Summary Report of AF1:Beam Physics and Accelerator Education within the Accelerator Frontier*

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1 Executive Summary

Accelerator and beam physics (ABP) is the science of the motion, generation, acceleration, manipulation, prediction, observation and use of charged particle beams. The impressive advancements of accelerator frontiers is inseparable from long-term fundamental accelerator and beam physics research and development. The quest of next generation accelerators and colliders for discovery science pushes the accelerator science towards ultimate beam with unprecedented beam energy, intensity and brightness. Four grand challenges in beam intensity, beam quality, beam control and beam prediction were identified by the US Accelerator and Beam Physics (ABP) R&D program [1]. AF community-wide discussion on the physics limits of ultimate beams also reached the conclusion that it is very difficult to reach the next generation of colliders that are another order of higher energy beyond currently proposed future colliders such as ILC, FCC and CEPC with today's conventional accelerator technology. Hence, intensified R&D in advanced beam physics and accelerator technologies is needed to address these grand challenges and reach ultimate beams.

Nevertheless support for fundamental beam physics research has been declining. NSF has terminated its program in Accelerator Science and funding by DOE through GARD and Accelerator Stewardship has been steady or declining. With the energy frontier shifted from US to Europe, the collider expertise in particular e^+e^- collider and muon collider has been facing difficulty of maintaining healthy profile. This situation not only slows down advances but also creates difficulty in maintaining the R&D portfolio and retain talents in the states. In addition, this declining support for accelerator research also threaten student training and work-force development in accelerator science.

Hence, we propose to further strengthen the current US AS&T R&D towards robust and scientifically challenging R&D program in accelerator and beam physics to position the field of US High Energy Physics to be productive and competitive for decades to come. This includes

- Establish a decadal road map of accelerator and beam physics research in the DOE OHEP General Accelerator R&D (GARD) to address the four

ABP "grand challenges"

- Re-establish a program to of beam physics research on general collider-related topics, in particular, towards future e^+e^- colliders and muon colliders

- Strengthen and expand capabilities of the US accelerator beam test facilities to maintain their competitiveness w.r.t. worldwide capabilities.

To build and maintain a strong diverse and inclusive workforce for future HEP accelerator facilities, we also propose that the community pursue the following efforts to further strengthen Beam physics and Accelerator Science & Engineering (AS&E) education and outreach program,

- Gather integrated statistics on gender and ethnicity for AS&E students and workers in the labs, universities, and industry to monitor progress and guide long-term efforts. This can achieved by extending roles of the USPAS.

- The AS&E field should run a yearly undergraduate level recruiting program structured to draw in women and underrepresented minorities (URM). This could be coordinated with the USPAS.

- Strengthen connections to professional societies serving issues on diversity, such as exploring collaborations with the National Society of Black Physicists (NSBP) and the National Society of Hispandic Physicists (NSHP).

- AS&E should target more scholarship and fellowship support to draw in women and URMs.
  - The Fermilab ASPIRE program started in 2021 and the VITA DOE Traineeship provide models.
  - The SLAC Al Ashley fellowship started in 2011 and has hired 19 fellows with a retention rate of 79%. Funding was recently increased for the program to support 4 fellows vs. 2 in the coming year (2022).

- APS-IDEA teams at several national labs, universities, and institutions are making recommendations to the physics community on DEI efforts. This work should be leveraged by the AS&E field.

- Encourage labs to reward employees for volunteering for outreach and inclusion efforts, hirings addressing diversity, and efforts to enhance community welcomeness to underrepresented groups.

2 Education and outreach

Summary of our white paper goes here.

Figure 1: Caption
Education and outreach progress since last Snowmass

3 Accelerator and Beam Physics

Beam physics has been the center part of modern accelerator science. A series of workshops to explore the direction and scope of the field were held by the US Accelerator and Beam Physics (ABP) R&D program, majorly funded by the HEP GARD including the Accelerator Stewardship, as well as jointly by AF1, AF4 and AF6. Through these workshops, the grand challenges of beam physics and accelerator science were emerged and physics limit of ultimate beam for future colliders was explored.

3.1 Grand Challenges

The US Accelerator and Beam Physics (ABP) R&D program explores and develops the science of accelerators and beams to make future accelerators better, cheaper, safer, and more reliable. Particle accelerators can be used to better understand our universe and to aid in solving societal challenges [1].

The primary scientific mission of ABP R&D is to address and resolve the four Accelerator and Beam Physics Grand Challenges (GC):
Grand Challenge 1 (beam intensity): How do we increase beam intensities by orders of magnitude?
Grand Challenge 2 (beam quality): How do we increase beam phase-space density by orders of magnitude, towards the quantum degeneracy limit?
Grand Challenge 3 (beam control): How do we measure and control the beam distribution down to the level of individual particles?
Grand Challenge 4 (beam prediction): How do we develop predictive "virtual particle accelerators"?

Other equally important ABP missions are associated with the overall HEP missions:

- Advance the physics of accelerators and beams to enable future accelerators.
- Develop conventional and advanced accelerator concepts and tools to disrupt existing costly technology paradigms.
- Guide and help to fully exploit science at the HEP accelerator R&D beam facilities and operational accelerators.
- Educate and train future accelerator physicists.

We propose a robust and scientifically challenging program in accelerator and beam physics to address the Grand Challenges. This will help position the field of US High Energy Physics to be productive and competitive for decades to come. We also call for a systematic and organized effort in research into the early conceptual integration, optimization, and maturity evaluation of future and advanced accelerator concepts. We emphasize that the accelerator and beam test facilities are critical to enabling groundbreaking research and to addressing the Grand Challenges. Finally, we remind that it is important to maintain support for the existing cross-cutting educational mechanisms in the field of accelerator science and technology such as US Particle Accelerator School (USPAS) and the Center for Bright Beams (CBB).

3.2 Research Areas

The research community input during the two ABP workshops [2, 3, 4] indicated the following areas of research are needed to address the above Grand Challenges (GC).

Single-particle dynamics and nonlinear phenomena; polarized-beams dynamics

- This impacts GC 1 and 2 and benefits from addressing GC 3 and 4.

Collective effects (space-charge, beam-beam, and self-interaction via radiative fields, coherent synchrotron radiation, e.g.) and mitigation.

- This impacts GC 1 and 2, and benefits from addressing GC 3 and 4.

Beam instabilities, control, and mitigation; short- and long-range wakefields.

- This impacts GC 1 and 2, and benefits from addressing GC 3 and 4.

High-brightness / low-emittance beam generation, and high peak-current, ultrashort bunches.

- This impacts GC 2, and benefits from addressing GC 3 and 4.

Beam quality preservation and advanced beam manipulations; beam cooling and radiation effects in beam dynamics.

- This impacts GC 2, and benefits from addressing GC 3 and 4.

Advanced accelerator instrumentation and controls.

- This impacts GC 3.

High-performance computing algorithms, modeling and simulation tools.

- This impacts GC 4.

Fundamental accelerator theory and applied math.

- This impacts all Grand Challenges.

Machine learning and artificial intelligence.

- This impacts GC 3 and 4 in the short term and GC 1 and 2 in the long term.

Early conceptual integration, optimization, and maturity evaluation of accelerator concepts.

- This focuses on science and technology gaps and bridges between various R&D efforts.

The ABP research area shares many topics and physics issues with RD activities at other (non-HEP) labs and universities.

Figure 2: Caption
Test facilities progress since last snowmass

3.3 Beam Test Facilities

Demonstrating the viability of emerging accelerator and beam physics research ultimately relies on experimental validation. The US (both at national laboratories and universities), has a portfolio of beam test facilities capable of providing beams over a wide range of parameters used to perform research critical to advancing accelerator S&T related to high-energy physics, basic energy science, and beyond. These accelerator test facilities have notably have enabled groundbreaking research in accelerator research essential to developing the next generation of energy-frontier and intensity-frontier user facilities; see Ref. [5] for an overview of the current portfolio.

The facilities include GARD-sponsored infrastructure whose principal mission is to support broad participation from the community of accelerator scientists including from Universities, Industry, and National Laboratories. These facilities enable research pertinent to APB and provide ideal platforms for training future accelerator scientists.

There are several ABP research facilities, such as FACET (SLAC), AWA (ANL), ATF (BNL), BTF (ORNL), IOTA/FAST (FNAL), and facilities at universities, including CBETA (Cornell), MEDUSA (Cornell), PEGASUS (UCLA) and SAMURAI (UCLA). Such facilities are invaluable for advancing new accelerator concepts and technologies, but a significant fraction of them are aging or sharing infrastructure with user facilities which significantly reduces their throughput.

It is critical for the US accelerator program to provide robust funding to operate, maintain, and upgrade these accelerator 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 started, e.g., in Europe [6, 7].

3.4 Physics limit of ultimate beams for future colliders

The development of accelerators and beams in the past century has led to incredible discoveries in physics, chemistry, biology, etc. Up to date, about 25 Nobel Prizes in Physics and 7 in Chemistry were due to the significant contribution of the development in accelerator and beams [1,3]. The quest of understanding matter and fundamental forces has pushed the energy of proton beams towards 10 TeV, while the synchrotron light sources are pushing towards the diffraction limit and the X-ray FEL is reaching atto-second scale.

Nevertheless, to go to the next level of discovery in fundamental physics as well as other transformative science fields, particle beams with beyond the state-of-art performance are required. The hunt for new physics beyond our current understanding such as the standard model pushes future colliders in the energy range beyond 10s TeV. The discovery of new fundamental constituents with the lepton collider requires the luminosity scaled with the centre-of-mass energy E_{cm} as $(\frac{E_{cm}}{10TeV})^2 \times 10^35 cm^{-2}s^{-1}$. It is clear that to realise the ultimate colliders with the conventional RF technology based accelerator technology requires either leap-forward developments of key technologies such as ultra high field magnets and ultra high gradient acceleration structure, or with significant increase of size and power consumption that results in staggering cost. Fig. 1 shows the maximum peak luminosity and size as function of beam energy of colliders in the past, current and proposed for future. Both future lepton and hadron colliders also have significant increases in size, both physically and economically.

It is evident that to reach ultimate collider energy, disruptive acceleration as well as beam technologies are required. Both laser driven and beam driven plasma wakefiled acceleration, aka, LWFA and PWFA, have been pursued and intensitfied worldwide. While unprecedented acceleration gradient has been demonstrated with both PWFA and LWFA, the path towards TeV collider still requires numerous marvelous in beam physics as well as engineering to meet the repetition rate, staging requirement and ultimately the beam performance that today's conventional accelerator has achieved. Nevertheless, as rapid development in the advanced concept acceleration field, it is not appropriate to estimate the performance limit at this point of time.

3.4.1 Opportunities with current Achieved extreme beam

4 Conclusion

- education and outreach
- Comprehensive accelerator science RD approach
- Test facilities

References

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