

SEPTEMBER 14TH, 2026

INJECTORS & BEAM PHYSICS FOR FUTURE ACCELERATORS WORKSHOP

ACCELERATOR & BEAM PHYSICS OVERVIEW – THE GRAND CHALLENGES



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THE ACCELERATOR & BEAM PHYSICS (ABP)

Vision & Mission

- ⑩ Advance the physics of accelerators and beams to enable future accelerators.
- ⑩ Develop conventional and advanced concepts and tools that can disrupt costly technology paradigms.
- ⑩ Guide and help exploit science at accelerator test facilities and at operational accelerators.
- ⑩ Educate and train the next generation of accelerator scientists and engineers.

Definition of ABP

The science of the motion, generation, acceleration, manipulation, prediction, observation and use of charged particle beams.

*Throughout this presentation
we focus on the electron-beam
aspects of the ABP roadmap*

APB GARD ROADMAP

Report published in 2023

DOE Accelerator Beam Physics Roadmap Workshop

September 6–8, 2022



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https://science.osti.gov/hep/-/media/hep/pdf/2022/ABP_Roadmap_2023_final.pdf



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ABP WORKING GROUP PROCESS

Preparatory meetings (~1 year) + two workshops in 2019 and 2020

Workshop 1 (LBNL, Dec 2019)

- ⑩ WG1: single-particle dynamics, nonlinearities, spin dynamics
- ⑩ WG2: high-brightness generation, transport, manipulation, cooling
- ⑩ WG3: mitigation and control of collective phenomena
- ⑩ WG4: connections to NCRF, SCRF, HFM, AAC roadmaps

<https://conferences.lbl.gov/event/279/>

Workshop 2 (FNAL, Apr/May 2020)

- ⑩ WG5: advanced instrumentation and controls
- ⑩ WG6: modeling, simulation, theory, and applied math
- ⑩ WG7: early conceptual integration and optimization
- ⑩ WG8: synergies with non-HEP accelerator science

<https://indico.fnal.gov/event/22709/>

ABP ROADMAP OUTCOME

Four Grand Challenges (GCs)



BEAM INTENSITY

How do we increase beam intensities by orders of magnitude?



BEAM QUALITY

How do we increase beam phase-space density by orders of magnitude toward quantum degeneracy limit?



BEAM CONTROL

How do we control the beam distribution down to the level of individual particles?



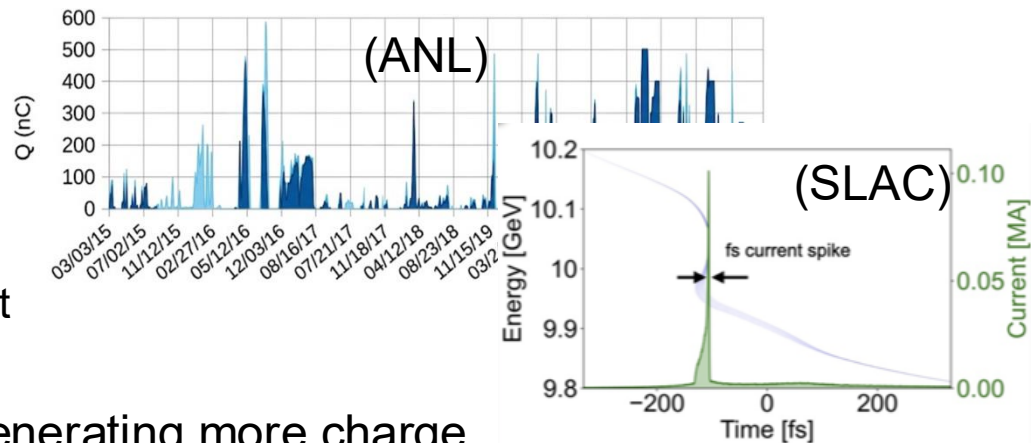
BEAM PREDICTION

How do we develop predictive “virtual particle accelerators”?

GC1: ELECTRON-BEAM INTENSITY CHALLENGE

The Intensity Challenge is Application-Specific

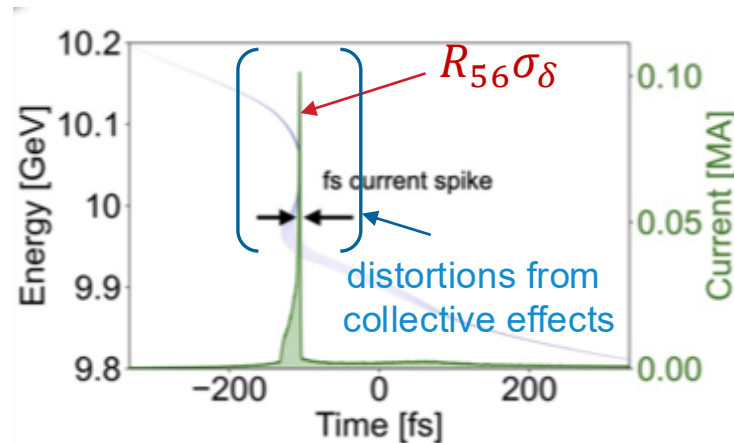
- For e- accelerators: intensity has several meanings (depending on perspective):
 - high bunch charge, (injectors for storage ring light sources)
 - high average current, (ERL-based light source, injection for rings)
 - high peak current, (FEL, colliders)
 - or combinations of all three without unacceptable loss of beam quality
- The central problem is not only generating more charge, but transporting, compressing, and using it while maintaining controllability
- Electron-beam intensity is tightly coupled to injector technology, compression strategy, collective effects, and machine protection



GC1: ELECTRON-BEAM INTENSITY CHALLENGE

Current Understanding of the Main Limitations

- For electrons, important limitations include:
 - Coulomb fields: Space-charge at low energy near the source and in early acceleration,
 - Radiative fields:
 - Short- and long-range in RF structures (esp. high-frequency) and beamline components
 - Coherent synchrotron radiation (CSR) during bunch compression
 - Microbunching instability during longitudinal phase-space manipulations
 - Halo formation and tails that can seed losses or degrade usable beam
- Increasing intensity without predictive control can trade charge for instability, emittance growth, timing jitter, and reduced experimental usability



GC1: ELECTRON-BEAM INTENSITY CHALLENGE

What We Understand Reasonably Well Today

- The community has strong experience with high-brightness RF photoinjectors and with multi-stage compression of relativistic electron beams
- Test facilities provide a flexible set of platform with tunable charge, high peak current, and energies up to the multi-GeV scale relevant for experimentally exploring the intensity frontier in electron beams
- Existing models and operational experience provide a solid baseline for:
 - Low-energy space-charge-dominated injector transport
 - RF compression and chirp (nonlinearities) control
 - Basic wakefield and CSR mitigation strategies
- The challenge is about achieving robust operation in extreme regimes with enough predictive accuracy to support routine tuning and extrapolation.

GC1: ELECTRON-BEAM INTENSITY CHALLENGE

R&D Opportunities for Electron-Beam Intensity

- Develop higher-fidelity models for collective effects in intense electron bunches, especially 2D and 3D CSR (including shielding effects), microbunching, and wakefield coupling during compression
- Use available Test Facilities for direct benchmarking of extreme compression scenarios and high-current transport
- Advance injector concepts that produce higher charge while reducing downstream burden on compression and correction systems (L/PWFA?)
- Develop halo-sensitive diagnostics and controls to identify the onset of unusable tails before catastrophic degradation
- Pursue integrated optimization across source, linac, compressor, and experimental beam delivery rather than local subsystem optimization

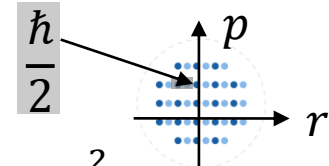
GC2: BEAM QUALITY

Electron-Beam Quality Challenge: Production & Conservation

- For electron beams, beam quality is fundamentally about maximizing phase-space density,
- Expressed through emittance, brightness, energy spread, and current profile
- Production: sets the lower-limit of the phase-space volume
- Transport at best conserves the phase-space volume, can possibly implement phase-space cooling (but challenging in a single-pass system and for electrons)

Quantum Degenerate

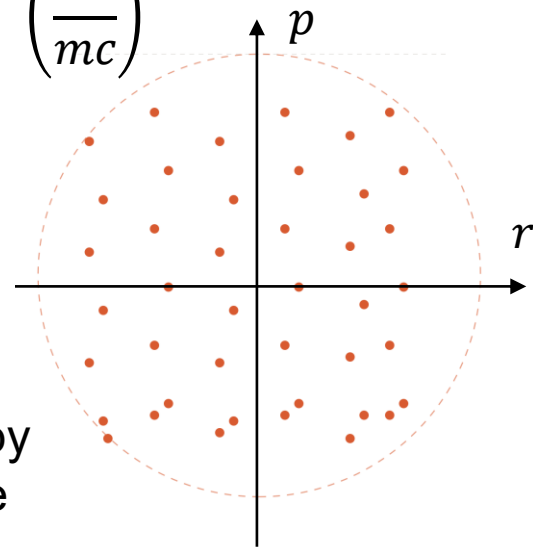
$$\varepsilon_{1dof} = \left(\frac{N_e}{2}\right)^{\frac{1}{3}} \left(\frac{\hbar}{mc}\right)^{\frac{2}{3}}$$



Classical

$$\varepsilon_{1dof} = \sigma_r \sigma_p$$

limited by
source



GC2: BEAM QUALITY

Current Understanding of the Main Limitations

- Major electron-beam limitations include:
 - Mean transverse energy at the cathode
 - Space charge driven emittance-growth
 - Intra-beam scattering effects (IBS) in ultra-bright regimes
 - Noise in beams
 - CSR and wakefield effects during compression and manipulation
 - Mismatch, chromatic aberrations, and nonlinear optics errors
- As beams become shorter and brighter, other effects prevail (e.g. IBS)
- The limitation is increasingly system-level preservation of brightness rather than merely initial generation

The diagram illustrates the relationship between 4D brightness and other beam parameters. It features the equation $B \propto \frac{E^\nu}{MTE}$. A green arrow points from the text "4D brightness (ideally invariant)" to the variable B . A blue arrow points from the text "E-field at the cathode surface" to the term E^ν . A red arrow points from the text "Mean-transverse energy (material properties)" to the term MTE .

E-field at the cathode surface

4D brightness (ideally invariant)

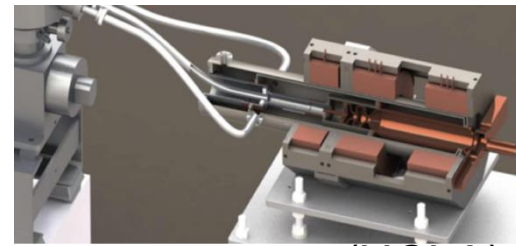
Mean-transverse energy (material properties)

$$B \propto \frac{E^\nu}{MTE}$$

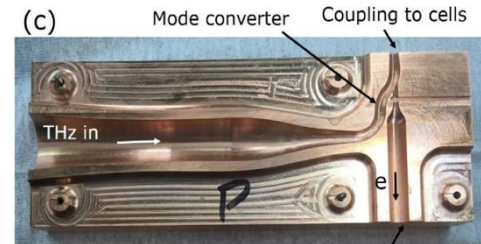
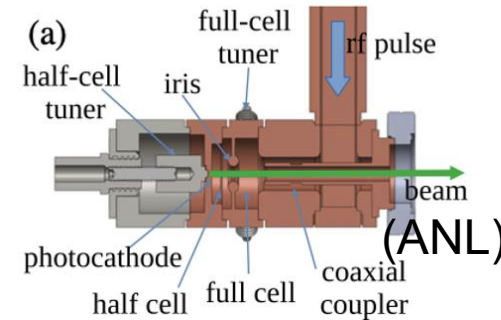
GC2: BEAM QUALITY

What We Understand Reasonably Well Today

- There is clear progress in high-brightness electron-source development, including photocathode optimization, high-field guns (independent demos of ~ 0.4 GV/m on cathode), cryogenic RF concepts, and superconducting injector ideas
- Concrete performance goals such as low-MTE photocathodes, high-field RF guns (cryo, and short RF pulses).
- We now understand many dominant degradation channels qualitatively and often semi-quantitatively
- The remaining gap is achieving *consistent* predictive closure between cathode physics, injector beam dynamics, compression physics, and end-use beam requirements



(UCLA)



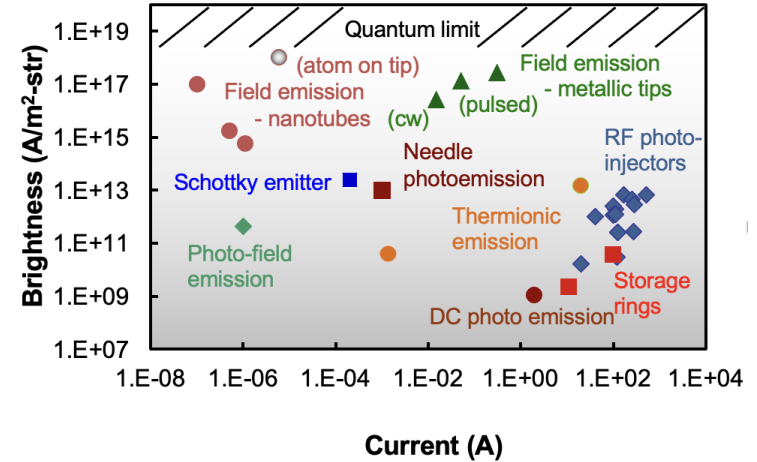
(SLAC)

GC2: BEAM QUALITY

R&D Paths for Electron-Beam Quality

- Improve source physics:
 - Lower MTE photocathodes
 - Higher-gradient guns
 - Better laser shaping for photoemission
- Improve preservation:
 - Better nonlinear correction and tolerance management
 - Beamline designs optimized for brightness preservation, not only transmission
- Use integrated experiment-model-data frameworks to identify the true limiting mechanisms in regimes where multiple effects overlap

(Adapted from C. Brau)



GC3: BEAM CONTROL

Current Understanding of the Main Limitations | Precise Control

▪ Ultimate Beam Control:

- controlling every particle's position and momentum within 6D phase space?
- Can accelerator control evolve from bulk beam steering to true distribution engineering?

▪ Levels of Control:

- Centroid control: fast feedback stabilizing orbit, timing, energy, and arrival phase.
 - RMS control: beam matching, emittance preservation, envelope control.
 - Higher-order control: deliberate phase-space tailoring beyond averages — from projected profiles to full 2D correlations and cross-plane coupling management.
- Distribution-level control: shaping the beam in all relevant dimensions to meet the exact needs of the application ➡ **single particle control?**

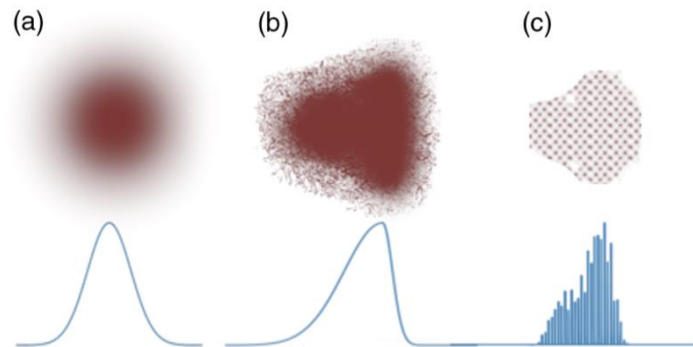


FIG. 1. Definition of the level of control on a beam distribution: (a) macroscopic, (b) mesoscopic, and (c) microscopic scales.

GC3: BEAM CONTROL

Current Understanding of the Main Limitations | Diagnostics

- The principal limitation is observability: we often cannot measure the full beam distribution at the resolution and rate needed to control it
- Electron beams in extreme regimes are hard to diagnose because they are:
 - Ultrafast ($< \text{fs}$)
 - High dynamic range (fC to nC)
 - Can have cross-plane correlation e.g. between the longitudinal and transverse phase space
 - Sensitive to shot-to-shot fluctuations
- Traditional diagnostics may be interceptive, too slow, too low-resolution, or incomplete in dimensionality
- ML techniques can diagnose complex distributions but so far using multiple shots

GC3: BEAM CONTROL

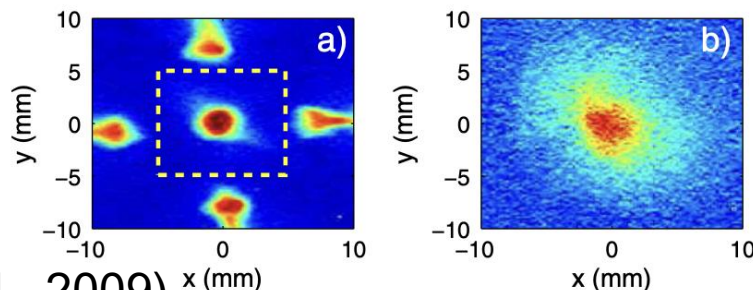
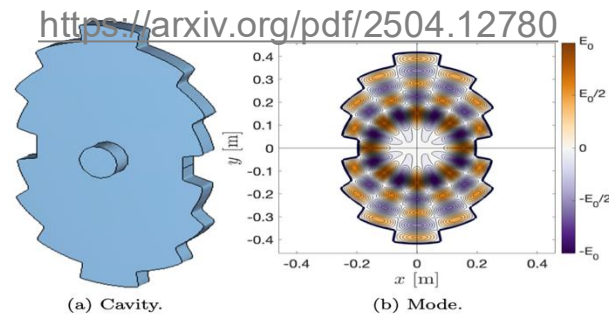
What we Understand Reasonably Well Today

- Strong progress has been made in timing, synchronization, beam arrival monitoring, profile measurements, and machine learning methods for accelerator tuning
- It is increasingly feasible to reconstruct latent beam properties from partial diagnostics using surrogate models, inverse methods, and ML
- There is growing experience with adaptive tuning and online learning in accelerator environments
- Still, the field is moving from device-level diagnostics toward system-level distribution control, which is a substantially harder problem
- Techniques for precise phase-space tailoring and/or control of emittance partitioning have been demonstrated and reliably used.

GC3: BEAM CONTROL

R&D Paths for Electron-Beam Control

- Develop non-invasive, high-resolution, high-repetition-rate longitudinal and 6D diagnostics suitable for ultrashort, high-current electron beams
- Fuse beamline design with beam design
 - Tailored external field with topologies optimized for precise beam manipulation in space and time
 - Use of self fields to control the beam at shorter time scale (wakefield for chirping or modulating the temporal distribution)

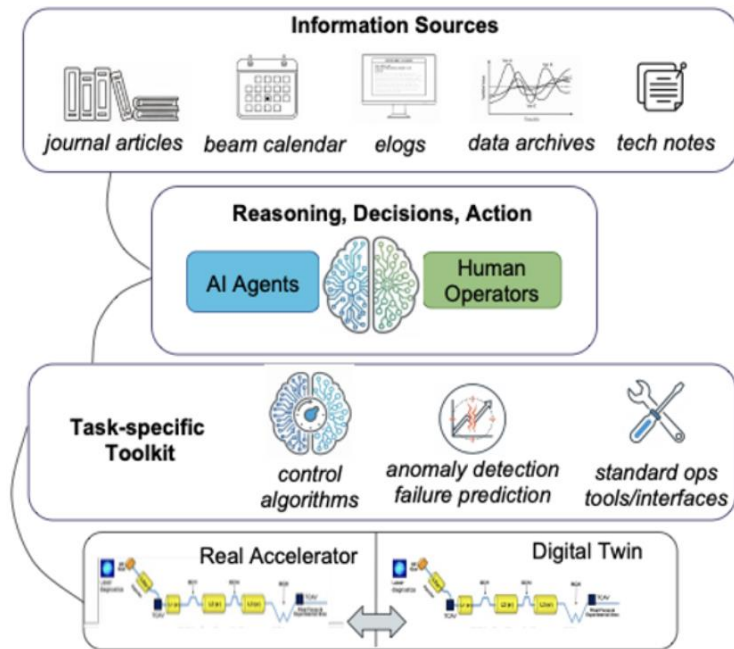


(ANL, 2009)

GC4: BEAM PREDICTION

Electron-Beam Prediction Challenge

- The goal is to create predictive virtual accelerators that can reproduce real electron-beam behavior with enough fidelity to support design, tuning, control, and extrapolation
- A predictive model is not just a simulation code; it is a validated digital representation of the machine and beam
- This is essential for operating near physical limits, where intuition and simplified models are insufficient



(the topics of VA was discussed in a previous FACET-II workshop)

GC4: BEAM PREDICTION

Current Understanding of the Main Limitations

- The ABP roadmap frames virtual accelerators as tools needing unprecedented accuracy and completeness
- Present limitations include:
 - Incomplete physics models in extreme regimes
 - Insufficient benchmarking against *high-quality* experimental data
 - Difficulty coupling source, lattice, collective effects, and diagnostics in one workflow
 - Computational cost of high-fidelity 3D modeling
- In extreme compression, existing simplified CSR treatments are often inadequate
- Prediction accuracy is further limited when measurements do not fully constrain the modeled state

GC4: BEAM PREDICTION

What We Understand Reasonably Well Today

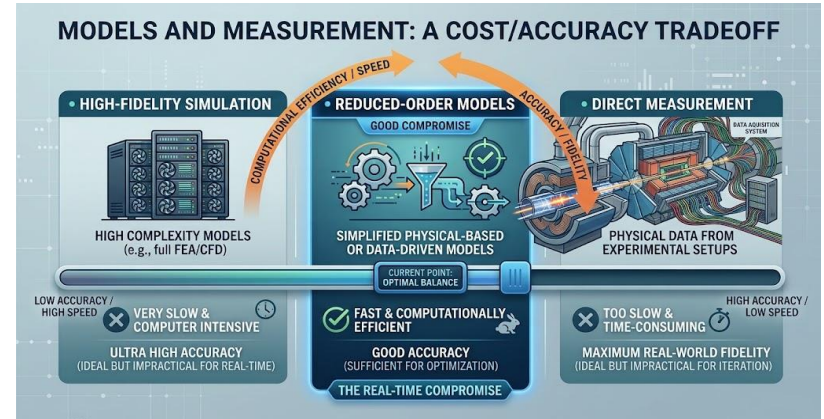
- The community already has a large ecosystem of beam dynamics codes and strong expertise in single-physics and subsystem-level modeling
- High-performance computing and accelerator data infrastructure are increasingly available to support integrated modeling and validation workflows
- Surrogate models and reduced-order approaches can accelerate otherwise expensive simulation chains
- There is a clear path toward hybrid physics-plus-data models, especially where fast online prediction matters
- **The main issue is not absence of tools, but the need to connect them into validated, operationally trustworthy predictive systems – e.g. PALS effort**



GC4: BEAM PREDICTION

Paths for Electron-Beam Prediction

- Build machine-validated virtual accelerators at accelerator test facilities
- Prioritize benchmark campaigns where the *same beam conditions* are validated across simulations and measurements :
 - High-fidelity simulation
 - Reduced-order models
 - Direct measurement
- Invest in coupled multi-physics modeling of source, collective effects, beam transport, and diagnostics
- Develop uncertainty-aware prediction, so models report confidence bounds rather than single deterministic outputs



THE ROLE OF TEST FACILITIES

Pushing science forward, building the workforce behind it

- **Serve as experimental test beds** to conduct exploratory accelerator research, validate emerging concepts and techniques, and advance promising accelerator technologies through sustained, programmatic development and testing.
- **Drive the accelerator science and technology innovations** required to enable the next generation of HENP user facilities and other scientific facilities, such as light sources.
- **Cultivate the next generation of accelerator scientists and engineers**, ensuring a pipeline of talent equipped to lead the field forward (AS&E) – there will be a shortage in workforce within the next decade.



ORGANIZING THE COMMUNITY

There is strength in unity

- **Question:** How do facilities work together to cover the full range of needs — and capitalize on the synergies across the US test-facility ecosystem?
- **Community efforts:**
 - **BeamNetUS** (DOE, HEP) — shared access across national beam-test facilities
 - **MOAT** — Multi-Office Accelerator Team: shared AI tools across accelerator sites

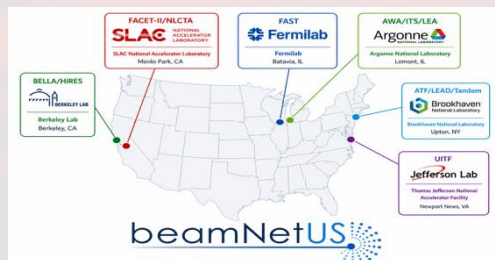


Table 1: Accelerator and beam physics (ABP) requirements in terms of theory and modeling, experimental beam studies, and integrated machine design for current and future HEP accelerators and facilities and beam tools for other SC offices. Brighter colors indicate progressively more critical need while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

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



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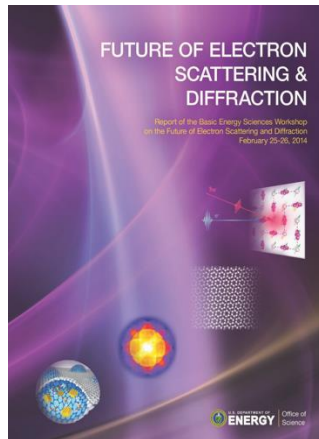
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OTHER RELEVANT REFERENCES

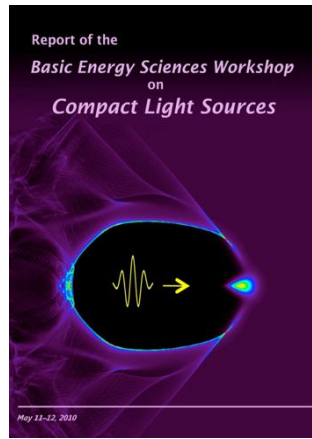
Relevant BES Round Tables and Basic Research Need (BRN) Workshops (non exhaustive list)



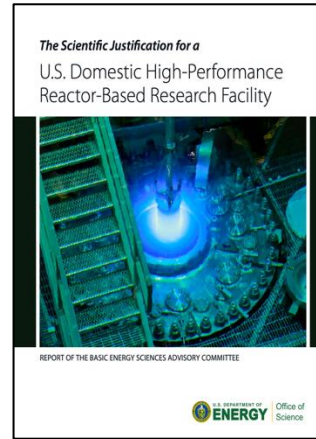
https://science.osti.gov/-/media/bes/pdf/reports/files/Future_of_Electron_Scattering.pdf



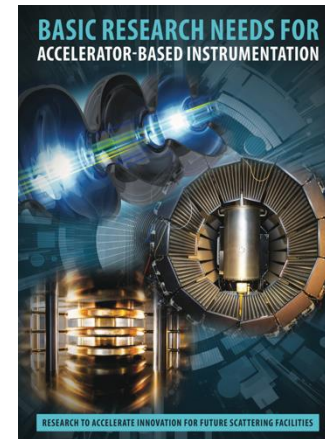
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