ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEZD1

ARDAP's PERSPECTIVE ON ACCELERATOR TECHNOLOGY R&D IN THE U.S.

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Abstract

DOE operates several particle accelerator facilities and is planning several new forward-leaning accelerator facilities over the next decade or two. These new facilities will focus on discovery science research and fulfilling other core DOE missions. Near and mid-term examples include PIP-II and FACET-II (for High Energy Physics); LCLS-II, SNS-PPU, APS-U, and ALS-U (for Basic Energy Sciences); FRIB (for Nuclear Physics); NSTX-U and MPEX (for Fusion Energy Sciences); and Scorpius (for NNSA). Longer-term examples may include future colliders, the SNS-STS, LCLS-II HE, and EIC. In addition to domestic facilities, DOE's Office of Science (SC) also contributes to several international efforts.

Together, these new facilities constitute a multibillion-dollar construction and operations investment. To be successful, they will require advances in state-of-the-art accelerator technologies. They will also require the National Laboratories to procure a variety of accelerator components.

This paper summarizes how DOE is working to address these upcoming R&D and accelerator component production needs through its new office of Accelerator R&D and Production (ARDAP).

ACCELERATOR R&D IN THE OFFICE OF SCIENCE

Facility-specific accelerator R&D is the purview of the specific SC Program Office (Fig. 1) planning the facility. For example, Basic Energy Sciences is responsible for the R&D needed for the high-average current, high-brightness electron injectors needed for LCLS-II and LCLS-II HE; Nuclear Physics will be responsible for the R&D needed for ion cooling for the upcoming EIC; and High Energy Physics will be responsible for the high-field magnet R&D needed for a 100-TeV hadron collider. The amount of accelerator R&D required for upcoming SC facilities is very significant, with several key enabling technologies still elusive (e.g., advanced accelerator schemes for future multi-TeV lepton colliders). Moreover, several emerging technologies may impact multiple facilities crossing different SC Program Offices, and the coordination of the required R&D between these offices needs to be considered.

While accelerator facility construction and operations costs have increased over the last decade, accelerator R&D in SC has decreased both in absolute terms (from about $164M in FY2011 to about $96M in FY2022) and in relative terms (from about 12% of the entire accelerator budget in 2011 to a minimum of 3.7% in FY2020, recovering somewhat to 5.2% in FY2023), as shown in Fig. 2.

Data calls and a Request for Information have helped quantify specific supply chain issues in accelerator technology and to outline the challenges faced by domestic industrial suppliers. In addition, over half of accelerator procurements for SC accelerator facility construction and operations are now coming from off-shore.

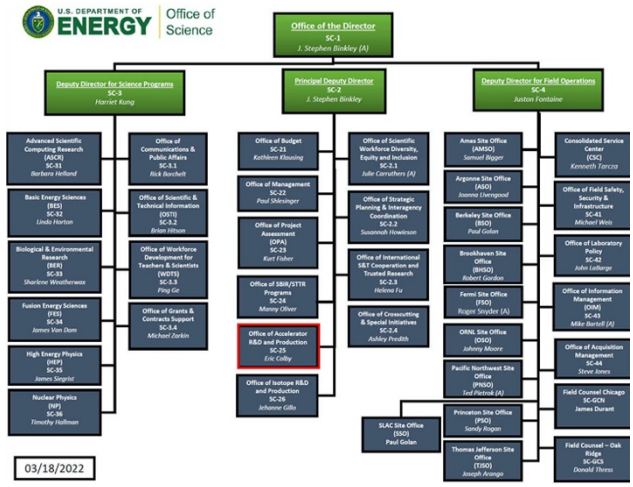

Figure 1: SC organization [1], including the Science Programs and the new Office of Accelerator R&D and Production (outlined in red).

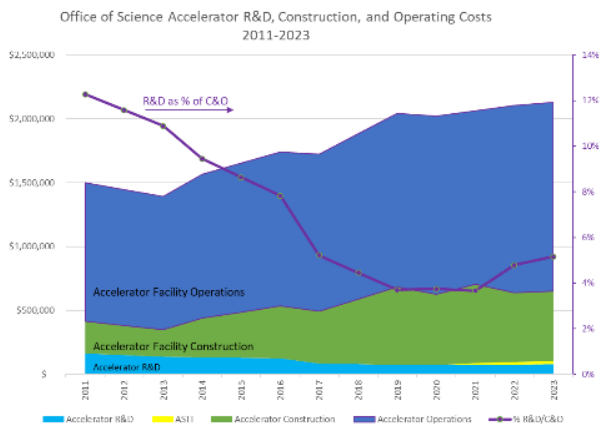

Figure 2: SC accelerator R&D, construction, and operating costs from FY2011 to FY2022 [actual] and FY2023 [request] (where "C&O" means construction and operations).

THE OFFICE OF ACCELERATOR R&D AND PRODUCTION

As part of a larger reorganization in SC, a new Office of Accelerator R&D and Production (ARDAP) was established to serve as a focal point for coordinating accelerator

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R&D and to specifically address supply chain issues. It is seated directly under the Principal Deputy Director of the Office of Science, along with the Offices of SBIR/STTR Programs and Isotope R&D and Production. ARDAP's mission is to ensure a robust pipeline of next-generation accelerator science and technology (AS&T) to support physical sciences research while providing technology advances and industrial strength that position the U.S. to lead the world for decades to come. ARDAP will accomplish its mission through:

- *Maintaining a strategic picture of AS&T needs and worldwide competition.* An inventory of R&D needs for future facilities was completed, resulting in the Accelerator Science and Technology Initiative described below. Analysis of accelerator technology purchases and market capabilities and configuration have informed supply chain vulnerability assessments.
- *Facilitating coordination of Programmatic AS&T R&D investments across SC.* Ongoing coordination across SC is accomplished through the SC Accelerator R&D Joint Oversight Group and frequent communication amongst the SC programs.
- *Investing in selected cross-cutting AS&T areas*. ARDAP supports special areas of cross-cutting need, such as ultrafast laser technology, beam physics and computation, and fundamental materials research, acting to complement investments made by the SC science programs.
- *Providing a system engineering perspective for SC facility projects*. While this role is still under discussion, functions include serving as a subject matter expert in facility construction knowledge, supplier capability, and procurement best practices. Longer term, hosting online information resources of broad use to facility construction and operation is also under discussion.
- *Supporting workforce development, when needed*. ARDAP currently supports workforce development primarily through R&D awards (that involve students), and by supporting the Brookhaven Accelerator Test Facility.
- *Maturing key AS&T technology and developing capable U.S. vendors*. Public-private partnerships are seen as the primary mechanism for accomplishing the transfer of know-how and for collaborative development of industrial capability to produce accelerator technology. Business sector studies have helped identify the landscape in specific areas (superconducting wire and cable, RF power sources) and these studies are planned to continue.
- *Transitioning accelerator technology to broader uses*. This has been the primary role of the Accelerator Stewardship program, which aims to make the technology advances developed for scientific instruments broadly useful in medical, industrial environmental, and security applications. An equally important objective of this effort is to increase the broader market pull for technologies SC needs, providing manufacturers with a more sustainable market.

The Accelerator Science and Technology Research Initiative

Concerned about strengthening accelerator R&D and reducing supply-chain vulnerabilities for accelerator technologies, SC instituted a new Research Initiative, the Accelerator Science and Technology Initiative (ASTI), beginning in FY2021. ASTI funding is embedded within the Science Program Offices and ARDAP. It is intended to support five primary technology areas that are strategically important for future SC facilities:

- Advances in superconducting accelerator systems, including SRF, superconducting magnets, and cryogenic engineering.
- Beam physics and high-fidelity computer modeling and control, including better diagnostics, control systems, advanced focusing, and beam cooling techniques.
- Advances in high intensity electron, proton, and ion sources, also including megawatt-class targets for secondary particle sources.
- Higher average-power radiofrequency and ultrafast laser sources, including power handling devices, and high accuracy X-ray optics.
- High-risk, high-reward R&D in advanced materials, particle sources, beam dynamics, acceleration techniques, and other advanced topics.

The ASTI initiative is intended to continue strengthening domestic accelerator capabilities by robustly funding mid- to long-term accelerator R&D aimed at the next generation of facilities.

ARDAP PROGRAMS

ARDAP supports the development of new technologies and the commercialization of new and existing technologies through its Accelerator R&D mission and its Accelerator Development mission. The R&D mission is addressed through the Accelerator Stewardship program and the Accelerator Development mission through the Accelerator Production program and its Accelerator Technology Maturation and Accelerator Technology Production sub-programs. ARDAP will support cross-cutting and use-inspired accelerator science and technology R&D in the TRL 1-4 range with the Accelerator Stewardship program and broad accelerator science and technology R&D in the TRL 5-7 range with the Accelerator Technology Maturation sub-program. ARDAP will support production development over the entire MRL 1-7 range in the Accelerator Technology Production sub-program. The TRL and MRL ranges of the different ARDAP programs are shown in Fig. 3.

The Accelerator Stewardship program supports early-stage (low-TRL) R&D that benefits a broad range of research for industrial, medical, and security applications; supporting workforce development and capability building at universities; and other R&D activities that broadly support the accelerator user community. The Accelerator Production program is to enhance the domestic industrial accelerator capability to address potential domestic industrial

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ACCELERATOR RESEARCH & DEVELOPMENT		ACCELERATOR TECHNOLOGY PRODUCTION	
TRL 1	Basic principles observed and reported	MRL 1	Manufacturing feasibility assessed
TRL 2	Technology concept and/or application formulated	MRL 2	Manufacturing concepts defined
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept	MRL 3	Manufacturing concepts developed
TRL 4	Component and/or breadboard validation in a laboratory environment	MRL 4	Capability to produce the technology in a laboratory environment
ACCELERATOR TECHNOLOGY MATURATION			
TRL 5	Component or breadboard validation in a relevant environment	MRL 5	Capability to produce prototype components in a production relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment	MRL 6	Capability to produce prototype system or subsystem in a production relevant environment
TRL 7	System prototype demonstration in an operational environment	MRL 7	Capability to produce systems, subsystems or components in a production relevant environment
TRL 8	Actual system completed and qualified through test and demonstrated	MRL 8	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production
TRL 9	Actual system proven through successful mission operations	MRL 9	Low rate production demonstrated; Capability in place to begin Full Rate Production

Figure 3: TRL and MRL levels for Accelerator Stewardship (red), Accelerator Technology Maturation (green) and Accelerator Technology Production (yellow). From Technology Readiness Assessment Deskbook, July 2009 [2].

accelerator capability to address potential supply chain vulnerabilities that add risk to new, upgraded, and operating accelerator facilities over the next 10-20 years.

Table 1 emphasizes how the ARDAP research program and the Office of Science General Accelerator R&D (GARD) program within the office of High Energy Physics complement each other.

The differences in these two distinct programs also generally apply between the ARDAP research program and the basic accelerator R&D programs within the other SC Science Program Offices of Basic Energy Sciences, Fusion Energy Sciences, Nuclear Physics, and Isotope R&D and Production.

Accelerator Stewardship

The Accelerator Stewardship program is intended to be flexible and responsive to national needs as identified by partner Federal agencies, including all SC Science Program Offices, NNSA (specifically NA-21, NA-22, and NA-80), AFOSR, ONR, DARPA, DHS, NIH, and NSF. Tracks 1, 2, and 3 in Accelerator Stewardship are well established, with Track 1 topics including focused research on particle therapy delivery systems, ultrafast laser technology, and high-power electron accelerator technology for industrial and environmental applications. As technologies mature, older Track 1 themes will be retired and new ones introduced. A new Track 1 activity was introduced in the FY2020 call for enabling technologies for compact accelerators based on security and medicine needs as identified in the Accelerator Stewardship compact accelerator workshop [3]. Since this is a relatively new program element, we have included Fig. 4 to indicate which beam energies and powers are most relevant to which application.

Track 2 currently funds broadly applicable basic research at universities, and is likely to evolve in the near- to mid-future. Track 3 provides assistance to industrial and other non-DOE entities to make short-term use of accelerator R&D capabilities at DOE SC National Laboratories.

Table 1: Comparison of the ARDAP Research Program and the Office of High Energy Physics General Accelerator R&D Program

	ARDAP	GARD
Customer	Office of Science, other Federal Agencies, US industry	HEP
Program Aim	• Acc. Stewardship expands market pull and funds cross-cutting basic R&D • Acc. Development strengthens suppliers	• Develops transformative new AS&T for HEP • Strengthens key suppliers needed for HEP facilities
Activities Funded	• Broadly applicable AS&T R&D • Tech transfer and new application development • Industrialization and supplier development for all SC Programs	• AS&T R&D primarily for HEP • Tech transfer • Industrialization and supplier development for HEP construction projects
Advisory Mechanisms	SC Accelerator Joint Oversight Group, other Federal Agencies, data calls, RFIs, and BRN Workshops	HEPAP, Snowmass+P5 process, and Research Roadmap Workshops
Metrics of Success	• Technologies put to new uses • Suppliers strengthened, new capabilities developed • Standard academic measures of R&D productivity	• HEP science that technology enables • Reduction of technical risk to science mission • Standard academic measures of R&D productivity
Follow-on Investment	Through SC facility projects, applied programs, and from industry	HEP-funded directed R&D projects to prepare for facility construction

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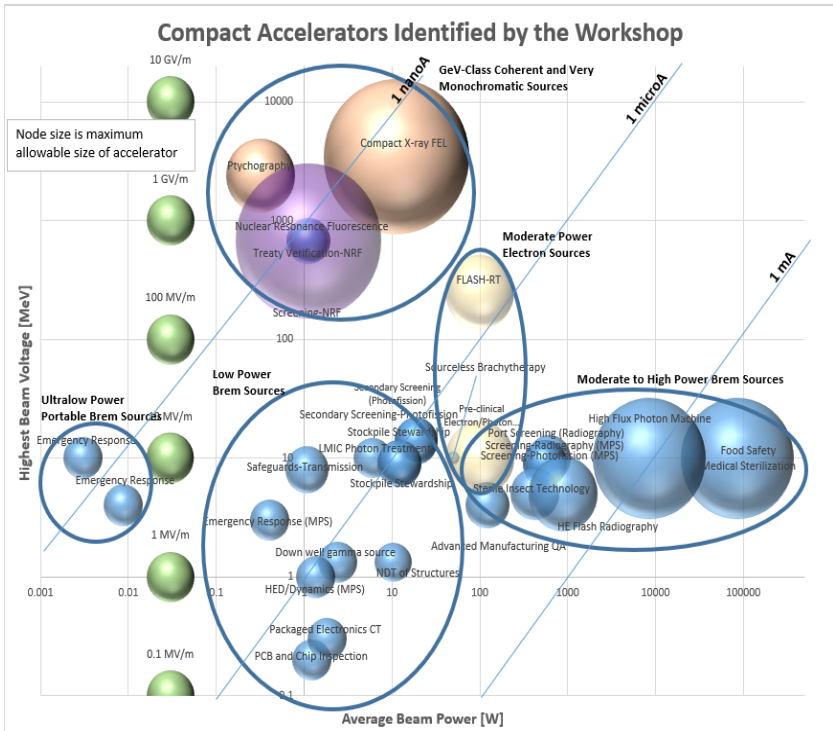

Figure 4: Diagram of compact accelerator applications (size of the bubble represents maximum allowable device size) versus beam energy and average power.

Accelerator Development

While the U.S. continues to excel in discovery and innovation, the applied research and development necessary to translate new emerging technologies into products remains a challenge for individual companies, leading to accelerator technology supply chain vulnerabilities for SC and other Government missions. Recent executive orders on America's Supply Chains [4] and on Ensuring the Future Is Made in All of America by All of America's Workers [5] emphasize the contemporary urgency of the issue. The ARDAP Accelerator Production program goal is to reduce these vulnerabilities by turning US-based accelerator inventions into products made by a skilled and diverse American workforce, as well as adapting foreign accelerator advances to domestic products as appropriate.

ARDAP's Accelerator Production program addresses this goal with an Accelerator Technology Maturation subprogram and an Accelerator Technology Production subprogram. Through these sub-programs, the Accelerator Production program ensures the TRL and MRL of selected critical accelerator technologies are both sufficiently high so the technologies can be commercialized by domestic accelerator technology vendors. Cross-cutting technologies within the five strategically important technologies areas will have the highest priority for investments by the Accelerator Production program. Funding for projects to develop business plans to enhance domestic vendor capability of selected accelerator technology sectors began in FY2021.

While "cross-cutting accelerator R&D" and "technology maturation" have relatively clear definitions, ARDAP is currently studying ways to most effectively develop and support domestic vendors through the Accelerator Technology Production sub-program, including possible public-private partnerships and other mechanisms such as consortia. As technologies mature, DOE needs to synchronize moving emerging technologies from universities and National Laboratories to industry while ensuring that investments lead to a viable industrial production capability. Similarly, effective technology maturation will be facilitated by strong partnerships between universities, National Laboratories, and industry that complements and leverages the SBIR and STTR programs.

In December 2020, ARDAP started the process of understanding commercialization needs and mechanisms with a data call to the National Laboratories to determine what accelerator technology is purchased through domestic vendors and what is through foreign sources. ARDAP followed this in February 2021 with a RFI soliciting community input on how to mature key accelerator technologies and optimally support domestic vendors. In the fall of 2021, the Office of Science Roundtable on Supply Chain Risk Mitigation for Facilities and Tools discussed supply chain risks in key technology areas including accelerator technology [6]. Recommendations from that workshop reinforce and elaborate many of the points uncovered in earlier data calls and the Request for Information.

In FY2022, ARDAP continued funding research that supports credible accelerator technology sector business plans and started to fund accelerator development enabled through public-private partnerships.

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Future Research Initiatives

In addition to continued participation in the Accelerator Strategic Technology Initiative, ARDAP will seek out opportunities to participate in SC-wide, DOE-wide, and Administration-driven Research Initiatives. Research Initiatives are cross-cutting multi-Office activities intended to solve highly complex problems of highest importance to SC, DOE, or the nation. Research Initiatives appear explicitly by name in the DOE budget request, and the highest-level initiatives also appears explicitly in appropriations language. ASTI, previously discussed, is an SC-wide initiative.

Upcoming initiatives include the Funding for Accelerated, Inclusive Research (FAIR), and Reaching a New Energy Sciences Workforce (RENEW). Within ARDAP, FAIR aims to enhance research on accelerator technology for clean energy, climate, and related topics at Minority Serving Institutions (MSIs), and build R&D capacity. RENEW leverages SC's unique National Laboratories, user facilities, and other research infrastructures to provide training opportunities for undergraduate and graduate students, postdoctoral researchers, and faculty at academic institutions not currently well-represented in the U.S. science and technology ecosystem.

CONCLUSION

Summarizing the main ARDAP functions:

- Through the Accelerator Stewardship program, it will continue to support accelerator R&D that is use-inspired and that is cross-cutting in the sense that the R&D is needed for the future goals of a multiple SC Program Offices; and
- Through the Accelerator Production program, it will work with industry, universities, and National Laboratories to mature and industrialize key accelerator technologies to reduce technical and supply chain risks for future SC (and other Federal agencies') accelerator projects.

ARDAP investment strategies will be informed by the Office of Science Accelerator Joint Oversight Group, discussions with other Federal agencies, data calls, Requests for Information, Roundtable Meetings, data calls, and through Basic Research Needs (BRN) workshops.

ARDAP encourages the entire accelerator community to participate in the data calls and other input processes as the opportunities arise. Ensuring that future Office of Science accelerators can be successfully built is an especially important challenge that we need to address together, and that we can be proud, as a community, of successfully meeting.

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