)	25
10:35 AM	***Coffee Break***		20
11:05 AM	Michael Blaskiewicz	Electron Ion Collider (zoom)	30
11:35 AM	John Byrd / Zhirong Huang	ABP challenges for the storage ring based light source and linacs	40
12:15 PM	***Lunch*** *(provided)*		65
1:15 PM	Bruce Carlsten	ABP challenges for applications for DOD (zoom)	35
1:50 PM	All	Group Photo	15
2:05 PM	***Coffee Break***		30
2:35 PM	Sub-group members	Sub-group discussions and preparation for the roadmap report	90
Summary Reports from sub-group leads			
4:05 PM	Sergei Nagaitsev / Linda S. Beam Intensity		20
4:25 PM	Zhrong Huang / Jamie R. Beam Qaulity		20
4:45 PM	John Power / P. Piot Beam Control		20
5:05 PM	Jean-Luc Vay / David B. Beam Prediction		20
5:25 PM	Adjourn		
6:30 PM	***No host dinner*** *(TBD)*		

Day 3—Thursday, September 8, 2022

TIME	SPEAKER	TITLE	DURATION
9:00 AM	Jerry Blazey / All	Roadmap discussion of priorities, milestones and connections	90
10:30 AM	***Coffee Break***		20
10:50 AM	Jerry Blazey / All	ABP Workshop Roadmap Report Discussions	90
12:20 PM	***Workshop close and Lunch*** *(provided)*		60

13 Appendix D: Glossary

This document contains acronyms and other terms that might not be easily deciphered even by experts in other areas of physics. Many of these terms are defined below. Some acronyms are defined using other acronyms. In those cases, please find the definitions of those acronyms at the appropriate place in this list.

AAC: Advanced Acceleration Concepts, include **DWFA, LWFA, PWFA, SWFA;** a thust in **GARD**.

ABP: Accelerator and Beam Physics thust in the **GARD** program of the **DOE**.

AI: Artificial Intelligence.

ANL: Argonne National Laboratory.

APS: American Physical Society.

ARDAP: Accelerator R&D and Production, an Office of the **DOE**.

ASCR: Advanced Scientific Computing Research, an Office of the **DOE**.

AS&E: Accelerator Science and Engineering.

AST: Accelerator Science and Technology.

ATF: Accelerator Test Facility, an accelerator R&D Users' Facility complex at **BNL**.

AWA: Argonne Wakefield Accelerator, a test beam facility at ANL.

BELLA: Berkeley Lab Laser Accelerator, a facility at **LBNL** for the development of laser-driven accelerators.

BNL: Brookhaven National Laboratory.

BTF: Beam Test Facility at the **ORNL** Spallation Neutron Source.

CDR: Conceptual Design Report.

CERN: Conseil Europeen pour la Recherche Nucleaire, the major European high-energy physics laboratory, located in Geneva.

CLIC: Compact LInear Collider, a concept for an e+e− linear collider, with center of mass energies up to 3 TeV, based on two-beam acceleration.

CM: Center of Mass, the system for viewing a particle collision or decay in which the overall system is at rest.

CSR: Coherent Syncrotron Radiation.

DARPA: Defense Advanced Research Projects Agency.

DIH: Disorder-Induced Heating.

DOE: U.S. Department of Energy.

DPB: APS Division of Physics of Beams.

DPF: APS Division of Particles and Fields.

Drive beam: A high-energy particle beam used to create an electromagnetic field that can then accelerate another beam to high energy.

DWFA: Dielectric Wake Field Acceleration.

DUNE: Deep Underground Neutrino Experiment, a next-generation long-baseline neutrino oscillation experiment, based at Fermilab and SURF.

EIC: Electron-Ion Collider, an electron-proton and electron-heavy ion collider to be constructed at **BNL**.

EM: Electro-Magnetic.

ERL: Energy Recovery Linac.

Exascale: Of the order of 1018, used in computing to refer to next-generation computation resources in memory or speed.

FACET-II: Facility for advanced ACcelerator Experimental Tests, a user facility at SLAC for experiments on high-gradient electron accelerator technology.

FAST: Fermilab Accelerator Science and Technology, an accelerator R&D facility at **FNAL**, includes IOTA.

FCC: Future Circular Collider, a large circular collider project proposed for CERN.

FCC-ee: A large circular e+e− collider proposed as a phase of the **FCC** project.

FCC-hh: A large circular proton-proton collider proposed as a phase of the **FCC** project.

FEL: Free Electron Laser, an electron accelerator that produces high-intensity coherent synchrotron radiation.

Fermilab, also **FNAL:** Fermi National Accelerator Laboratory, in Batavia, Illinois.

FFAG: Fixed-Field Alternating Gradient accelerator, an accelerator design concept with time-independent magnetic bending fields and strong focusing.

GARD: General Accelerator Research and Development program of the DOE.

HEP: High-Energy Physics, the generic term for particle physics research.

HOMs: High Order Modes in **RF** cavities.

HTS: High-Temperature Superconductivity.

IBS: Intra-Beam Scattering.

ILC: International Linear Collider, an electron-positron linear collider with design **CM** energy 500 GeV.

IOTA: Integrable Optics Test Accelerator, an electron and proton storage ring at **FAST** for beam dynamics research.

IP: Interaction Point of a colliding beams facility.

JLab: Thomas Jefferson National Accelerator Facility, in Newport News, Virginia.

KEK: Ko-Enerugi Kenkyusho, the major high-energy physics laboratory in Japan, located in Tsukuba.

LBNF: Long Baseline Neutrino Facility, two facilities—Near Site at **FNAL** and Far Site at **SURF**—which together furnish the beam, underground facilities, and infrastructure required to support DUNE.

LANL: Los Alamos National Laboratory.

LHC: Large Hadron Collider, a large proton–proton collider at CERN, with design CM energy 14 TeV. LWFA: Laser Wake Field Acceleration in plasma.

ML: Machine Learning.

MDP: Magnet Development Program in **GARD**.

MTE: Mean Transverse Energy.

NNSA: National Nuclear Security Administration, a **DOE** agency.

NSF: US National Science Foundation.

OHEP: Office of High-Energy Physics of the US **DOE**.

ORNL: Oak Ridge National Laboratory.

PWFA: Beam-driven Plasma Wake Field Acceleration.

P5: Particle Physics Project Prioritization Panel, an advisory subcommittee of the High-Energy Physics Advisory Panel.

RF: Radio Frequency.

RFQ: Radio Frequency Quadrupole.

SciDAC: Scientific Discovery through Advanced Computation, a program of the **DOE**.

SLAC: SLAC National Accelerator Laboratory, originally named the Stanford Linear Accelerator Center, a US national laboratory in Menlo Park, California.

Snowmass’21: the US **HEP** community strategic planning exercise, organized by the DPF.

SNS: Spallation Neutron Source, at **ORNL**.

Space-Charge: beam dynamics effects in high-intensity beams due to self **EM** fields.

SRF: Superconducting Radio Frequency (**RF**) cavities and associated technology.

SWFA: Structure Wake Field Acceleration, beam- or laser-driven.

SuperKEKB: A high-luminosity electron-positron collider, with **CM** energy about 10 GeV, at **KEK**. S

SURF: Sanford Underground Research Facility: An underground laboratory in the former Homestake Mine in Lead, South Dakota.

TDR: Technical Design Report.

VTS: Virtual Test Stand, virtual realization of a particle accelerator or its components.

Wakefield: The electromagnetic field trailing a bunch of high-energy particles in an accelerating structure.

14 Bibliography

This document contains acronyms and other terms that might not be easily deciphered even by experts in other areas of physics. Many of these terms are defined below. Some acronyms are defined using other acronyms. In those cases, please find the definitions of those acronyms at the appropriate place in this list.

[1] "Accelerating Discovery: A Strategic Plan for Accelerator R&D in the U.S.; April 2015." https://www.osti.gov/biblio/1320612.

[2] S. Nagaitsev, Z. Huang, J. Power, J.L. Vay, P. Piot, L. Spentzouris et al., "Accelerator and Beam Physics Research Goals and Opportunities." https://arxiv.org/abs/2101.04107, 2021. 10.48550/ARXIV.2101.04107.

[3] C. Clarke, E. Esarey, C. Geddes, G. Hofstaetter, M. Hogan, S. Nagaitsev et al., *U.S. advanced and novel accelerator beam test facilities, Journal of Instrumentation* **17** (2022) T05009.

[4] H. Abramowicz and R. Forty, *Physics Briefing Book [Input for the European Strategy for Particle Physics Update 2020]*, 1910.11775.

[5] "Snowmass'2021 Wiki Page." https://www.snowmass21.org/.

[6] P.C. Bhat, S. Belomestnykh, A. Bross, S. Dasu, D. Denisov, S. Gourlay et al., "U.S. National Accelerator R&D Program on Future Colliders." https://arxiv.org/abs/2207.06213, 2022. 10.48550/ARXIV.2207.06213.

[7] E.A. Nanni, M. Breidenbach, C. Vernieri, S. Belomestnykh, P. Bhat, S. Nagaitsev et al., "C^3 Demonstration Research and Development Plan." https://arxiv.org/abs/2203.09076, 2022. 10.48550/ARXIV.2203.09076.

[8] S. Belomestnykh, P.C. Bhat, A. Grassellino, M. Checchin, D. Denisov, R.L. Geng et al., "Higgs-Energy LEptoN (HELEN) Collider based on advanced superconducting radio frequency technology." https://arxiv.org/abs/2203.08211, 2022. 10.48550/ARXIV.2203.08211.

[9] B. Cathey, S. Cousineau, A. Aleksandrov and A. Zhukov, *First Six Dimensional Phase Space Measurement of an Accelerator Beam, Phys. Rev. Lett.* **121** (2018) 064804.

[10] V. Shiltsev and F. Zimmermann, *Modern and future colliders*, Rev. Mod. Phys. **93** (2021) 015006.

[11] V. Shiltsev, *Particle beams behind physics discoveries, Phys. Today* **73**.

[12] V. Yakimenko, S. Meuren, F. Del Gaudio, C. Baumann, A. Fedotov, F. Fiuza et al., *Prospect of studying nonperturbative QED with beam–beam collisions, Phys. Rev. Lett.* **122** (2019) 190404.

[13] G. White and V. Yakimenko, *Ultra-short-z linear collider parameters*, 2018. 10.48550/ARXIV.1811.11782.

[14] C. Mayes, *Computational approaches to coherent synchrotron radiation in two and three dimensions, Journal of Instrumentation* **16** (2021) P10010.

[15] G. Ha, K.-J. Kim, J.G. Power, Y. Sun and P. Piot, *Bunch shaping in electron linear accelerators, Rev. Mod. Phys.* **94** (2022) 025006.

[16] Z. Huang and G. Stupakov, *Control and application of beam microbunching in high brightness linac-driven free electron lasers, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **907** (2018) 182.

[17] C.G. Schroer, I. Agapov, W. Brefeld, R. Brinkmann, Y.-C. Chae, H.-C. Chao et al., *PETRA IV: the ultralow-emittance source project at DESY, Journal Synchrotron Radiation* **25** (2018) 1277.

[18] Y. Cai, *Single-particle dynamics in electron storage rings with extremely low emittance, Nuclear Instruments and Methods in Physics Research A* **645** (2011) 168.

[19] S. van der Meer, *Stochastic cooling and the accumulation of antiprotons, Science* **230** (1985) 900.

[20] A.A. Mikhailichenko and M.S. Zolotorev, *Optical stochastic cooling, Phys. Rev. Lett.* **71** (1993) 4146.

[21] J. Jarvis, V. Lebedev, A. Romanov, D. Broemmelsiek, K. Carlson, S. Chattopadhyay et al., *Experimental demonstration of optical stochastic cooling, Nature* **608** (2022) 287.

[22] K.-J. Kim, *Analysis of optical stochastic cooling including transverse effects, in Particle Accelerator Conference,* (Dallas, TX, USA), pp. 2786–2788, IEEE, May, 1995.

[23] S. Brooks, K. Brown, F. Méot, A. Nomerotski, S. Peggs, M. Palmer et al., *Ion coulomb crystals in storage rings for quantum information science, arXiv preprint arXiv:2203.06809* (2022).

[24] T. Shaftan and B.B. Blinov, *Cold ion beam in a storage ring as a platform for large-scale quantum computers and simulators: Challenges and directions for research and development, Phys. Rev. Accel. Beams* **24** (2021) 094701.

[25] I. Lobach, S. Nagaitsev, A. Romanov and G. Stancari, *Single electron in a storage ring: a probe into the fundamental properties of synchrotron radiation and a powerful diagnostic tool, Journal of Instrumentation* **17** (2022) P02014.

[26] A.J. Dragt, F. Neri and G. Rangarajan, *General moment invariants for linear Hamiltonian systems, Phys. Rev. A* **45** (1992) 2572.

[27] C.K. Allen and T.P. Wangler, *Beam halo definitions based upon moments of the particle distribution, Phys. Rev. ST Accel. Beams* **5** (2002) 124202.

[28] W.H. Tan, P. Piot and A. Zholents, *Formation of temporally shaped electron bunches for beam-driven collinear wakefield accelerators, Phys. Rev. Accel. Beams* **24** (2021) 051303.

[29] E. Hemsing, G. Stupakov, D. Xiang and A. Zholents, Beam by design: *Laser manipulation of electrons in modern accelerators, Rev. Mod. Phys.* **86** (2014) 897.

[30] J.A. Holmes, T. Gorlov, N.J. Evans, M. Plum and S. Cousineau, *Injection of a self-consistent beam with linear space charge force into a ring, Phys. Rev. Accel. Beams* **21** (2018) 124403.

[31] A.G. Ruggiero, Crystalline beams, in *The Physics of High Brightness Beams*, pp. 124–145 DOI [https://www.worldscientific.com/doi/pdf/10.1142/97898127921810008].

[32] N. Friis, O. Marty, C. Maier, C. Hempel, M. Holäpfel, P. Jurcevic et al., *Observation of entangled states of a fully controlled 20-qubit system, Phys. Rev. X* **8** (2018) 021012.

[33] P. Catravas, W.P. Leemans, J.S. Wurtele, M.S. Zolotorev, M. Babzien, I. Ben-Zvi et al., *Measurement of electron-beam bunch length and emittance using shot-noise-driven fluctuations in incoherent radiation, Phys. Rev. Lett.* **82** (1999) 5261.

[34] V.D. Elvira, S. Gottlieb, O. Gutsche, B. Nachman et al., *The future of high energy physics software and computing, arXiv preprint arXiv:2210.05822* (2022) .

[35] S. Biedron, L. Brouwer et al., Snowmass'21 *Accelerator Modeling Community White Paper, arXiv preprint arXiv:2203.08335* (2022).

[36] "NSF report: A vision and strategy for science, engineering, and education." https://www.nsf.gov/pubs/2012/nsf12113/nsf12113.pdf, 2012.

[37] B.R. Barricelli, E. Casiraghi and D. Fogli, *A survey on digital twin: Definitions, characteristics, applications, and design implications, IEEE access* **7** (2019) 167653.

[38] "ORNLs Frontier First to Break the Exaflop Ceiling." https://www.top500.org/news/ornls-frontier-first-to-break-the-exaflop-ceiling/.

[39] "Plasma simulation code wins 2022 acm gordon bell prize." https://www.olcf.ornl.gov/2022/11/17/plasma-simulation-code-wins-2022-acm-gordon-bell-prize/, 2022.

[40] L. Fedeli, A. Huebl, F. Boillod-Cerneux, T. Clark, K. Gott, C. Hillairet et al., *Pushing the frontier in the design of laser-based electron accelerators with groundbreaking mesh-refined particle-in-cell simulations on exascale-class supercomputers, i n 2022 SC22: International Conference for High Performance Computing, Networking, Storage and Analysis (SC)*, (Los Alamitos, CA, USA), pp. 25–36, IEEE Computer Society, nov, 2022, https://www.computer.org/csdl/proceedings-article/sc/2022/544400a025/1I0bSKaoECc.

[41] P. Bhat, S. Jindariani, G. Ambrosio, G. Apollinari, S. Belomestnykh, A. Bross et al., *Future Collider Options for the US, arXiv preprint arXiv:2203.08088* (2022) .

[42] V. Shiltsev, *Accelerator Physics Center at Fermilab: History and Accomplishments (2007–2018),* Tech. Rep. FERMILAB-FN-1059, Fermi National Accelerator Lab. (FNAL), Batavia, IL (United States) (2018).

[43] "Center for Advanced Studies of Accelerators." https://www.jlab.org/accelerator/casa.

[44] "The US QCD Collaboration." https://www.usqcd.org/collaboration.html.

[45] "Report of the Accelerator Test Facility science planning workshop." https://www.bnl.gov/atf/docs/atfsciencework shopreport2019.pdf, 2019.

[46] "Argonne Wakefield Accelerator Facility." https://www.anl.gov/awa.

[47] "Berkeley Lab Laser Accelerator (BELLA) Center." https://bella.lbl.gov/.

[48] "Facility for Advanced Accelerator Experimental Tests FACET-II." https://facet-ii.slac.stanford.edu/.

[49] "Fermilab Accelerator Science and Technology FAST-IOTA facility." https://fast.fnal.gov/.

[50] Z. Zhang, S. Cousineau, A. Aleksandrov, A. Menshov and A. Zhukov, *Design and commissioning of the Beam Test Facility at the Spallation Neutron Source, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **949** (2020) 162826.

[51] S. Antipov, D. Broemmelsiek, D. Bruhwiler, D. Edstrom, E. Harms, V. Lebedev et al., *Iota (Integrable Optics Test Accelerator): facility and experimental beam physics program, Journal of Instrumentation* **12** (2017) T03002.

[52] "Advanced Accelerator Development Strategy Report: DOE Advanced Accelerator Concepts Research Roadmap Workshop." https://www.osti.gov/biblio/1358081, 2, 2016. 10.2172/1358081.

[53] R. Assmann, M. Weikum, T. Akhter, D. Alesini, A. Alexandrova, M. Anania et al., *Eupraxia conceptual design report, The European Physical Journal Special Topics* **229** (2020) 3675.

[54] C. Adolphsen, D. Angal-Kalinin, T. Arndt, M. Arnold, R. Assmann, B. Auchmann et al., *European strategy for particle physics–accelerator R&D roadmap, arXiv preprint arXiv:2201.07895* (2022).

[55] M. Bai, W. Barletta, D. Bruhwiler, S. Chattopadhyay, Y. Hao, S. Holder et al., *Strategies in Education, Outreach, and Inclusion to Enhance the US Workforce in Accelerator Science and Engineering, arXiv preprint arXiv:2203.08919* (2022).

[56] W. Barletta, S. Chattopadhyay and A. Seryi, *Educating and training accelerator scientists and technologists for tomorrow, in Reviews of Accelerator Science and Technology: Volume 5: Applications of Superconducting Technology to Accelerators,* pp. 313–331, World Scientific (2012).

[57] M. Bai, Z. Huang and S. Lund, *Summary report of AF1 to Snowmass 2021: Beam physics and accelerator education within the Accelerator Frontier, arXiv preprint arXiv:2209.07668* (2022).

Cover page image credits:
J.Jarvis (Fermilab, IOTA ring),
J.-L.Vay (LBNL, beam dynamics simulations),
S.Winchester (Fermilab, the US Particle Accelerator School)