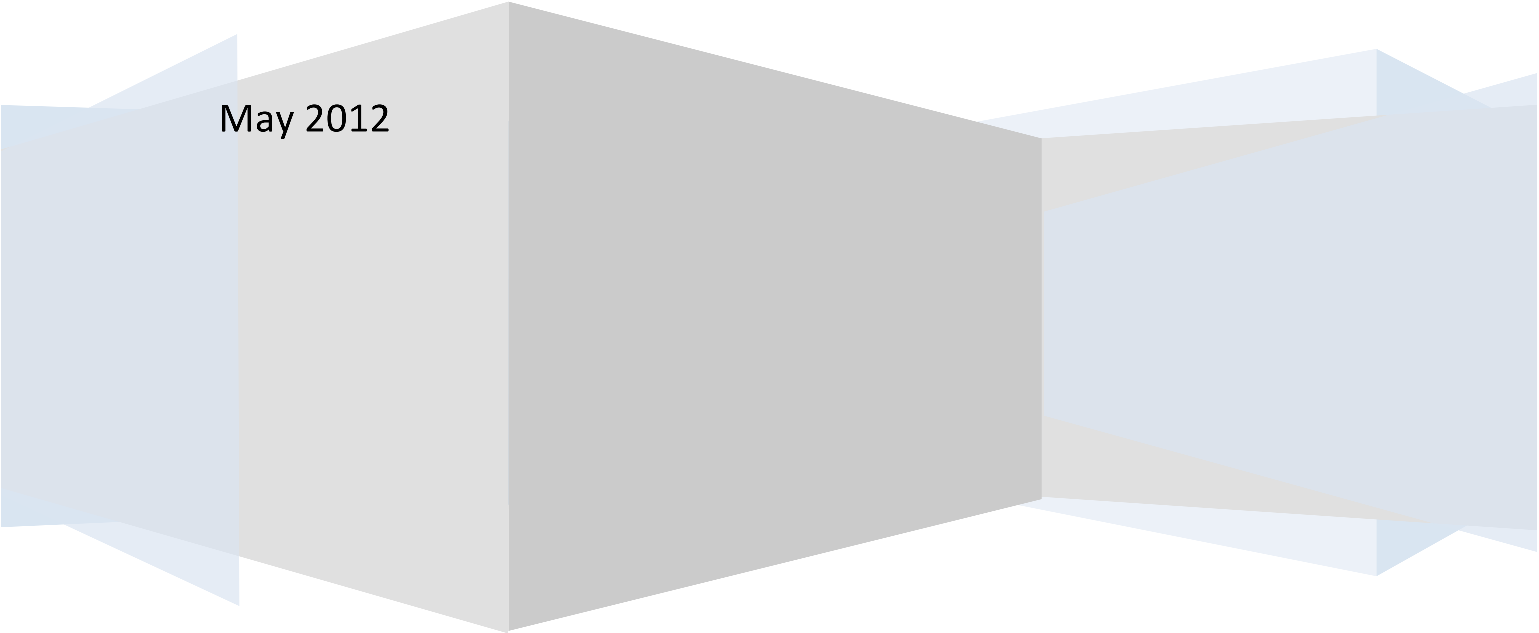
Task Force on Accelerator R&D commissioned by Jim Siegrist, Associate Director High Energy Physics, Office of Science

Office of High Energy Physics Accelerator R&D Task Force Report



May 2012

Preface and Acknowledgment

This report has been produced in response to a tasking letter from James Siegrist, Associate Director of Science for the Department of Energy's Office of High Energy Physics, to Dr. Norbert Holtkamp, director of the SLAC National Accelerator Laboratory (SLAC) Accelerator Directorate. The tasking letter instructed SLAC to form a task force composed of various experts to cover all the fields and application areas included in the report, and further instructed that task force members would be providing their individual inputs in their areas of expertise. We acknowledge and thank all of the individuals from DOE, DOE laboratories, academia, industry, and other services and agencies who responded to our requests for rapid input of information.

Disclaimer

This report and much of its content addresses the broad question of how accelerator R&D benefits the nation and how it can further benefit the nation's needs in the future.

Accelerator R&D is a broadly owned subject in which many offices in the Office of Science play a major role. In addition and complementary to these offices, the nation's universities, the National Science Foundation, the National Nuclear Security Administration and industry itself all drive a great deal of accelerator R&D.

Nevertheless, this task force was requested by the Office of High Energy Physics (HEP) and mostly uses material provided by HEP throughout its report. The predominant use of HEP material is not meant to diminish the roles or the contributions from its other partners. Rather it is meant to give an accurate picture of long-term accelerator R&D within the required time constraints. We make every effort to give credit wherever major contributions are made, as we recognize that these contributions are crucial to the accelerator field. At the same time, the task force does propose ideas to better leverage others' programs with those of HEP's for our nation. This report reflects an effort to do this without changing the stewardship model or the funding stream.

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Executive Summary

Accelerator science and technology, along with their associated R&D programs, have a major impact on many fields in our society. The largest and most obvious is discovery science, where accelerators are used as tools and are sometimes the only option to provide the answers sought. It is natural then that the stewards of discovery science in the US—the Department of Energy Office of Science and the National Science Foundation—are major users and drivers of innovation in accelerator science and technology.

The reach of accelerators, though, extends beyond the purview of discovery science and today spans almost all aspects of our lives. Still, their impact is not readily recognized. Accelerator applications, with their potential for continued innovation, can help drive US economic competitiveness both here and abroad. Such applications were clearly identified in the 2009 workshop on Accelerators for America's Future (AfAF) organized by the DOE Office of High Energy Physics (HEP), the acknowledged steward of long-term generic accelerator R&D. As part of the recommendations resulting from this workshop, accelerator applications in energy and the environment, medicine, industry, defense and security, and discovery science were identified by the fields' experts and customers as the most promising areas. A number of accelerator R&D pursuits that would help the US to maintain its competitive edge were singled out to help develop a coherent program.

In September 2011, in recognition of these opportunities, the Senate Appropriations Committee requested that the DOE develop a 10-year strategic plan "...for accelerator technology research and development to advance accelerator applications in energy and the environment, medicine, industry, national security, and discovery science" for accelerator stewardship by June 2012. The Office of High Energy Physics then established the current task force, made up of representatives from the national laboratories, universities and industry, to provide input for that plan.

Now the accelerator community needs to address these R&D areas, feed the results back, and at the same time keep an eye on what comes next. We also need to keep current on who the customers of these technologies are and what they want and need. Publicly funded research, such as accelerator research at national laboratories, has the potential to contribute to the creation of new businesses and jobs and strengthen our economy. Both program managers in the DOE and researchers working in the programs are committed to meeting these challenges and exceeding expectations.

In order to foster the advancement of the application of accelerator technology for issues of national importance, it is essential that new relationships be formed and nurtured between those who are empowered to develop this technology and those who are the ultimate beneficiaries of this technology. A more "customer-focused" approach will help ensure that the research and development program take deliberate steps to meet user demands rather than rely on chance or serendipity. To that end, one of the most important suggestions resulting from the work of this task force is the establishment of a steering group made up of senior leadership of the various stakeholders, supported by periodic, dedicated workshops. For example, such a meeting could involve both intra-agency and interagency program managers along with industry representatives and technical advisors in the area of accelerators and their applications. Clearly a strong interconnection between the provider and the customer would help bridge the divide between breakthroughs in accelerator science and their prompt translation into practical and/or commercial applications. A meeting of these stakeholders would provide a venue in which the long-term R&D programs could be steered with the desired customer-focused approach, guided by the question: "What do the users of accelerators and accelerator R&D outside of discovery science need in order to be successful in their areas?"

With input from those who develop or utilize accelerators in industry and other government agencies, the task force identified a number of administrative impediments where removal would facilitate a stewardship program. They include the lack of easy access to existing DOE facilities and expertise, issues associated with protecting and/or sharing intellectual property, lack of infrastructure development, the insufficient availability of professional services, and lengthy processing and approval times for establishing contractual or other agreements, which must be completed prior to the initiation of work. With coordination in place and these barriers removed, we see no reason why many of the useful ideas from the workshop would not begin to pay off in the next one to three years, with the impact increasing as time goes on.

The DOE Office of Science and other funding agencies have an extensive infrastructure that, if needed, could be made available to those who at present have no chance to use it or aren't aware of these resources and capabilities. Much of this infrastructure can be easily modified to accommodate the needs of industry or other agencies. To leverage its use, we can define the specific needs of all stakeholders and jointly define any required additions. In the case where demonstrations are needed, they can be based on existing expertise and facilities within individual national laboratories.

Many of the opportunities for advancing the application of accelerator technology outlined in the Accelerators for America's Future report are interdisciplinary in nature; progress requires bringing together the required expertise in accelerator technology with the expertise in the end-use of that technology. For example, progress in medical accelerator applications requires teams of accelerator technologists and medical professionals working closely together. Realizing the opportunities outlined in the AfAF report could be achieved in a competitive manner by creating Collaborative Accelerator Research Teams (CARTs). These teams would be focused on specific issues and challenges within the areas of energy and environment, medicine, industry, defense and security and discovery science. CARTs can easily grow from the individual strengths of each national laboratory, yet integrate the strengths of other laboratories, other agencies, universities and industrial partners to best meet the technical challenges. Thus, CARTs would have a clear mission and a limited duration, and their funding could be competitively bid through a peer-reviewed process. In addition, a road for development of the major application programs can be opened via government initiative, as is being established in some foreign countries, strongly integrating certain industries that express interest. For instance, if the government identifies a need for a hadron therapy facility based on light-ion beams in the US, the Office of Science has substantial scientific and technical capability to form a CART to develop a concept and to provide this infrastructure in a minimum amount of time.

Finally, the task force has recognized with great satisfaction that many necessary programs identified in the AfAF workshop already exist. In addition, subtopics are being pursued in one form or another under the leadership of the Office of Science's Office of High Energy Physics, as well as those of Basic Energy Sciences and Nuclear Physics, of the NSF and of the defense sector. With the exception of Nuclear Physics and accelerator-based isotope production, their mission today is focused on science goals. Though this work is largely geared toward discovery science, they could easily support areas of accelerator applications by connecting those areas to their present work and by giving customers an opportunity to define goals. Establishing a new program in HEP as an umbrella under which all of these efforts could be gathered is an appropriate step in realizing the workshop's output and has been one of the main considerations of this task force report, which has been assembled from the individual contributions of its members.

Introduction: Building on a Strong Foundation

Particle accelerators are well known as discovery tools for probing matter at the molecular, atomic and subatomic scales. They are also important tools outside the basic sciences, and advances in accelerator technology are frequently put to use in other fields, finding their way into our everyday lives.

The DOE Office of Science (SC) is the steward of ten national laboratories and operates or supports eight large accelerator installations across the country. Over the last five decades it has continually constructed new, cutting-edge accelerator facilities and further developed existing ones in support of specific scientific missions. Today, the Office of Science operates a suite of accelerator-based user facilities that is the envy of the world. That success would not have been possible without the investment made over many decades in both near-term, targeted, and longer-term accelerator technology development.

The SC Office of High Energy Physics (HEP) maps out specific goals for advanced generic accelerator science, providing resources to the Office's accelerator research programs to improve the very technology that gives rise to science discoveries a decade or more into the future. Program stewardship and technology development are not limited, however, to HEP. These have a much broader base in the SC directorates, including Nuclear Physics (NP)[1], Basic Energy Sciences (BES), Fusion Energy Sciences (FES) and Advanced Computing (ASCR), to name the offices most involved. Equally important, the National Science Foundation (NSF) and its university programs are major contributors, as are the laboratories working under the stewardship of the National Nuclear Security Administration (NNSA) and other defense departments.[2]

In order to better understand the needs from the users and builders of accelerators outside SC, the Office of High Energy Physics initiated a workshop to identify areas where accelerator R&D does have, or can have, an impact beyond its core mission to develop new tools of discovery for particle physics. These areas provide new opportunities, spur spin-off technology and strengthen the nation's leadership role in accelerator science. To remain at the competitive edge of these markets, the accelerator community must be willing to make improvements, both in accelerator technology and in the infrastructure in which these technologies are developed. The necessary improvements and R&D priorities are summarized in Fig. 1, taken from the report of the Accelerators for America's Future workshop.

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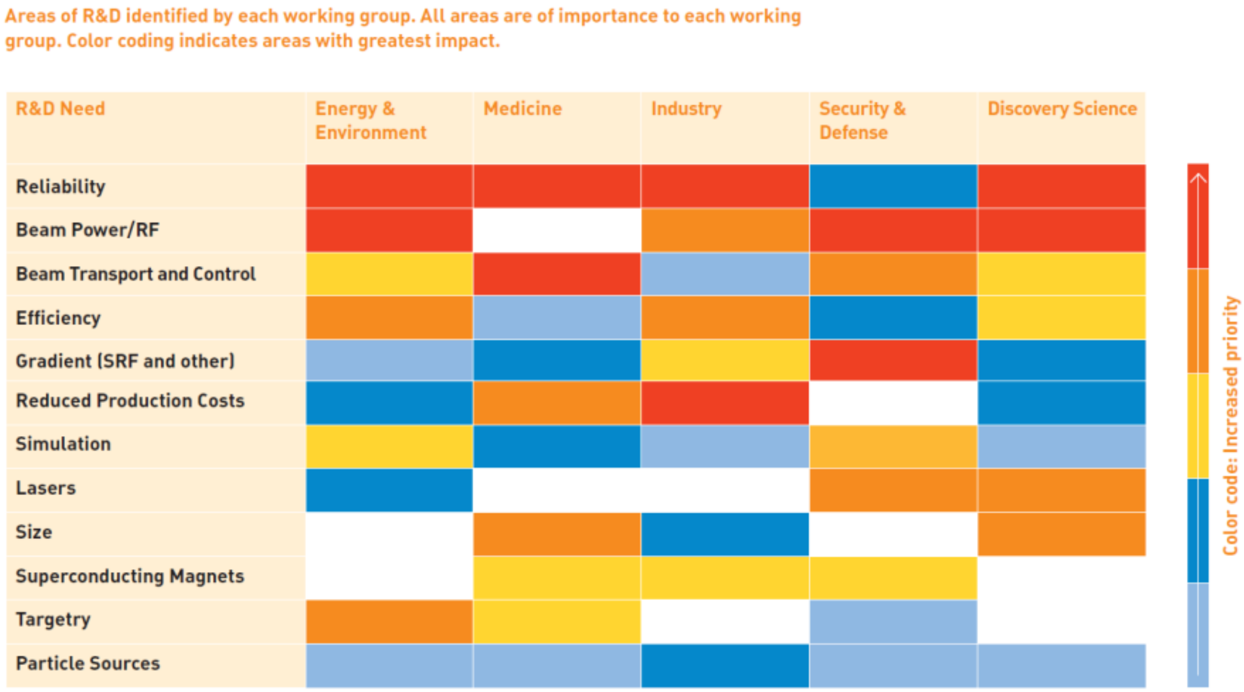
[1] An exception is the Office of Nuclear Physics to whom the stewardship of the nation's isotope production program has been given (see: http://science.energy.gov/np/research/idpra/ and http://science.energy.gov/~/media/np/nsac/pdf/docs/nsaci_ii_report.pdf). The development of systems for the production of isotopes is the responsibility of the Office of Nuclear Physics, which actively supports these efforts through two annual solicitations, the SBIR/STTR grants and funded programs at national laboratories. This is a possible model of how comparable challenges facing our nation in other areas where accelerators play a role could be pursued.

[2] Within NNSA and DOD (DARPA, DTRA and ONR), stewardship and development of specific technologies has been assigned.



Areas of R&D identified by each working group. All areas are of importance to each working group. Color coding indicates areas with greatest impact.

R&D Need	Energy & Environment	Medicine	Industry	Security & Defense	Discovery Science
Reliability	🟥	🟥	🟥	🟦	🟥
Beam Power/RF	🟥		🟧	🟥	🟥
Beam Transport and Control	🟨	🟥	▨	🟧	🟨
Efficiency	🟧	▨	🟧	🟦	🟨
Gradient (SRF and other)	▨	🟦	🟨	🟥	🟦
Reduced Production Costs	🟦	🟧	🟥		🟦
Simulation	🟨	🟦	▨	🟧	▨
Lasers	🟦			🟧	🟧
Size		🟧	🟦		🟧
Superconducting Magnets		🟨	🟨	🟨	
Targetry	🟧	🟨		▨	
Particle Sources	▨	▨	🟦	▨	▨

Color code: Increased priority

Fig. 1. R&D needs identified during the Accelerators for America's Future workshop in 2010, indicating the need then that arose in various applications that use accelerator technology. Courtesy: Accelerators for America's Future workshop report.

The Seven Grand Challenges

The core of the Office of Science's mission is science investigation. In order to address the "R&D Needs" (see Fig. 1) of partners whose work lies outside this science mission, such as industrial companies or other government agencies, a healthy relationship between the goal to deliver science and the need to solve particular technology challenges must be cultivated. Detailing the various facets of that relationship helps clarify how R&D partners in other fields draw from accelerator science.

We therefore describe how the science mission supports the "R&D Needs" listed in the first column of Fig. 1.

Because of accelerator science's positive impact on other fields, one of its broad goals is developing the technology and fundamental understanding of beams to deliver transformational capabilities to meet the needs of medicine, energy, the environment, defense and security, industry and discovery science in the 21st century. Indeed, accelerator science is a science in its own right, where development in the field is motivated by the desire of accelerator scientists to extend the state-of-the-art in technology and fundamental understanding of beams. We have summarized the long-term development of the field of accelerator science along seven Grand Challenges:

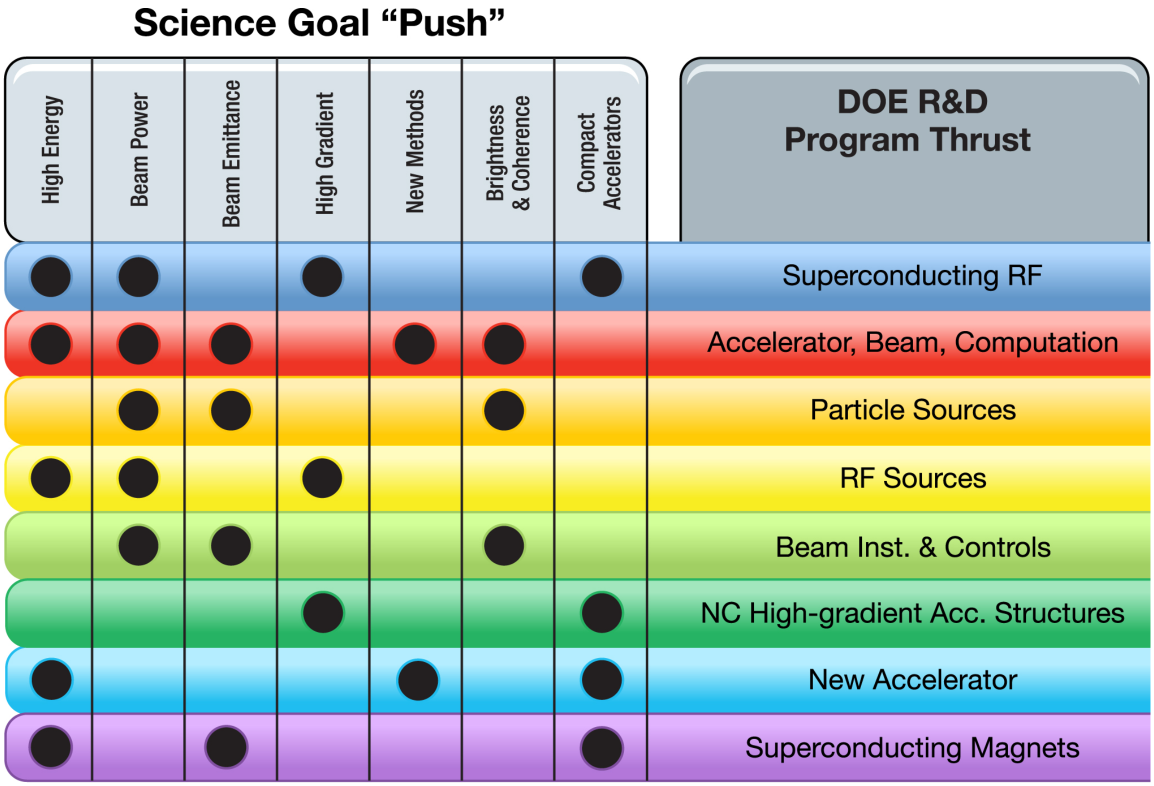
1. High Energy: Extend the energy reach of collider technology to probe fundamental phenomena at the multi-TeV scale
2. Beam Power: Extend the beam power and intensity reach of hadron accelerator technology to enable next-generation capabilities in fundamental physical sciences and applications in energy
3. High Gradient: Extend the capability and understanding of performance limits of radio-frequency accelerating structures and technology
4. New Acceleration Methods: Break the "radio-frequency barrier" by developing scalable next-generation acceleration methods in the 10 GeV/meter range
5. Beam Emittance: Develop tools and technologies for the manipulation of particle beam phase-space and the exploration of limitations to beam emittance
6. Brightness & Coherence: Develop concepts and technologies to extend the brightness, brilliance and coherence of photon sources to meet the challenges of 21st-century materials science
7. Compact Accelerators: Develop accelerator systems to serve as compact sources of photons, neutrons, protons and ions

HEP's Advanced Accelerator R&D program (including both national laboratories and universities) addresses each of the above challenges. Together with contributions from the other Offices (NP, BES, FES, ASCR), the NSF and the laboratories operated by the NNSA, the skills and resources exist to meet these Seven Grand Challenges.

The contributions of NSF, for example, connect to the challenges not only by R&D but also by promoting accelerator education, in particular when students pursue R&D projects on operating accelerators. In a similar way, programs operated under NNSA bring accelerator development to bear on the needs of defense. The larger science community can and does help bring the strength or needs of the nation to the forefront of accelerator R&D.

Among all the sponsors of the field, HEP retains a special role in stewarding the long-range R&D for accelerators and beams. Indeed, HEP manages by far the largest accelerator R&D portfolio, with a total yearly investment of approximately $160 million in FY11. This special role is fitting given the historical importance that high-energy physics has played in driving many of the significant leaps in technology and approach that are now utilized by many fields of science, medicine and industry. For these reasons, we discuss principally the organization and program management of accelerator science within HEP while keeping in mind that substantial capabilities exist elsewhere.

The management of the HEP accelerator R&D portfolio within HEP is presented in Fig. 2, which illustrates the coupling between these grand challenges and the R&D portfolio thrust areas, which are the programs that HEP is funding.



Science Goal "Push"

High Energy	Beam Power	Beam Emittance	High Gradient	New Methods	Brightness & Coherence	Compact Accelerators	DOE R&D Program Thrust
●	●		●			●	Superconducting RF
●	●	●		●	●		Accelerator, Beam, Computation
	●	●			●		Particle Sources
●	●		●				RF Sources
	●	●			●		Beam Inst. & Controls
			●			●	NC High-gradient Acc. Structures
●				●		●	New Accelerator
●		●				●	Superconducting Magnets

Fig. 2. The Office of Science spends approximately $160 million annually to support technology development in the "DOE R&D Program Thrust" areas shown at the right. They couple well to the technical solutions required for the next generation of accelerators to address the Seven Grand Challenges (upper left). Other agencies, especially NSF and NNSA, make major contributions to, or in some cases lead, initiatives relevant to the solution of the Grand Challenges. Universities also make technical contributions to these programs.

Connecting the Dots: Technology Developments Leading to Products

Through the development of the technologies under the DOE R&D Program Thrust areas, the DOE, NSF, NNSA and universities, as well as other agencies, are currently addressing many of the R&D needs listed in Fig. 1.

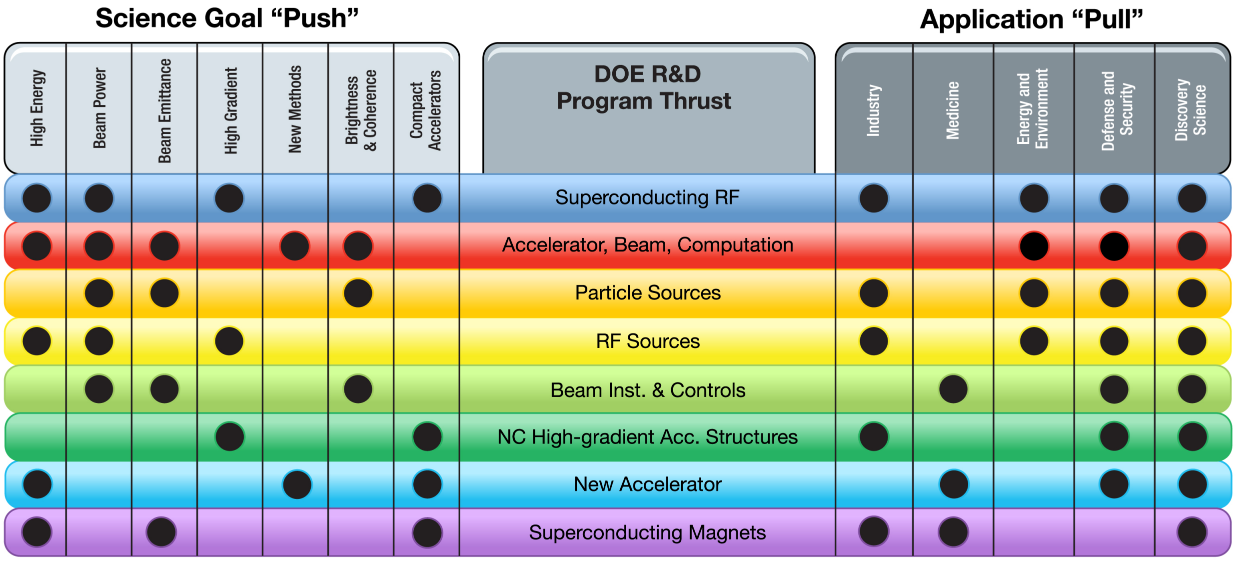
Yet at times these agencies' work to address these R&D needs goes unacknowledged because they are not a stated goal of the HEP accelerator program. The area of reliability in accelerators is one example (see Fig. 1). When designing high-power proton accelerators for spallation neutron sources or neutrino beams, accelerator builders must obviously design and build highly reliable systems. The components developed as highly reliable subsystems become a byproduct. Reliability, then, though often at the core of technology development, is thus a product of the R&D programs outlined in Fig. 2, not a program in itself. Many other examples could be mentioned.

It is of concern that many of the R&D needs listed in Fig. 1 are either inconsistently or not explicitly outlined in the nation's accelerator programs as technological goals. They become less emphasized, and researchers could eventually lose sight of them.

The unfortunate consequence is that our clients' R&D needs often go unidentified, leaving unanswered the question of how to close the gap between science "push" and application "pull". Delivering technology to those clients can become erratic and undirected.

Yet there is a strong, widespread base and a vast number of resources that could immediately be put into action to meet the needs of our partners if relationships are clarified and firm channels of communication and coordination are established.

Just as it is useful to outline the relationship between the Office of Science's science mission and accelerator R&D, as Fig. 2 does, it is also helpful to spell out how accelerator R&D benefits industry, medicine, energy, the environment and defense and security—that is, to show how accelerator R&D addresses needs beyond those of SC. This is illustrated in Fig. 3. A program that addresses these needs would not have to start from ground zero—there is a well-established foundation already. Indeed, accelerator science has a well-documented history of producing numerous technology spin-offs, some of which are described in a later chapter ("Changing the Landscape: Previously Successful Technology Transfer Examples"). It is important to understand how to build on this strength.



Science Goal "Push"								Application "Pull"				
High Energy	Beam Power	Beam Emittance	High Gradient	New Methods	Brightness & Coherence	Compact Accelerators	DOE R&D Program Thrust	Industry	Medicine	Energy and Environment	Defense and Security	Discovery Science
●	●		●			●	Superconducting RF	●		●	●	●
●	●	●		●	●		Accelerator, Beam, Computation			●	●	●
	●	●			●		Particle Sources	●		●	●	●
●	●		●				RF Sources	●		●	●	●
	●	●			●		Beam Inst. & Controls		●		●	●
			●			●	NC High-gradient Acc. Structures	●			●	●
●				●		●	New Accelerator		●		●	●
●		●				●	Superconducting Magnets	●	●			●

Fig. 3. This table zooms out from Fig. 2 to show how broad applications (right) benefit from advancements toward accelerator science's primary R&D goals, the Seven Grand Challenges (left). The DOE programmatic thrust areas, listed in the middle column, are the means by which progress in accelerator science can be delivered to fields outside discovery science.

The R&D needs identified in the Accelerators for America's Future workshop can largely be addressed within the existing program thrust areas. An optimized program would ensure that the application "pull" is fed back to the science "push" so that the application needs can be met in a more deliberate way. This circular flow would signify that our partners have a means for feeding back into both the science goals and the program thrusts. Such an arrangement would allow researchers to cater to their specific R&D needs, providing directed R&D to drive the development of accelerator technology to specific ends.

The following chapter is a discussion of a series of ideas and proposals that could promote this scheme from mere concept to action. By building out the various thrust areas or providing an effective mechanism for feedback, we can facilitate and establish a productive and useful cycle of accelerator R&D, closing the circle.

Immediate Actions on the Route to Success

The Accelerators for America's Future workshop identified a large number of opportunities that span the fields of energy and environment, medicine, industry, defense and security and discovery science. In addition, it identified specific R&D needs, from reliability to particle sources, that would have to be addressed to give a competitive edge to many of these applications. This chapter lists the major ideas to which a follow-up program could be directed and outlines areas where it would make sense for stakeholders to collaborate more effectively. Some of these proposals would have either immediate or short- and mid-term impact: these address points 2 and 4 of the charge to the Task Force (Appendix 1). The first few listed here really address the impediments, whose removal would allow for a very solid foundation for a successful program. Following the Accelerators for America's Future workshop layout, specific proposals are given in each of the core chapters, but the following points are highlighted here because their implementation would be transformational.

General observations

Encourage stakeholder engagement

- The Office of High Energy Physics (HEP), being the historical steward of long-term accelerator and accelerator-related research and development, could consider leading an accelerator working group, an oversight panel, a steering group or a Board of Stakeholders. This would involve intra-agency and interagency program managers as well as industry representatives and technical advisors in the area of accelerators.

A stakeholder panel would change the dynamics within the DOE R&D program because it would provide a venue in which the long-term R&D programs are steered with a "customer-focused" approach guided by the question: "What do the users of accelerators and accelerator R&D outside of discovery science need in order to be successful in their areas?" The working group could meet once or twice yearly and could be closely coordinated with NSF. It could be modeled after similar S&T workgroups within DOD that meet on a regular basis to leverage investments from many branches (for example, Army, Air Force, Navy, DTRA, DARPA). This new group would not control monetary portfolios but would advise HEP and other participating agencies on 1) avoiding duplication and 2) distributing workloads and activities to maximize relevance of the program, turnaround, and progress. Individuals from the following organizations might be considered for membership: the Air Force Research Laboratory, Army Research Laboratory, AFOSR, DARPA, DTRA, EPA, Naval Research Laboratory, NCI, NIH, NNSA, NSF, Office of Naval Research, and industry and academia. As observers and sounding boards, DHS, MDA, NASA and academia could be considered. Another option with the same integrating effect would be to have a yearly higher-level meeting among leaders of the various agencies supported by annual and special workshops where program directions would be discussed and fed back to HEP for consideration. Dissemination of the information is of course essential as part of the process. Similar ideas have been presented by previous panels related to accelerator R&D and seem to resonate with this new model of a more customer-oriented approach. With the fast-changing pace of research required in some agencies and in industry, such a panel would provide feedback quickly to redirect programs as quickly as appropriate.

Engage partners by communicating capabilities and streamlining access

- National laboratories, user facilities and other accelerator R&D facilities of the Office of Science would all benefit from more direct and open communication. This would include the development of simple user-friendly procedures to give customers (for example, other agencies and industry) access to national laboratory infrastructure (computing centers, test facilities, test stations and technology infrastructure) and, equally importantly, to expertise (people and results). This could include a provision to perform proprietary research, or at least research in access-controlled areas. In many cases the use of this infrastructure could be modeled after well-established principles for user facilities and could be represented by the National User Facility Organization (http://nufo.org/).

Several user facilities operated by the national laboratories and funded by the Office of Science have developed effective methods for allowing access to industry or other agencies. Basic Energy Sciences provides an excellent example that deals with a large variety of users and whose practices could be applied. Today, these methods are not implemented universally or even broadly. For many facilities, the process and practice of industry access could be significantly streamlined. A great deal of expertise and infrastructure is or could be of interest for industry and other agencies, but these customers have indicated that it takes too long to engage. Whether it is the reality of the situation or only a perception, the concern has to be effectively addressed in order to be able to engage in an effective working relationship. Various national laboratories proactively involve their technology transfer experts in a dialogue with industrial partners. This should become a general practice as part of an effort to streamline the process of involving industry. As one of the lab directors (E. Isaacs) who spoke with the task force said: “The real issue is to reach out to industry to let them know that we’ve changed and we’re ready to serve as real partners and build strong new relationships.”

Streamline processes to encourage partnerships with industry

- The Office of Science should work to identify, understand and resolve the concerns from industry and other agencies regarding protection of incoming and generated intellectual property or information. It would be useful to have, for this purpose and as a basis, a template applicable to all user facilities and infrastructures at Office of Science national laboratories. Such templates could cover all aspects of a contractual arrangement that is typically negotiated every time an arrangement is put in place.

An ongoing theme in discussions with potential industrial partners is the concern that intellectual property (IP) is not well protected in current collaboration vehicles (CRADAs, WFO agreements, accelerated-use permits, licenses). Protecting incoming IP is at least as important as protecting generated IP and, if carried out to the advantage of US companies, could provide the competitive advantage needed to stay ahead. The possible methods for doing this are diverse. They could include standardized agreements, establishment of access-controlled areas, even if they are set up temporarily to different indemnity provisions, smaller or no-advance-payment requirements, or even significantly decreasing the turnaround time during negotiations. Finally, having dedicated laboratory employees shepherd customers through these processes has proved to be very successful where applied. These topics would have to be addressed in dialogue with experts from other agencies, industry and the DOE.

Leverage the SBIR/STTF programs

- Leveraging the SBIR/STTR funding with a specific focus on energy and environment, medicine, industry and defense and security apart from discovery science could strengthen these parts of the program, providing an easy way to direct funding towards the topical areas identified in the Accelerators for America's Future workshop.

The existing SBIR/STTR program has successfully supported many areas of accelerator R&D and has helped small businesses both with startup funding to implement their new businesses and with access to expertise within the Office of Science laboratories. The Office of Science could consider a targeted approach with these above-listed areas in mind in the next few solicitations. The approach is especially attractive since no new funding is required, yet would still support the accelerator builders and potentially foster the establishment of new companies in this country.

Focus efforts by forming interdisciplinary teams to solve specific challenges

- The Office of Science HEP's wealth of knowledge and vast infrastructure could be channeled to establish Collaborative Accelerator Research Teams (CARTs) focused on specific challenges detailed in the Accelerators for America's Future workshop. HEP with its stewardship program and the other directorates through their national laboratories could direct their capabilities to tackle issues in the areas of energy and the environment, medicine, industry, defense and security and discovery science. The interdisciplinary Teams, drawing from national laboratories, other agencies, industry and universities, would have a clear mission, a limited duration and would be competitively bid.

Collaborative Accelerator Research Teams could be one way to address the many developments in accelerator R&D that must necessarily proceed at a rapid pace. Such a team, drawn from existing resources and focused on a clear mission, would have the capabilities to deliver on the issues in a timely way. National laboratories, academia, other agencies and industry with existing programs and specific expertise would naturally focus on the challenges that are closest to their core capabilities and could direct resources towards the goals set out in the competitive bid. Programs with an intentionally time-limited plan or layout would be measured against their deliverables and could be turned on and off as approaches show or fail to show success. This would be done in a manner that attempts to provide reasonable continuity in participants' careers. Such a process is well-established, for example under DARPA, and could translate well for an HEP-managed program.

Establish a program in applied accelerator technology

- The Office of Science could establish a program with the purpose of bringing industry, laboratories and universities together to foster the application of accelerator technology in energy and the environment, industry, medicine, defense and security and discovery science.

A program could address specific challenges discussed in the Accelerators for America's Future report. It would provide a specific funding line at the same time, similar to the other eight "DOE R&D Program Thrusts." Ensuring the relevance of HEP accelerator R&D activities and fulfilling the stewardship mission to meet the needs of stakeholders beyond discovery science require establishing the program explicitly to nurture applications of accelerator technology and to enhance technology transfer.

Ensure the accelerator workforce of tomorrow by expanding educational programs

- The particle accelerator workforce would significantly benefit from an extension and addition of education programs to what is currently available. Workforce development for particle accelerator R&D has traditionally been a major emphasis of the Office of Science, in particular at HEP, and of the NSF, in particular through the Physics Division. Though close contacts between universities and national laboratories exist, the Office of Science could help involve more universities in accelerator education programs. A greater integration with industry into educational programs would be beneficial.

While many students have been supported by various programs of the Office of Science and by NSF, in particular through the Physics Division's operation of university-based accelerators, recruiting offices at many laboratories still report a shortage of accelerator physicists and engineers whenever job postings appear. The NSF has provided an essential part of the US accelerator education at universities with operating accelerators. However, only six universities have accelerator education programs; more should be instituted. Because of the particular value from university programs where students are educated at an operating accelerator, it could therefore be effective to have new educational programs coordinate projects with existing university programs or national accelerator laboratories. Closer contact to industrial companies needs to be established, providing a natural path for students into industry. Cornell's program for co-op students in industry, the NSF's GOALI program, and the US Particle Accelerator School (USPAS) internship program are steps in this direction. These would provide an attractive student pool to draw from, particularly for small companies, because their time and monetary commitment is small, and a recruiting venue is already provided. Both USPAS and conferences will need continued support. Even funding a certain number of USPAS participants from selected companies is an option to be considered.

Specific technologies that will play a key role in the next decade

Explore opportunities for enabling the development of hadron therapy

- The medical community would benefit from a discussion of how the current R&D program could help on the route to National Resources for Hadron Beam Medical Facilities. The Office of Science could develop a stepwise implementation plan for providing beams, developing beams and beam delivery systems for a cost-efficient production of such facility.

Medical applications of accelerators include treatment either as a monotherapy or combined with surgery and/or chemotherapy. Over the last decade, proton therapy has been developed to the point that more than a dozen medical centers using it in the US are in operation or under construction. Other countries are building up this capability and US industry is successfully competing in this market. Light-ion beam applications are still in the development stage. The part of the medical community that is interested in the advantages of these beams is very active and involved in a graded approach to developing the technology, performing the clinical trials and eventually working through FDA licensing. The Office of Science can help in various ways through the adaptation of user facilities where existing accelerators are leveraged to provide beam time. New technology in this area will be the natural result.

Consider incorporating laser R&D for accelerator applications into the research portfolio

- The Office of Science could consider providing a home for laser R&D under its auspices. An enabling technology, lasers have become an integral part of accelerators and provide tremendous potential for new methods of acceleration, for miniaturization of accelerators and as part of accelerator systems.

Lasers are instrumental in every aspect of accelerator physics and application. They are used to generate and diagnose particle beams, to pump and probe matter and to act as a direct driver for advanced acceleration processes. As such they could become enabling tools for compact accelerators, for medical accelerators, for very high-gradient, high-energy accelerators and as drivers for a new generation of light sources or colliders. Today the fast development of lasers is largely driven by industry, defense and other applications, but the specific technological needs for lasers driving accelerators are rarely taken into account. A dedicated program as part of the accelerator R&D portfolio would cover all these aspects and integrate well with the needs in the areas of energy and the environment, medicine, industry, defense and security and discovery science, as well as with the needs of user facilities.

Changing the Landscape: Previously Successful Accelerator R&D Programs (M. Zisman)

Over the years, the High Energy Physics (HEP) Accelerator R&D program has enabled a number of successful spin-off activities. Some of these have happened in the natural course of performing HEP-related R&D and/or project construction. Other recent examples represent a more focused effort toward transfer of the technology to industry as a commercial product.

Examples of the former category include the development of superconducting accelerator magnets for the Tevatron, which in the 1980s provided a useful superconducting cable technology that strongly benefited the widespread commercial production of magnetic resonance imaging (MRI) magnets. The technology advances made in niobium titanium (NbTi) wire for the Tevatron enabled higher performance and lower cost in NMR and MRI wire, contributing strongly to the commercial growth of these markets. This is now a large, $4.5 billion/year industry worldwide, with $2.3 billion/year contributed from the North American market. Most large hospitals today have at least one MRI for diagnostics purposes. There are roughly 30 companies worldwide engaged in providing MRI systems commercially. Superconducting accelerator magnets have been industrialized in the sense that they can now be produced in industry, although the primary customer for such devices remains the discovery science community, which is mainly funded by the government at present.

Superconducting radio-frequency (SRF) cavities were first used for an accelerator at Stanford University's High Energy Physics Laboratory in the period from 1964–1981. In the US, the technology was further developed for nuclear physics at Argonne National Laboratory for ATLAS[3], the world's first superconducting heavy-ion linac, and developed for synchrotrons and recirculating linear accelerators at Cornell University[4] and Jefferson Laboratory[5], respectively. Jefferson Laboratory also provided the SRF technology used for the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. Although SRF technology has been under development—and in use in a research setting—for many decades, in terms of commercialization it is still a fledgling technology, currently motivated primarily by the desire to construct a large-scale linear electron-positron collider (the International Linear Collider) that would require roughly 16,000 such cavities and their ancillary components. Free-electron lasers based on SRF cavities are of interest both to the discovery science and defense communities, and several such devices have been built for testing purposes. Two US companies, AES and Niowave, currently offer to fabricate SRF cavities commercially. Key to their success will be the development of an ongoing market for such devices.

A more focused effort has taken place in the past decade to develop niobium-3 tin (Nb_3Sn) superconductors in partnership with industry. To date, the vast majority of superconducting magnets (both for accelerators and for MRI systems) have been based on NbTi superconductor,

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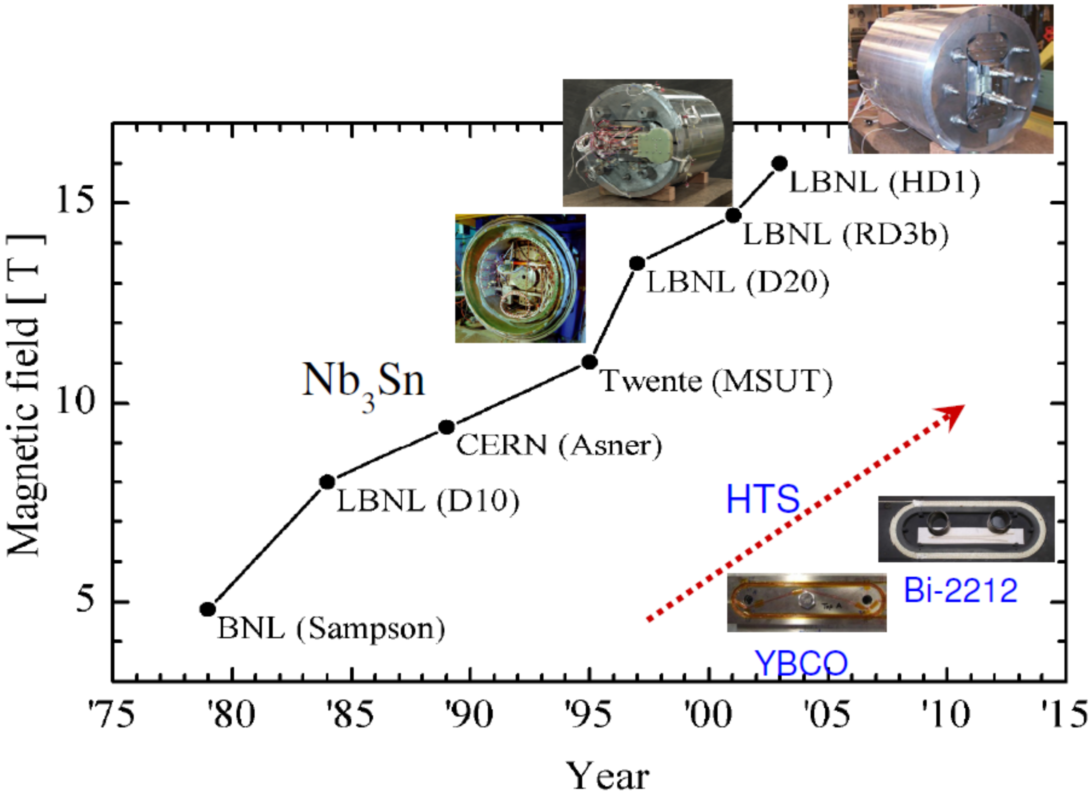
[3] Supported by Dept. of Energy Office of Nuclear Physics funding.
[4] Supported by National Science Foundation Particle Physics funding.
[5] Supported by Dept. of Energy Office of Nuclear Physics funding.

the technology developed for the Tevatron. The next generation of accelerators, particularly planned upgrades to the Large Hadron Collider (LHC) at CERN, will require higher magnetic fields than can be supported by NbTi conductor. Nb_3Sn, which has a higher critical field than NbTi, is the conductor of choice for this next generation of magnets. A proof-of-principle high-field magnet, "D20," was fabricated at Lawrence Berkeley National Laboratory (LBNL) in 1997 and reached a field of 13.5 T at a temperature of 1.8 K. However, this magnet was fabricated using a "brute force" approach based on low-performance conductor. Over the next several years, improvements in cable quality (see below) and fabrication techniques allowed further increases in field. Successor magnets, RD-3b (2001) and HD-1 (2003) reached 14.7 T and ~16 T, respectively, using improved conductor, albeit in simplified test configurations with no usable bore. A more recent dipole magnet, HD-2 (2009) was more realistic, in the sense of allowing clearance for a beam pipe, and nonetheless reached 14.5 T. Further optimization and testing are under way, with the goal of reaching the full potential of this design, namely 15 T at 4.5 K or 17 T at 1.9 K. Overall progress is illustrated in Fig. 4.



Fig, 4. Growth in magnetic field over development period (technological tests)

It was clear that improvements in the superconductor strand would be required to construct magnets suitable for use in a particle accelerator. Required improvements include raising the critical current density (J_c) to enable compact windings, reducing the effective filament size to reduce higher-order multipoles in the magnetic field and to minimize AC losses, and increasing the cryogenic conductivity of the strand matrix to maximize stability. To address these development needs, HEP organized the Conductor Development Group (CDG) in 2002 and funded it (see Table 1) with $500,000 per annum in its initial years. The great majority of these funds were used to pay for development of an engineering conductor in US industry. Such an investment is valuable to encourage industrial involvement, as it provides an initial "market" to spur (and fund) the development costs of a new product. The CDG is managed by LBNL with an advisory group whose members come from magnet groups at each of the national laboratories and from university grantees whose research supports conductor development. Advanced material from the program has been used to leverage magnet development in the HEP base program as well as in the LHC Accelerator Research Program (LARP). In complementary fashion, measurements and performance data from these "customer" programs are fed back to the industrial conductor developers via the CDG. The CDG benefits from economy of scale and helps to ensure that Nb_3Sn makes the transition to a practical engineering material. As is obvious from Table 1, the investments in both time and money are substantial.

Table 1. CDG and magnet development core program funding.

Year	CDG ($K)	LARP ($K)	Core Program ($K)
2002	500		7291
2003	500		6800
2004	500	163	6416
2005	500	606	7139
2006	200	2909	7223
2007	390	2782	7229
2008	296	3020	6961
2009	396	3171	6790
2010	1020	3367	6022
2011	585	3124	5972

A major success in the early years of the CDG program is that the J_c nearly doubled (at 4.2 K and 20 T) between 2000 and 2005 from 275 to 525 A/cm^2. During roughly the same time period, the effective filament diameter decreased by roughly 30%, from 70 to 50 μm.

The cryogenic conductivity of the strand matrix, as measured by the residual resistivity ratio (RRR, the ratio of the electrical resistance at room temperature to that at cryogenic temperature), has also been improved, but performance optimization requires balancing between improved RRR and improved J_c. For fields beyond those obtainable with Nb_3Sn, high-temperature superconductor materials offer promise, as they have a very high critical field when operated at 4 K, and are now being studied. A corresponding effort focused on conductor improvements has gotten under way.

(Most of the commercialization cost lies in the adaptation of accelerator R&D for commercial applications because, at present, the core content is optimized solely (or primarily) for discovery science. Commercialization costs could be reduced by having a more collaborative relationship with industry prior to and during the accelerator development process so that needs and requirements of other stakeholders are developed side-by-side with the discovery science element.)

From the above brief summary, two things are clear:

- The time scale from initial development of accelerator technologies to their commercialization can be lengthy, sometimes decades. Having a substantial market, as in the case of MRI development, can drastically reduce this interval.
- The investment required to ready an accelerator technology for commercialization can also be substantial, and must often be borne by government-supported accelerator R&D institutions.

Research Opportunities with Potential for Broad National Benefit

The next five major sections describe in detail the existing opportunities, or "R&D Needs," that were identified in the Accelerators for America's Future workshop, detailed Fig. 1, top row.

Energy and Environment (S. Henderson, F. Pilat)

Energy

As detailed in the Accelerators for America's Future report, there is tremendous, largely untapped potential to deploy accelerator technology for the nation's and world's energy problems. Particle accelerators could be used for the transmutation of nuclear waste, power generation and the breeding of fissile material for use in critical or subcritical reactor systems. Field-specific knowledge is prevalent and advanced in the US, yet the nation is rapidly losing ground to China, European nations and India in research leading to the deployment of accelerators for nuclear energy as there is no focused US effort. The report details potential uses of accelerator-driven systems, accelerator-based irradiation facilities, and fusion energy utilizing heavy-ion accelerators capable of igniting inertial-fusion targets for electric-power production.

US technology is driving accelerator-driven systems in other countries. Where ADS-related enabling technologies are concerned, the US is in the technological lead. The next obvious step is to connect the nation's technological capabilities with a dedicated energy program, closing the gap between know-how and application.

Should future priorities require the deployment of high-power proton accelerators for accelerator-driven systems or the construction of an irradiation facility, the US is in a strong position to do so.

What existing programs address energy and which can be leveraged?

Government programs for accelerator-based energy R&D exist but are fragmented. The DOE Office of Nuclear Energy previously addressed the topic of accelerator-driven systems (ADS) research, with a focus on nuclear waste transmutation, although the program was terminated in the early 2000s. Other offices within DOE have a stake in the topic of materials irradiation: the National Nuclear Security Administration (NNSA), the aforementioned Office of Nuclear Energy (NE), the Basic Energy Sciences (BES) program and the Fusion Energy Science (FES) program.

Between them these programs cover various but related areas of research, including nuclear power, waste and fuel cycle issues, materials for fusion reactors, materials for fission reactors, materials irradiation capability and the know-how for constructing a facility.

The capability for constructing a future materials irradiation facility derives from institutional high-power proton accelerator programs, such as the Los Alamos National Laboratory (LANL) linear accelerator and Materials Test Station and Oak Ridge National Laboratory's (ORNL) Spallation Neutron Source.

Future projects such as Fermilab's Project X R&D activities could also have capabilities for the construction of a materials irradiation facility.

Accelerator developments carried out for the above-mentioned current projects feed into the sort of R&D needed for ADS machines. A consortium of Virginia universities and industries is writing an initiative for a future ADS demo facility with Jefferson Lab at the helm. Texas A&M University is pursuing a Fission Technology Center. LANL is proposing a domestic irradiation facility, the Materials Test Station, which is presently seeking CD-1 approval.

DOE FES is running in FY12 a heavy-ion fusion program through Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory. It focuses on heavy-ion accelerators, sources and injectors, beam transport and targets. This last area in particular is one that carries extreme, severe technological challenges. In fact, the future focus of the program is likely to be directed towards identifying and addressing beam-target interaction issues. Therefore, there is an opportunity to coordinate driver linac R&D with HEP.

The needs of ADS are similar to those of materials irradiation. Researchers focusing on accelerator and target technology for ADS will at the same time move irradiation facility R&D forward.

Yet despite the evident relationship of these research topics and the already-existing infrastructure for cooperation between and among these establishments, there is no coherent US program that pursues accelerator R&D for addressing the nation's energy needs.

It should be noted that the US is not participating in the International Fusion Materials Irradiation Facility (IFMIF) that is currently under way in the Broader Approach agreement between the EU and Japan.

What is the connection to the private sector?

A few firms and some venture capitalists are active in their pursuit of ADS and thorium energy. Aker Solutions, for example, has developed a conceptual design of an accelerator-driven thorium reactor. Other firms are actively watching the ADS situation, in particular the development of the US's policy directions regarding management of spent fuel.

What technical difficulties need to be overcome?

ADS

An accelerator-driven system refers to a nuclear reactor system in which a high-power proton accelerator is coupled to subcritical core to produce electrical power and/or transmute nuclear waste. Unlike a critical nuclear reactor, where each fission of a uranium 235 nucleus generates a new neutron that then splits the next nucleus, an ADS subcritical nuclear reactor generates neutrons from a particle accelerator. This neutron supply, external to the reactor, allows the reactor core to be designed so that it remains below criticality at all times. As a result, a subcritical reactor offers potentially enhanced safety. Moreover, ADS systems offer great flexibility with respect to fuels. An ADS can burn fuels that would be difficult to incorporate in a critical core, such as pure minor actinides, which are among the most problematic components of spent nuclear fuel. As a further advantage, it can also make use of thorium, for which the spent fuel generates far fewer problematic or long-lived isotopes than uranium.

ADS accelerator technology R&D opportunities

A working group was commissioned by the DOE Office of Science through the Office of High Energy Physics in 2010 to assess the technological readiness of accelerator and spallation target technology for energy production and waste transmutation. It concluded that the technology is ready for demonstration, but industrial scale deployment requires further R&D.

To demonstrate the potential and viability of ADS, researchers must make advances in front-end injector systems, superconducting radio-frequency (SRF) cavity technology, beam dynamics, beam instrumentation and reliability.

The front end of an accelerator is one of its most challenging systems, as it must produce a high-quality beam of very high intensity with high reliability. Necessary advancements in front-end systems include long-term demonstration at high continuous-wave power levels with assessment of reliability and availability, and construction and operation of an ADS plant-level accelerator front end. It also includes further research in beam delivery, including matching beam quality, minimizing halo growth, exploring beam collimation schemes, and demonstrating fast beam switching capability from a hot-spare front end.

Advancing SRF cavity technology is also critical for ADS research. Researchers must demonstrate, with beam, robust cavity designs for all beam velocities. They must develop and experimentally verify fast beam trip recovery techniques. SRF development also requires robust coupler and fast-tuner technology as well as improvements in cleaning and processing techniques for low-frequency elliptical and spoke cavities. For it to be economically competitive, researchers must also develop reliable low-cost radio-frequency power sources.

Another priority area for ADS is beam dynamics. This involves modeling beam loss and halo mechanisms, benchmarking beam loss and halo models with actual accelerator performance, and designing a superconducting linear accelerator lattice for maximum fault tolerance.

ADS systems must operate with very high reliability to minimize thermal stress and fatigue in the subcritical reactor core. Therefore, reliability of accelerator components and systems is a dedicated pursuit that is critical to future deployment of ADS systems.

This requires conducting analyses of beam trip data in existing prototypical accelerators and developing and deploying rapid fault recovery schemes in existing SRF linear accelerators, as well as system-level reliability engineering studies.

ADS target technology R&D opportunities

The work that goes into developing a target for a particle beam is every bit as crucial as that of the particle beam itself. Further research is needed in both liquid and solid targets.

Regardless of the target material, scientists and engineers must test numerous aspects of the target and its associated systems. These include subscale heat transfer and flow tests at operating temperatures; full-scale tests at operating temperatures; off-normal safety system testing; natural convection testing for decay heat removal; component tests under operating and off-normal conditions; and remote-handling development component tests.

For effective operation, researchers must also develop several components and techniques for target R&D. Part of this development involves higher frequency, redundant and fail-safe raster power supplies and magnets with telescopic image magnification (2 to 4 times magnification) for uniform circular beam spots. They must also develop real-time, non-destructive beam imaging for 10- to 100-mA beams. Development also involves large-scale simulations to come up with detailed criteria for beam-trip recovery scenarios, helping to minimize damage to a liquid target or to a solid or liquid fuel containment vessel.

Areas for further examination include integral cooling for the target and the subcritical blanket via a single loop and the interface between the target and the accelerator and subcritical blanket.

Liquid metal targets

A major concern of liquid metal targets is the corrosion of steel when it makes contact with a liquid metal target, in particular when utilizing liquid lead-bismuth eutectic alloy (LBE). One way to keep corrosion at bay is to control the oxygen in the LBE environment. A number of out-of-beam LBE loops with oxygen control exist today that can be used to further develop appropriate operating conditions that limit corrosion of steels in contact with LBE. To advance liquid metal target research, researchers will need to test these loops, augmenting such tests with one or more long-term in-beam tests.

Another way to limit corrosion of steels that come into contact with LBE is to investigate and develop LBE cleanup chemistry techniques.

The problem of removing highly radiotoxic polonium from an LBE loop is an important area of study. Researchers have examined several techniques for extracting the element from the liquid target metal. To support safety analyses, scientists must measure polonium release fractions from LBE as a function of LBE temperature and concentration of trace contaminants.

It will be important to mitigate risk resulting from any spallation target plate fragments that make their way into the circulating liquid metal system, for example, the piping, heat exchanger(s) or filters. This occurrence is likely with a liquid metal target, and researchers should investigate its impact on personnel dose, different ways to ensure RAMI (Reliability, Availability, Maintainability and Inspectability) and ways to mitigate adverse consequences.

Related to this, target developers will also have to create criteria, verified by testing, required for safe and reliable operation of a windowless (LBE) liquid target.

Solid targets

While liquid metal targets have several benefits for high-power density compact applications, solid targets have their own benefits, the primary of which is that its radioactive spallation products are generally confined to the solid target material and are localized in the target proper. Solid target options should be evaluated and their performance and environmental, safety and health characteristics compared to those of liquid metal targets. Carrying along a solid-target option at the early stages of ADS conceptual design, if warranted by comparative studies, can reduce programmatic risk.

Heavy-ion fusion

The possibility of utilizing heavy-ion accelerators to ignite inertial-fusion targets for electric-power production motivates worldwide research activities for heavy-ion fusion. Two principal ingredients are required: a heavy-ion driver accelerator capable of producing extremely intense pulses of heavy-ion particles and an appropriate nuclear fuel target.

To advance heavy-ion fusion applications, researchers will need to develop high-brightness heavy-ion injectors, capable of delivering approximately 1 A of current (if singly ionized). They will also have to develop reliable, high-field transverse focusing lenses, including solenoid magnets, magnetic quadrupoles and electrostatic quadrupoles.

Eliminating beam instabilities is essential for producing a reliable, steady beam. Research on electron clouds and beam background-gas interactions is essential to ensuring beam stability. An extremely important topic of research is the compression of beam bunches into very short and very small beams.

What research results from existing programs will be relevant for the next few years for energy?

The continued development of high-power proton accelerators for programs in BES, NP and HEP addresses some of the needs in ADS and irradiation R&D, and several of the needs can be addressed with existing infrastructure and at operating facilities such as Brookhaven National Laboratory, Fermilab, Jefferson Lab's CEBAF and Oak Ridge's SNS.

To address these needs, researchers are developing and improving liquid metal target systems and improving rapid fault recovery at operating superconducting linacs. They are also developing and demonstrating specialized beam diagnostics and instrumentation for high-power beams.

Heavy-ion fusion experimental programs will be carried out at NDCX-II at Lawrence Berkeley National Laboratory and perhaps at FAIR at GSI in Germany.

What investments in the existing infrastructure would be necessary?

The operating lifetime of a nuclear reactor depends in large part on its structural materials being able to withstand neutron bombardment. Developing radiation-hard materials requires test facilities for developing materials for the reactor structure and for the fuel itself. Facilities with sufficient neutron fluxes do not exist.

As noted above, front-end technology demonstrations can make use of existing facilities at the LANL Low-Energy Demonstration Accelerator, or LEDA. The operating superconducting linacs at the Spallation Neutron Source at ORNL and Jefferson Lab's CEBAF accelerator are well suited for research in rapid beam fault recovery. Current laboratories could also be used to benchmark intense beam dynamics and demonstrate specialized beam diagnostics and instrumentation for high-power beams.

What new infrastructure would need to be built?

Taking advantage of the current knowledge base of ADS and materials irradiation will require new facilities to test and demonstrate accelerator technology.

The community developing ADS technology would benefit from a front-end test demonstration facility to progress towards continuous operation with high power, high reliability, and rapid recovery. A facility to test transmutation concepts and transmutation-relevant physics, such as that currently envisioned at J-PARC in Japan, would require a modest upgrade to an existing facility, either in the future or at a currently operating facility such as ORNL's Spallation Neutron Source or the LANL linear accelerator. Establishing a target test facility at a high-power proton accelerator would require a modest addition to an existing high-power accelerator facility with a target hall.

Serious pursuit of ADS development would ultimately require building a high-power proton facility to work with a subcritical core, such as that planned to be built for the MYRRHA program in Belgium. The investment here would be on the order of a billion dollars. US participation in the MYRRHA program would represent a significant step in the right direction. ORNL's second target station at the Spallation Neutron Source could also serve irradiation needs.

A major step toward advancing materials irradiation research would be to build a megawatt-class irradiation facility. The knowledge and capabilities for building such a facility exist—one could be built now. To build the proposed fusion-relevant IFMIF, which would push at the boundaries of what is ultimately possible, requires a demonstration both of very high-current deuteron beams as and of a target proof of principle.

What interagency barriers exist that are specific to energy?

The primary barrier to executing a successful accelerator-based energy plan is a lack of cohesiveness and focus. Many players inside and outside DOE have a say in the aforementioned applications, but there is no clear owner or champion for accelerator technology developments or for applications for energy. A few DOE offices, such as FES and NE, have their high-priority commitments set with projects such as ITER or conventional reactor work, hindering active pursuit of accelerator-based energy and energy applications.

Environment

The effectiveness and efficiency of electron particle beam technology to clean up the environment have been demonstrated in a number of applications. It has been proven to be effective for flue gas emission treatment, primarily in the removal of sulfur oxides and nitrogen oxides. It has also been shown to be beneficial for treatment of drinking water, wastewater, and ultrapure water for industry. In addition, electron beams have been shown to be useful for the remediation of soils and sewage sludge.

The potential for new applications of electron beams to tackle environmental challenges is there. For example, electron beams could be used to remove organic compounds and polycyclic aromatic hydrocarbons, which are products of waste incineration. They could also be used to remove pharmaceuticals from the water supply and mercury from coal-fired boilers.

The greatest advantage of using electron beams to treat waste and contaminants is its efficiency, measured to be at least 80%. Higher efficiency, of course, leads to less power consumption. It's worth noting that the processing and transport of water uses approximately 20% of all electricity spent in the US, so the potential for energy-saving is high.

The great need for high-intensity, high-power, high-reliability and high-efficiency electron accelerators is evident.

What existing programs address the environment?

Both pilot plants and industrial plants are available and operating in Asia and Europe. Their programs could easily be adapted for an environmental program in the US, which lags behind the rest of the world in this area.

Japan developed electron accelerators for flue gas treatment in the 1970s. Since then, pilot plants have sprung up in that nation as well as in Bulgaria, Germany, Korea and Poland.

Radioisotope sources, primarily cobalt-60 and cesium-137, have been used for environmental applications, but the tool of choice is electron accelerators in the energy ranges of 0.5 to 10 MeV, typically 0.5 to 5 MeV for treatment of gases and water, and 5 to 10 MeV for solid waste.

Bulgaria's Maritsa East thermal power plant uses three 30-kilowatt, 800-keV electron accelerators to treat sulfur oxide gases emitted from coal combustion. The plant removes the gases with an efficiency of between 87 and 97 percent. Poland has a similar facility in Kaweczin, whose power station has 2 electron accelerators, each operating at 50 kilowatts and 700 keV.

Larger, industrial-scale plants are also doing their part to clean up emissions. The power station in Pomorzany, Poland, uses a megawatt of power to treat 270,000 cubic meters of flue gas per hour. It removes sulfur oxides with 95% efficiency and nitrogen oxides with 70% efficiency. One byproduct of this process is high-quality fertilizer. In Chengdu, China, a megawatt-scale electron beam accelerator is also used to treat flue gas. Its total investment is roughly $11 million.

Industrial-scale plants can also be used to treat wastewater. The plant in Daegu, Korea, began as a pilot plant and has undergone reconstruction to run at 400 kilowatts. It treats textile-dyeing wastewater. The total investment in the plant lies between $4 million and $4.5 million.

Electron beams are useful for treating solid waste and sewage sludge—the waste yield after the second stage of wastewater treatment. The product, fertilizer, is made by irradiation in a process approved by the EPA. A plant in Vadodara, India is used for such a purpose.

The common accelerator types accelerate the electrons using either a steady electric field (DC power) or a linear accelerator (radio-frequency power).

What technical difficulties need to be overcome?

Current technological challenges lie in increasing accelerator power and efficiency and in reducing costs. Though accelerators produced by and used in industry already routinely achieve the required performance—beam energies of between 0.8 and 10 MeV and beam powers of between 0.4 and ~2 MW—more should be done to reduce the price and operating costs to be competitive with existing non-accelerator-based processes. This means that R&D should be directed towards generating higher intensities, higher power, greater reliability and greater efficiency for accelerators. The goal is to achieve reliability, performance and cost at the level of a conventional scrubber (flue gas treatment) or chemical and biological water treatment systems.

As with the R&D proposed for energy applications, a vigorous program in SRF technology can be leveraged towards environment applications. For example, a continuous-wave superconducting linear accelerator operating at 4.5 K—the present RF technology requires operations at 2 K and more expensive cryogenic plants—will lead to simpler and cheaper cryogenic plants and lower operating costs. Once such a facility is achievable, it could be commercialized and used by industry.

What new infrastructure would need to be built?

There are virtually no large-scale operating accelerator-based environmental systems in the US. The best way to focus resources towards a program for the use of accelerators for the environment would be one or more joint ventures (or Collaborative Accelerator Research Teams; see Executive Summary) between accelerator industries, water and power companies, universities and government agencies such as the Department of Energy and the Environmental Protection Agency. These could lead the planning process and eventually develop a demo facility leading to a full-scale plant.

Several existing regional joint ventures could serve as models. Jefferson Laboratory, for example, has taken the lead in establishing the Hampton Roads Energy Corridor to develop a variety of long-term sustainable power options for the region's facilities. The partnership includes the State of Virginia, regional universities and industries, utilities companies, the Army, Air Force and the Navy.

What interagency barriers exist that are specific to the environment?

There is a large potential market for accelerators for the environment, yet interagency barriers could prevent or slow its growth. As mentioned in the first half of this chapter, the effort to pursue accelerator R&D for the environment is highly fragmented, a situation that is only made more severe by the complex regulatory framework that governs agencies and by minimal interagency communication.

Though HEP is the natural overseer of long-term accelerator-based research, there is very little overlap between its current program and research thrusts for radiation processing of flue gases and water.

Agencies' aversion to taking risks in developing better accelerators for environmental application, instead relying on established conventional methods, is another inhibiting factor to developing a forward-looking accelerator-based program for the environment.

What future demonstration or technology projects for the environment are possible?

Industry produces accelerators for existing applications for the environment. However, large-scale deployment of this technology will require further development with an emphasis on higher beam power, higher electrical efficiency and lower capital costs. In particular, high-power, high-reliability and cost-effective radio-frequency electron linacs have great potential to widen the environmental applications. National laboratories with experience and existing infrastructures in superconducting radio-frequency technology are natural R&D centers for irradiation and environmental applications.

Medicine (L. Boeh, J. Clayton, S. Gourlay, G. Zdasiuk)

Particle accelerators in the field of medicine are used for imaging, diagnosis, radiation therapy and developing pharmaceuticals. As the Accelerators for America's Future report outlines, the greatest needs for accelerators in medicine lie in radioisotope production and particle beam therapy. Advances in these areas require new facilities, proof-of-principle demonstrations and substantial technological development, not to mention initiative on the part of accelerator researchers to address the needs and demands of both the medical industry and medical practitioners. Though there is an approximately $5 billion/year market for accelerators in medicine, their widespread use is severely constrained by the large size and prohibitive cost of accelerator facilities.

In 2008 the Office of Nuclear Physics (NP) assumed the stewardship role for a national isotope production program, noting the nation's need for a secure supply of radioisotopes. Today NP operates this program successfully through various initiatives. One of these initiatives is the National Isotope Development Center (NIDC), which interfaces with the user community and manages the coordination of isotope production across facilities and business operations involved in the production, sale and distribution of isotopes. A virtual center, the NIDC is funded by the Isotope Development and Production for Research and Applications subprogram of NP in the DOE Office of Science.

In the case of particle beam therapy, the demand is high and mostly unmet. Estimates suggest that of those that receive conventional x-ray therapy, approximately 15% would significantly benefit from particle therapy (12% with protons and 3% with heavier ions). For the US this is more than 100,000 patients per year. Currently only 4000 patients per year in the US are treated with protons and none with heavier ions. As accelerator technology improves and becomes more practical, hospitals and clinics will not only be able to better afford them, but the quality of patient care and outcomes should improve.

Currently the main thrusts in particle therapy are in two complementary directions. The first is towards compact, relatively low-cost, proton-only treatment centers that could provide the majority of particle therapy treatments. The second is towards large multi-room centers that would provide the most advanced treatments.

There are a number of significant challenges. This is a partial list:

1. Developing technology to reduce the costs of construction and operation, reducing the installation time and improving the ease of operation. This is of great importance for single-room facilities.
2. Treating moving organs. The goal is fully adaptive therapy that includes real-time dose detection, real-time tumor monitoring, and accelerator and delivery systems that can quickly adjust the beam energy and positions so that the radiation dose is delivered to the right place at the right time.

3. Reducing the size and improving the functionality of accelerators. This is particularly true for light ions where at present the only option for light ions are conventional synchrotrons.
4. Reducing the size and improving the functionality of gantries (rotatable delivery systems). Gantries are the largest structures in a particle beam therapy facility.
5. Improved understanding of the biological mechanisms to fully exploit particle beams.

The US has extensive resources to realize the medical potential of current accelerator technology that can be brought to bear on biological studies and clinical trials, development of imaging technologies, exploring scanning technologies, experiments with a range of ions and development of patient protocol. Through access to existing beam facilities, many of these initiatives could start today without major investment.

What existing programs address medical applications and which can be leveraged?

SLAC National Accelerator Laboratory and Los Alamos National Laboratory (LANL), equipped with electron linear accelerators, have contributed significantly to the development of x-ray radiotherapy. This technology can also be used to further imaging and diagnostic research.

There is growing use worldwide of proton machines for cancer therapy. There are approximately 10 proton facilities now in the US with several more in the planning and construction stages. Underpinning the improvements in accelerator technology is the concurrent need for improving the understanding of the biological mechanisms to fully exploit particle beams. At Brookhaven National Laboratory's (BNL) NASA Space Radiation Laboratory, protons are used for animal and tissue studies for radiobiology effectiveness. Cyclotrons at Lawrence Berkeley National Laboratory (LBNL) and Michigan State University could be used for biological studies and development of dosimetry and imaging techniques.

Superconducting magnet programs at BNL, Fermilab and LBNL, have technology that could easily be applied to developing compact beam delivery systems.

The Argonne Tandem Linear Accelerator System (ATLAS) produces ions from 7–17 MeV per nucleon and could possibly be used for medically related biological studies.

Laser plasma accelerators have unique properties that may be exploited in a number of medical-related areas. Resources at BNL, LBNL, SLAC and UCLA and a laser plasma proton facility at LANL could be made available to develop advanced modalities for medicine.

Another alternative technique, the dielectric wall accelerator, being developed at Livermore National Laboratory, has potential in the longer term for very compact proton sources.

BNL's Microbeam Radiation Therapy facility provides a practical tool for beginning investigations into targeting tumors, attacking cancerous tissue while helping to preserve healthy tissue. The facility could be made available to medical researchers, physicians and patients.

BNL, Fermilab and LBNL all have invested in research in non-scaling fixed-field alternating-gradient (NS-FFAG) accelerators, a technology that could drastically reduce the scale and expense of equipment used for particle beam therapy, particularly in the gantries and associated magnets. LBNL has investigated the use of superconducting magnets that can significantly reduce the weight and size of gantry systems.

What technical difficulties need to be overcome?

Near-term advancements

The efficiency of beam delivery is kept low by energy degraders, or blocks placed in the beam path to reduce its energy to a prescribed level. A good deal of current is wasted in energy degraders, but the loss of current could be minimized with more efficient materials and better beam transport strategies. Efficiency would be further improved with the elimination of energy degraders altogether, which necessarily lead to scattering, beam emittance increases and energy spreads. Replacing the energy degrader with a new technology or developing a technology that could obviate it requires new accelerator designs, a more-future R&D goal.

There is also a need for multi-ion source development and mixed-ion sources (for example, lithium or carbon) for multi-species therapy as well as radioactive beams for imaging (i.e., PET).

Effective diagnosis depends a great deal on clear imaging. One way to achieve this is to aim for smaller focal spots. Yet another is to deliver x-rays at a higher rate than what's possible now. The technological cost of delivering more beams to achieve clearer images, however, is the target's mechanical stress, heat dissipation and material fatigue. Thus, researchers must also put effort towards developing materials that can withstand more and more intense particle beams.

It's helpful to be able to image precisely and know a target's composition. Medicine would benefit from techniques that could determine a material's electron density and its atomic number more precisely. This is especially important for systems that use protons or carbon ions as the treatment particle.

Medium-term advancements

The medium-term needs for technological advancement in medicine relate to the development of monochromatic sources, radiotherapy, and finding ways to cut through sizeable and complicated systems of patient scanning.

One area for improving patient treatment precision is targeting the treatment volume with beam. X-ray machines use a broad spectrum of energies. Monochromatic beams allow better imaging as the scattering effects can be more accurately estimated. For example, their elemental absorption edges can be identified more easily with monochromatic sources.

Microbeam therapy shows great promise by treating tumors and regions with alternating thin sheets of very high dosage and low-dose regions. It is thought that this allows the affected healthy tissue to regenerate with less morbidity. With more research, microbeam therapy may be shown to work for cancerous tissue in humans, potentially a significant breakthrough in cancer treatment. Synchrotrons could be made available for this type of research.

A formidable challenge to developing accelerators for medicine is designing them to be smaller and simpler. Reducing the cost by building room-sized accelerators that cost a fraction of the price of a typical multi-gantry proton therapy center would go a long way towards making these technologies available to more patients. This would also reduce the financial burden for health care providers.

There are several alternatives that could be explored for improvements in accelerator technology: high-field isochronous cyclotrons for single room facilities, cyclinacs for protons and carbon and rapid-cycling synchrotrons.

Developing technologies in superconducting magnets and multiple-function magnets could help reduce the size of treatment rooms and bring this beam-directing network to a more compact scale, saving significant costs at the same time.

Long-term advancements

Technical challenges that will require the most time and energy are the development of newer accelerator designs, namely NS-FFAG accelerators cyclinacs, dielectric wall accelerators and laser-driven systems. Rapid energy selection should be a common goal of any future technology.

In order to realize the full potential of laser-based systems, there must be a concurrent program in high-average-power, short-pulse lasers.

Developing NS-FFAGs should be a long-term priority as they are promising for use in proton therapy and ion therapy. Beams can be extracted and redirected prior to delivery through the gantry, so allowing the gantry to be smaller. However, though researchers have been developing the enabling technology, no NS-FFAG system exists in the US today.

Another priority is advancing research in laser-driven accelerator systems for photons, electrons and ions in order to bring a diverse array of therapy treatments to patients optimized for their needs. Laser-driven systems have the potential for new scanning techniques, real-time dosimetry and image-guided particle therapy.

What investments in the existing infrastructure would be necessary?

Stronger connections between accelerator R&D and radiobiology research are needed to more effectively direct progress made in the area of radiobiological effectiveness.

In the same way, accelerator R&D and MRI-related studies would each benefit from a stronger link between the two. A magnetic resonance imaging machine working together with linear-accelerator-delivered beam could help track a tumor in real time, facilitating the targeting of unhealthy tissue. While commercial companies are beginning to examine this combination, and a few academic researchers worldwide are investigating the possibility, the practical complexities remain significant, suggesting the need for an innovative breakthrough.

What new infrastructure would need to be built?

There is no focused national program for laser-driven accelerators. If created, the program could focus on developing high-average- and high-peak-power accelerators with high efficiency and high-power optics.

The ideal platform is a fully operational accelerator-based medical research facility, providing protons up through carbon ions. Financing could be accomplished through a combination of government and public funds or through a cost-shared public-private partnership. Operations would be government-funded. The facility or facilities (perhaps one on each coast) would host clinical trials, offer patient treatment using protons initially, and conduct radiobiology studies along with accelerator and imaging R&D to continually improve the technology. The role of the DOE would initially be to help integrate the accelerator design and later to provide technology that would aid such a facility in exploiting the full potential of particle therapy.

BNL is now in Phase 2 of a CRADA with Best Medical International (BMI) to develop and build a rapid cycling synchrotron, the ion Rapidly Cycling Medical Synchrotron (iRCMS) that will produce spot-scanning beams of protons in the conventional manner and a carbon beam that will paint a complete spread-out Bragg peak in a longitudinal column at a given transverse position. It will be the first therapy machine in the US capable of delivering light ions for cancer therapy and is expected to provide more controlled dose delivery than is available presently from machines in Japan and Germany.

What interagency barriers exist that are specific to medical applications?

Advancing accelerator-based research for medicine will require an unprecedented level of cooperation among all stakeholders—government agencies, health care providers, laboratories and industry. Legal restrictions, aversion to risk and intellectual property issues on all sides currently hamper successful cooperation between and among these potential partners.

The cost of accelerator projects in medicine is so high—currently in the range of $25 million–$200 million—that very few industrial companies can totally absorb the R&D cost as well as the technology risk.

Research risks with larger potential rewards also need to be shared between labs, industry and the DOE. These include areas such as carbon therapy, which is not currently pursued in the US, and radiobiological effectiveness studies. Despite their scientific merit, new ideas involving carbon, heavier ions and multiple species of beams are often underfunded because of a lack of coordination.

There is some precedent and success for cooperation among the various sectors of society to advance high-level technology. The National Institutes of Health Academic Industrial Partnership is one example. This partnership helps mitigate risk and promotes collaboration by treating partners as equals.

What are some examples of successful medical applications?

The LBNL heavy-ion program developed technology that was picked up by Japan (HIMAC) and Germany.

Fermilab, LBNL and Loma Linda collaborated on the first proton therapy facility in the US.

The side-coupled standing-wave linear accelerator, originally developed by Los Alamos National Labs, now forms the basis of the majority of accelerator-based treatment systems today, treating over 100,000 patients every day.

Industry (R. Hamm, S. Ozaki, L. Merminga)

Industry is both a manufacturer and a consumer of particle accelerators. Companies use electron beam accelerators to modify material properties, for example, to cross-link polymers or to treat surfaces and destroy pathogens for the food, pharmaceutical and medical devices sectors. Ion beam accelerators are extensively used in the semiconductor manufacturing industries and in the manufacture of radioisotopes and micropore filters. They are also used in the medical industry to harden the surfaces of materials used in making artificial joints. The majority of electron and ion beam accelerators are produced by industry.

A new class of accelerators—superconducting radio-frequency (SRF) accelerators—is now used primarily in research and defense, but should soon find uses in industrial applications.

The Accelerators for America's Future report notes how federal resources could help the accelerator development program in industry. Funds would boost the development of new and existing industrial applications, encouraging the replacement of inefficient and environmentally harmful processes with greener electron beam or x-ray processes. Increased DOE engagement to create national centers of expertise and university programs could result in training grounds and nexuses of education in the areas of accelerator technology, which in turn would be valuable to industry. The establishment of large-scale, industry-friendly user facilities could help confirm the practical aspects of accelerator technologies for environmental applications. A federal education campaign for the public would also get the word out about the many benefits of accelerator technology.

There are two factors that slow the growth of accelerator technology in industry. One is a lack of R&D resources for small companies that need a way to address their research needs while developing and protecting their intellectual property. The DOE could connect with small companies in these areas by engaging in technology exchanges that might take the form of workshops or regular interactions with industry. The second is that potential customers perceive a great risk in switching from existing manufacturing or processing methods to accelerator-based technologies. The government could provide support through user facilities and demonstration sites to help establish the value of accelerators in saving energy and preserving the environment.

The impact of accelerator technology applications in industry is significant. Approximately 75 vendors worldwide produce particle accelerators. These vendors are primarily in Europe, Japan and the US, with growth increasing in China, India and Russia. Of these 75 companies, only 15 are in the US. Worldwide total sales of accelerators increase roughly 10% per year. This includes equipment for ion implantation, non-destructive examination, materials processing and irradiation, and neutron generators. Worldwide (including the US) industrial products that are processed, treated or inspected by particle beams have an annual value exceeding $500 billion. (This figure does not include the cost of cancer therapy.)

What existing programs address industry and which can be leveraged?

Industry is recognized by government as a key player in accelerator innovation. Industry usually plays an important role in the development of new accelerators for discovery science as vendors and sources of technology. Industry is also recognized as an important consumer of accelerator technology developed by government laboratories. Science programs with accelerator technology that industry can use currently and imminently span a diversity of uses.

The Small Business Innovation Research (SBIR) program provides US government R&D grants to small businesses on a competitive basis for the purpose of technological innovation and commercialization. It has proven to be one of the most effective methods for leveraging taxpayers' money to get the most benefit for the programmatic needs of the nation. With the passage of HR1540 in December 2011, the SBIR/STTR program has been extended for six more years and the portion of each participating agency's extramural R&D budget earmarked for the grants has been increased. Within the mission of this program, the DOE could consider directing more of its SBIR funds to the R&D of accelerator technology with significant commercial potential to better address US society's needs and contribute to a strong national economy.

With Grant Opportunities for Academic Liaison with Industry (GOALI), the National Science Foundation (NSF) promotes university-industry partnerships by making funds available to support a mix of industry-university linkages. GOALI seeks faculty, postdocs and students to conduct research and gain experience in an industry setting. It also seeks industrial scientists and engineers to bring industry's perspective and integrative skills to academia, as well as interdisciplinary university-industry teams to conduct research. GOALI's focus is transformative research that lies beyond that which industry would normally fund. GOALI's goal easily lends itself to being applied in existing accelerator industry-laboratory partnerships or to forging new ones within the DOE or other agencies.

A Cooperative Research and Development Agreement (CRADA) is an agreement between the DOE and a member of the private sector to provide mutual R&D benefit. It is an excellent tool for encouraging businesses to advance accelerator R&D to solve the nation's energy and environmental problems while simultaneously promoting industry's economic and technological growth. These agreements could be made uniform across the entire DOE complex and streamlined for more timely response to industrial needs.

For specific examples of science-business partnerships between laboratories and industry, see the later section "DOE-National Laboratory-Industry-Other Government Agencies Collaborations: Learning from Success and Overcoming the Hurdles."

Synchrotron light sources are a critical and useful tool for industrial research in materials, biology, drug development, environmental monitoring and mineral exploration. Industry will benefit from increased access to existing user facilities and from research into the development of compact, high-brightness, single-user light sources.

Researchers in accelerator science can help industry by finding ways to make accelerators more compact, more efficient and more robust. Advances in SRF cavities could help increase the efficiency and decrease the size of accelerator systems for cancer therapy and for radioisotope and neutron production by the lower radiofrequency power they use and their increased accelerating gradients.

Research programs developing fixed-field alternating-gradient (FFAG) accelerators could be applied to industrial neutron beam applications.

What technical difficulties need to be overcome?

The industrial accelerator challenge is to develop equipment that is reliable, compact and efficient so that it requires low capital and operating costs. Unlike high-energy laboratories that make use of large accelerators, industry needs efficient, compact accelerator and beam delivery systems to minimize production facility and installation costs. As in all businesses, a prime motivation for adoption of new equipment is the monetary return on the investment (ROI) that it will produce.

The high cost and high risk of doing business in accelerator science result in a "valley of death"—a large gap across which available and demonstrated technology is unable to make it from the initial demonstration phase to the profitable marketplace. The government could provide assistance through the commercialization phase to market penetration, mostly through financial support. An example is the recent XLerator program implemented by the DOE SBIR program.

However, a real lack of connection also exists in the R&D phase when the government is trying to move a development from the laboratory to industry. This "technology chasm" is brought on by complex R&D funding mechanisms, inconvenient industry-government policies that hinder coordination between them, a lack of facilities and demonstration projects, high laboratory overhead costs, high initial costs and an aversion to risk by both parties. Such factors hamper industry's ability to take formative or nascent technologies to the next level, making it costly or difficult to test or demonstrate accelerator usefulness.

The steady loss or outright lack of knowledge and experience among industry personnel is becoming a significant problem in accelerator technology and its end-use applications, especially in small companies.

Industrial intellectual property must be preserved and respected, but even though improvements are being made, current policies are still too inflexible for industry and stand in the way of industry getting the best deal they can on technological innovations they originate.

The public is not well acquainted with how widely accelerators are used in industry,

What research results from the existing programs will be relevant for the next few years for industry?

The accelerator industry will quickly adopt proven new technology. New developments on the horizon include superconducting cavities and magnets, which are key to the development of compact accelerators for medical and industrial use. FFAG accelerators could be adapted for neutron beam applications. Free-electron lasers and energy recovery linacs will serve as future light sources. High-current hadron accelerators will be useful for radioisotope and energy production systems. High-gradient accelerator cavities will aid in the miniaturization of beams.

What investments in the existing infrastructure would be necessary?

As noted in the Accelerators for America's Future report, strengthened relationships and cross-fertilization between industry and DOE program offices through workshops, established institutions and regular interaction with academic, industry and laboratory partners would encourage the development and use of accelerators to meet national needs in many areas.

One way to accomplish this would be to establish direct access routes between test facilities and industry. For example, the BNL Tandem Van de Graaff accelerator provides beams of more than 40 different types of ions and is available to outside users on a full cost-recovery basis. Of the 18 users, all but 3 are industrial. The National Synchrotron Light Source has 34 domestic and 6 overseas users from industry. In addition, the NASA Space Radiation Laboratory at Brookhaven could easily be configured for hadron therapy R&D.

Yet another example is provided by UK's Science & Technology Facilities Council (STFC). STFC operates Daresbury Lab's Science and Innovation Campus, which encourages business-science collaborations for the UK's economic growth. New and established businesses are given access to state-of-the-art facilities and scientific expertise to help develop their products and services. More than 200 small-to-medium-sized companies rent space on the Daresbury and Harwell campuses. If a company does its own research and simply uses the STFC facilities, the company owns all of the rights to the resulting product. If a company collaborates with STFC on the research and business development, intellectual property rights agreements exist to make sure that both parties benefit.

In these partnerships, not only can researchers and industry work side by side, but industry can also decide whether they like a new technology and whether they deem it marketable.

Additionally, new infrastructure in the form of a technology and R&D user facility, run by a government agency or contractor, would tighten the ties between government, industry and laboratories. It would be available to interested users in specified application fields. There should be two types of access to the facility. In one mode of access, users are allowed free use under conditions set by a committee based on the proposal's merit with the understanding that the results of the study will be in the public domain. In a second mode, which applies to proprietary R&D, access is paid for and granted on a first-come, first-served basis. Both cases are consistent with DOE's definition of a user facility.

The partnership could also work the other way: scientists could 'use' or work at industrial companies. Large companies could support their scientists to work in a lab to acquire knowledge or help direct program goals. Small commercial companies could host lab scientists on paid sabbaticals, further encouraging them as engines of technology commercialization.

In addition to the user facilities supported by the DOE Office of Science, pilot facilities could be supported by the industrial and manufacturing development programs of the DOE Offices of Energy Efficiency and Renewable Energy, Fossil Energy and Nuclear Energy.

Yet another relationship that must be fostered is that between the private sector and the public. Stimulating collaboration between public and private enterprise is vital to identify what public research is ready for private sector deployment. Research outside of commercial interest is of course the primary role of publicly funded labs, but being unaware of the needs of the "real world" is at best inefficient and unproductive, and at worst, simply irresponsible.

What are some examples of successful industry-laboratory collaborations?

The Loma Linda proton therapy facility was developed and built by Fermilab under DOE funding with many of the components procured from industry.

The Conductor Development Group, funded by HEP and managed by Lawrence Berkeley National Laboratory, funded the development of a new superconductor in American industry, particularly the development of compact cyclotrons for medical therapy and higher-field and -frequency MRI systems.

Brookhaven National Laboratory carried out a successful collaborative development of cryogenic and high-critical-temperature superconducting wire and cables, acting as an experimental magnet fabrication facility and as the test center of the industrial partners.

Michigan State University's FRIB facility, funded by the Office of Nuclear Physics, and industrial company Niowave's work on SRF cavities have helped contribute to the recovery of economically hard-hit Michigan.

What interagency barriers stand in the way of advancing accelerators for industry?

The primary barrier within government agencies to industry innovation is the current philosophy on patents and intellectual property. The US government protects patents to prevent an invention developed by taxpayer money from being monopolized for third-party profit. This reasonable protective measure prevents the spread of innovative technologies to others who may be able to repurpose or redirect the technology for other applications. Industry holds a similar view with regard to their inventions, which they protect to maintain profit.

Breaking this barrier requires new, collaborative agreements between industry and DOE labs—agreements that respect intellectual property while maintaining reasonable flexibility.

What future demonstration or technology projects for industrial accelerator applications are possible?

New accelerators currently being developed for discovery science may require the industrialization of new technologies. Readying US industry to meet the demand for these technologies over the next five years will require a formal industrialization program between government and industry similar to programs in place in many other countries. Such formal industrialization programs, with federal funding supporting nonrecurring engineering expenses to share the risks of developing critical components, would encourage more vigorous growth of accelerator technology in US industry.

The application of electron beam processing in coating technologies, sterilization, material modification, food irradiation and remediating air pollution and ground and water contamination can have a significant impact on energy and resource conservation. There is a need for large-scale facilities to evaluate the practical aspects of electron beam processing in several of these areas. This is particularly the case for stack gas cleansing and wastewater remediation. Such facilities would augment existing or new installations. Also needed is technology development in the US accelerator industry to make costs and size smaller. Any demonstration project should therefore include an accelerator industrialization program as described above for discovery science.

Defense and Security (S. Biedron, S. Milton)

Accelerators for defense and security have many uses for our nation and allies, though its users are different from those of other accelerators: war fighters, civilians and assets (non-human resources belonging to US or NATO). Accelerators can help in a variety of applications, including war-fighter and asset protection, interrogation of cargo and stockpile stewardship, to name just a few. Accelerators can replace radioactive sources and materials and can be used for isotope production. Defense and security also make use of accelerators for light sources and neutron sources in thousands of ways. In short, accelerator technologies find applications for a diverse and growing set of defense and security needs. Furthermore, accelerator laboratories and developed technologies have the potential to make more significant contributions to the needs of defense and security.

What existing programs address defense and security and which can be easily leveraged?

Many accelerator and peripheral activities that are headed by DOE's Office of High Energy Physics (HEP) or that are found in other Office of Science programs could be leveraged by defense and security. For example, facilities at Argonne National Laboratory (ANL), Fermilab, Jefferson Lab, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL) and Sandia National Laboratories could all serve as valuable resources for the nation's security, as could any US synchrotron light source or neutron source facility.

One example is in the area of superconducting radio-frequency (SRF) technology. Advances in the area of SRF accelerator technologies have made it quite robust, but are still a long way from calling SRF "turn-key." Improvements are still required to make such systems truly fieldable. Fortunately there are existing facilities working on such technologies that are improving them all the time. Laboratories with major SRF programs currently include Fermilab (HEP) and Jefferson Lab (NP), and to a lesser but still significant degree, Argonne National Laboratory (HEP and NP). All are working to improve SRF technology for their own programs, but their work also benefits the needs of defense and security. One immediate notable beneficiary of any improvements to SRF would be the existing Navy free-electron laser (FEL) program, as it relies heavily on the use of this technology.

FEL programs, such as those at Jefferson Lab, are multiply useful for security. As mentioned above, prime among their uses is their application to the Navy's future FEL weapon system, designed to be game-changing. The capability of having speed-of-light delivery for a wide range of missions and threats is a key element of a future shipboard layered defense. The design is to be able to have selectable wavelengths for use at sea. An innovative naval prototype program for FEL technology has begun. Infrared FELs with high power and tunability can further be applied for photochemistry and materials synthesis. Ultraviolet FELs utilizing similar technologies and with photon energies upwards of 10 eV can also be used to study nonlinear effects in matter and materials processing.

An interesting need for the FEL programs is that for a high-brightness (high-quality), high-current electron source. Of course, this is not special to the FEL program. Many accelerator-based defense and security concepts require such sources, so there is a significant need to develop these further. Currently there are a number of research groups working on various high-brightness electron sources, and some, such as LANL and LLNL, have their programs already focused on defense and security applications. While other programs, such as those at Argonne, Fermilab or SLAC National Accelerator Laboratory, are not necessarily defense-and-security-oriented, there are commonalities that can certainly benefit the defense and security communities and so should be exploited.

Additional capabilities suitable for the defense and security field also come with improvements in electron beam quality and laser technology. Recent advances in accelerator and laser technologies suggest they might be exploited to enable much less expensive and smaller x-ray sources that could be readily deployed in military field hospitals or on selected military platforms to improve combat casualty care. They might also lead to new advanced imaging capabilities that most modern laboratories and hospitals could afford. An example of such a program is DARPA's Advanced X-ray Integrated Sources (AXIS) program, where the goal is to develop advanced x-ray source technology that will enable high contrast when imaging low-Z materials such as soft biological tissues.

One possible way to do the above is to utilize Compton scattering to produce the hard x-rays. Various research groups are exploring this, such as the one at LLNL. These Compton scattering experiments can also be applied to interrogation methods based on high-brightness electron beams and detector systems.

The development of high-power terahertz sources and detectors is also a hot area of pursuit, applicable to many defense and security strategies. As an example of development of an existing exploitable source, researchers at Jefferson Lab are working on terahertz sources that provide record power, many orders of magnitude over conventional sources. Production of these sources could be useful for imaging, high-data-rate communication and standoff detection of explosives, all of which have direct application in defense and security. They could be further useful for spectroscopy and molecular dynamics.

In a supporting, developmental role for much of this technology, computational and simulation tools can help make great strides. Several institutes such as Argonne and Los Alamos National Laboratories have developed useful computational and simulation tools for modeling electron beam dynamics and interactions and can run these on some of the fastest computers in the world. SCIDAC is of interest to defense and security, and industry could partner in investigations and use.

What is the connection to the private sector?

Government defense and security agencies are of course not the only interested parties in accelerator applications. Science labs develop detector and accelerator technologies that not only have use for commercial pursuits, but whose applications in industry are easily mapped to applications in defense and security. Both sectors, then, support laboratories' research as much as they technologically support each other.

Industry's role in defense is also more direct, as it develops machines for use in defense.

The biggest gap in the relationship between defense and industry concerns the regions where companies are domiciled. It is plainly more desirable for defense and security to work with US vendors than with foreign vendors, yet the US lacks vendors with expertise in accelerator and detector technology. This leads defense agencies outside the US to locate suitable companies for building machines or using facilities. This, in turn, raises a problem in export control—keeping tight control of classified information while sharing the information the company needs to fulfill its task.

What technical difficulties need to be overcome?

To advance the needs of defense and security, scientists and engineers must innovate: accelerator technology needs to become more compact, more rugged and more efficient.

One enabler to more compact machines is the ability to achieve high accelerating gradients. Achieving such gradients via conventional concepts is straightforward, but the work must continue. That said, true enabling breakthrough technologies would be welcome. This means further research in laser drivers, new radio-frequency sources, two-beam concepts and wakefield concepts, to mention a few.

The pursuit of compactness applies not only to high gradients, but to high average powers as well. The ideal situation is to achieve both high gradient and high power simultaneously. High-power particle sources are also needed. These can range from 1 A of ion current to 100 kA of electron current.

To convert an electron beam's kinetic energy into radio-, terahertz- or x-ray-frequency photon beams, researchers need to find novel beam and wave interactions.

They also need to develop methods for ruggedizing superconducting and novel accelerating structures so that they are vibration- and shock-tolerant for compatibility with shipboard and other exotic environments. These structures must also be suitable for ampere-class currents and be compatible with simpler and lower-cost cryogenic plants operating at 4 K rather than 2 K, or even serving high-temperature superconducting structures.

Cavity development should also include innovative concepts for energy-recovered operation at high current.

There is a need to develop efficient and compact low-energy, large-area, high-current electron beams. These sources need to operate at repetition rates of 5 to 10 Hz, so the related pulsed-power modulators are also imperative.

Another challenge is developing short-pulse lasers to produce high-current, low-emittance ion beams. Such devices could replace costly ion sources and low-energy accelerator stages of ion beam accelerators.

An area ripe for progress is the development of multi-modal probes, that is, combining a variety of beam and detector technologies into an integrated package. This would greatly improve the capabilities to probe containers and other objects in a manner that allows one to "see" a wide variety of "items."

In short, accelerators of the future for defense and security should have one or more of the following qualities—compactness, high efficiency, high gradients, high power, higher-current systems and, for superconducting machines, higher operating temperatures and more rugged construction.

At the same time that scientists work on the above accelerator-related advancements, it would be valuable to make comparable advances in detector and software technology as well so that all parts work together efficiently. Defense requires smaller detectors that are high-resolution (similar to high-purity germanium detectors), but that do not require cooling to cryogenic temperatures. And with the fulfillment of compact accelerator gradients, one also needs detectors that are compact and robust enough to work with the attendant accelerating forces.

Researchers should also pursue simpler and lower-cost cryogenic plants, including the option to use cryocoolers where applicable.

Pushing modeling software technology is also important. Software should help researchers optimize operating regimes and reduce the overall risk that underlies all modern accelerator design. Much of the current software has not taken advantage of the many computer improvements that have been developed in the last few decades. Such progress includes vastly increased processor speed, exploding memory capabilities, disk storage growth and cloud computing. There is not enough overall commercial demand for such high performance accelerator design software to have confidence this problem will be solved without US government intervention. Real-time comparison with models for optimization, scenario development, and war-gaming is needed for defense and security applications.

What investments in the existing infrastructure would be necessary?

Available test and user facilities and access to them are of utmost importance. The defense and security sector needs access to these facilities and at various levels: open, FOUO (government-only) and SECRET (and maybe even above). This would require, in some cases, an investment in an administrative structure that would allow DOE to arrange for secure visits to relevant facilities. The Department of Defense has such an infrastructure in place. Perhaps DOE could pattern a secure-facility program after DOD. There are experts in superconducting radio-frequency in both the DOD enterprise and in the Department of Homeland Security who may be helpful. As a nation, we need to streamline the security challenges, especially between DOE and DOD.

What new infrastructure would need to be built?

New test facilities, as well as dedicated, secure beam lines would expedite research for defense. More ambitious, dedicated defense facilities for accelerators would ensure a high degree of security. Secure and/or specialized test facilities meet an obvious defense and security need, and using existing laboratory capabilities takes advantage of resources.

Test facilities would come in at least two varieties. One would capitalize on existing facilities to build in additional capabilities. Examples are the addition of specialized beam lines at existing synchrotron light sources or neutron sources. The other variety would be a dedicated facility. Examples here are facilities that could provide extensive cryosystem capabilities, possibly one with extensive radio-frequency capabilities and sources, and the co-location of such facilities with ones that have "special materials."

What interagency barriers exist that are specific to defense and security?

Though necessary, the US citizenship requirement in many US DOD defense services and agencies to perform science and technology development affects individuals and organizations on the non-DOD side, both nationally and internationally. In fact, this is of particular concern in the area of accelerators, beam, and peripherals, since much of the talent in the US is foreign nationals without green-card status or who lie outside US borders. Further, some DOD services and agencies do not consider a green card sufficient evidence for dedication to the US whereas DOE does.

One long-term solution is to foster more US scientists and engineers in the accelerator field. A more immediate, but more complicated, solution may be to forge bilateral agreements routed through the military departments of our allies' countries. As noted above, export control is challenging. The situation would be radically simplified by a stronger US vendor base, one the country could draw from to obtain equipment fabricated in the US in large quantities and at a reasonable price.

As it is, the field of accelerator science in the US is geographically widespread and loosely knit between labs. Tighter coordination would facilitate activities across labs, academic institutions, industrial companies, services and agency borders. This would include better coordination between DOE and DOD, DHS and the National Nuclear Security Administration. Rewards to individuals for making these connections would facilitate such coordination.

As noted in the above section on beneficial infrastructure investments, the Department of Defense may provide a model to follow. The DOD Research and Engineering Enterprise has a board of all the technical executives from the various DOD services and agencies.

Although these technical executives have their own funding to distribute, this board ensures that related items are not duplicated but that their connection of the related activities is linked, delivering all capabilities in a coordinated way.

A board to coordinate accelerator stewardship activities might be composed of one or more “accelerator czars,” points of contact who may have multiple appointments between agencies and services.

The DOE HEP office, being the historical steward of long-term accelerator and peripheral research and development, might further consider leading an accelerator and peripheral working group that involves other intra-agency and interagency program managers and technical advisors in the area of accelerators, who would meet twice yearly.

Again, other science and technology workgroups may serve as a model here. Those close to both the current research and security needs will best know how to leverage investments from the many branches that make use of accelerator technology, for example, Army, Air Force, Navy, DTRA and DARPA.

Discovery Science (G. Hoffstaetter, M. White)

Particle accelerators are essential tools of discovery for particle and nuclear physics and for sciences that use x-rays and neutrons. Additionally and perhaps obviously, particle accelerators help further the field of accelerator science, which is the research of the generation, characterization, manipulation, and interactions of the particle beams themselves.

Although accelerator design and technology must be optimized for particular applications, there is significant overlap in the kinds of R&D that must be performed to realize the next generation of accelerators for all these fields of discovery. Much of this R&D is cross-disciplinary, involving researchers in fields that have not been traditionally associated with accelerator development.

There is long-term research in novel acceleration techniques that will be essential for tomorrow's discovery machines. However, as is often the case in research, it has yet to be seen which discovery science direction will most benefit from these new acceleration techniques.

What existing programs address discovery science and which can be leveraged?

Currently almost all programs related to accelerator science and technology in the Office of Science (SC) are targeted towards discovery science. Few exceptions, in Nuclear Physics for example, exist (see footnote on page 8). All SC offices contribute significantly to the development of accelerator technology; the specific program in HEP stewards the advanced R&D. All can be leveraged, and many already are. Although Fermilab's Tevatron accelerator was shut down in the fall of 2011, the US contributions to discovery science at the energy frontier continue with the US program at CERN's Large Hadron Collider. These experiments complement those at the intensity frontier with Fermilab's Long Baseline Neutrino Experiment, which has a strong development program on high-intensity proton accelerators.

For nuclear physics experiments, important contributing Nuclear Physics-funded facilities include Argonne's ATLAS facility, Brookhaven National Laboratory's RHIC, Jefferson Lab's CEBAF, Michigan State University's future FRIB facility, the 88" cyclotron at LBNL, the HiGs facility at Duke and the Texas A&M cyclotron facility.

Light sources, including free-electron lasers (FELs), and neutron sources will continue to be discovery machines for the future. Synchrotron-based sources typically serve thousands of users per year from domestic and foreign universities, labs, and industries of all types. They have excellent user support for experiment and data analysis and are extremely reliable. X-ray and neutron science benefits from about a dozen user facilities across the US.

What technical difficulties need to be overcome?

As with other areas of accelerator-driven R&D, discovery science will benefit greatly from machines that have higher reliability and higher energy efficiency, as well as from beams with higher energy, higher intensity and higher power. A multitude of technological opportunities lie in moving towards these goals, and accelerator-related projects of all relevant fields should coordinate and cooperate as these goals for discovery-science accelerators overlap significantly with those in the areas of energy and environment, industry, medicine and defense and security.

A few examples of common interest follow: All particle physics experiments and accelerator programs benefit from the development of reliable particle sources with suitable beam parameters. Developing tools and methods for better diagnostics are critical for generating the required beams. Accelerators across the board also need advanced simulation studies, and long-term support for code development and maintenance is therefore needed. Finally, the matter of energy-efficiency from the power substation to the experiment has an obvious impact on the financial and ecological sustainability of accelerator physics projects.

High-energy physics

Accelerators serving high-energy physics are characterized by high energy or high intensity. Colliding beams, with either leptons or hadrons with high luminosity, or beams impinging on a target to generate secondary beams, are required. Also required are high-intensity test and calibration beams, radiation-hard materials and higher-field superconducting magnets, perhaps with higher-critical temperature and higher-gradient accelerating structures. Superconducting radio-frequency (SRF) accelerating structures have reached high gradients, which reduces construction and operational costs.

The highest gradients are needed for pulsed accelerators, for example at a linear collider with either superconducting or normal-conducting accelerating structures. For continuous-wave accelerators using SRF, the lowest wall losses and therefore the highest quality factors are needed at medium voltages at projects such as the proposed Project X, Jefferson Lab's CEBAF and its FEL or at future energy recovery linacs (ERLs).

Advancing SRF also requires new and improved cavity construction techniques, such as surface treatments for conventionally deep-drawn niobium cavities; hydroforming and spinning niobium to create seamless cavities; combining niobium with copper for cost-effectiveness by coating copper with thin niobium layers; and experimenting with new superconducting materials such as Nb_3Sn, MgB_2, and multi-layers.

It is also important to find efficient ways to keep cavities at a temperature where they remain superconducting, and for this reason further investigation is needed in the areas of efficient cryogenics and on the use of cooling loops, rather than helium baths, to cool niobium-on-copper cavities.

The beam dynamics in ERLs needs to be investigated to overcome beam-breakup instabilities and unwanted halos, both of which lead to beam loss. The timing and synchronization of very short particle bunches is also crucial. ERLs require particle sources, in particular, high-quantum-efficiency photocathodes and robust DC or SRF electron guns.

Muon colliders require a combination of many of these and other technologies beyond the state of the art to be feasible.

An important pursuit of advanced accelerator R&D is ultrahigh gradients, which would dramatically decrease the required physical size or length of future colliding beam facilities. Questions of feasibility, efficiency and cost are to be addressed at the same time. Laser-driven or charged-particle beam-driven plasma and direct-laser acceleration techniques are major technologies under development.

Nuclear physics

Nuclear physics programs are in need of higher-energy, high-intensity, continuous-wave proton and ion accelerators on the order of 1-100 mA and 1 GeV. Next-generation nuclear physics facilities, such as an electron-ion collider, require advances in key technologies in beam cooling, energy recovery linac and high-intensity and highly polarized electron and light-ion sources. Higher-power targets and strippers as well as advanced diagnostics are also needed.

These require SRF accelerators, higher-quality production techniques and new superconducting-material developments, perhaps on a time scale of roughly 10 years. SRF technology has become important in nearly all large-scale accelerators including Brookhaven's RHIC, MSU's future FRIB facility and Oak Ridge's SNS, to name only a few.

X-ray, photon and neutron science

Investigations into the atomic and molecular make-up of nature require ultra-stable x-ray and photon beams with very high brightness. These beams are produced by storage rings, ERLs and FELs, each with overlapping R&D needs. More compact sources are under development and use high-gradient acceleration techniques or inverse Compton scattering, all of which are under active development.

ERLs are useful for generating coherent x-ray beams at light sources. As in high-energy physics (see earlier subsection), the beam dynamics of ERLs for light sources require further study.

For FEL-based sources, multiple users need to be able to precisely isolate and farm out individual pulses from a train to create particular pulse distributions. This means that scientists need to advance precision timing and synchronization capabilities in light sources.

Undulators deliver bright beams to experiments. Researchers are currently working to develop shorter-period undulators, superconducting undulators and RF-field-based undulators, which could lead to more compact FELs and higher photon energies at smaller synchrotron light sources. High-heat-load optics and high-heat-load front ends in the experimental stations can take advantage of the more powerful photon beams.

The research required for the development of permanent-magnet undulators involves investigations of fixed- and variable-gap devices for cost reduction and flexibility. There is no longer a domestic source for large quantities of extremely high-quality permanent magnets, thus US researchers are looking for new abundant materials to reduce the dependency on foreign supply.

Advances in superconducting technology could make it possible to construct devices with a period length of 10 millimeters or less, especially with the development of small-filament wire with a current density of at least 5000 A/mm^2 at 3 T. This advance hinges not only on superconductor technology, but also on cooling technology. If the devices could be cooled without cryogenics, it would reduce costs.

For ring-based sources, there is a need for novel optics for ultra-low emittances. These will also help with halo and loss rate analysis for the ultra-low-emittance beams. These could be tested at existing rings with sufficiently flexible magnet settings.

Advances in neutron science will require high-intensity proton and neutron beams as well as high-power targets and moderators. Neutron sources require multi-megawatt beam power with moderate energy. In addition, they must be reliable, low-beam-loss machines. Their high power requires compatible targets that can withstand the high instantaneous and average power, which in turn requires a better understanding of the limitations of current targets.

What investments in the existing infrastructure would be necessary?

Advances in accelerator technology have traditionally been driven by the need to develop higher-energy or higher-intensity accelerators. These developments have supported mostly the HEP or NP mission, sometimes the defense sector and, increasingly in recent decades, new capabilities to meet the BES mission. Infrastructures to support technology development are typically needed either at existing accelerators or in dedicated demonstration facilities, where these technologies are tested and which prove feasibility.

Often such demonstration facilities find applications after their technology has been developed successfully. For linear colliders, for example, many of these facilities have been built around the world and today serve as more than only test beds. For muon colliders or advanced plasma-wakefield accelerators, test facilities are under construction. Intense proton and ion beams are probed in dedicated test facilities or at existing accelerators. The necessary technology infrastructure for SRF work, high-field magnets, high-gradient structures, RF power sources and many other programs often exists in more than one national laboratory and may need to be improved or expanded.

Expertise in a wide range of techniques and technologies beyond what is traditionally used in accelerator R&D is prevalent in the national laboratories and universities. Advances in material development, surface science and laser technology can all have a major impact on accelerator development, and through cross-collaboration in these and related pursuits accelerator science could progress even further. In order to fully utilize this expertise, it will be beneficial to support scientists and engineers in non-accelerator fields who have relevant expertise, for example in metallurgy and materials science, and whose R&D effort may utilize particle beams.

Facilities that could easily be leveraged for external users include the Argonne Wakefield Accelerator, BELLA at LBNL, Brookhaven's Accelerator Test Facility (ATF), CESR-TA at Cornell University, FACET/NLCTA at SLAC, the FEL at Jefferson Lab and NML at Fermilab. A significant number of these can support a large number of users, as demonstrated at Brookhaven's ATF. The design of such facilities should allow for flexibility in beam parameters, charge, energy, emittance and bunch length.

Since lasers will play a major role for accelerators in the future, a dedicated effort to develop them further in support of the accelerator R&D mission is required.

What new infrastructure would need to be built?

Risky accelerator studies that could potentially cause damage or otherwise reduce machine availability are typically not permitted at user facilities, yet they are critical to development of the reliable, high-power, high-brightness, high-reliability accelerators of the future.

Dedicated facilities that are consistently supported for many years are required to support fundamental long-term development because experience has shown that accelerator R&D of high impact requires a dedicated effort of many years.

What future demonstration or technical projects for discovery science are possible?

Discovery sciences will drive accelerator R&D and will have a broad impact in the coming years. This is especially true in the areas of superconducting radio-frequency acceleration, superconducting magnets and particle sources.

Projects that apply SRF accelerators abound. This technology is widely used in support of the HEP, NP and BES missions. The US Navy ERL-FEL and the commercial programs at AES and Niowave are examples of projects that lie outside the national laboratory system and also benefit from SRF R&D.

The country also has multiple programs for the advancement of superconducting magnet technology. The US contribution to CERN's Large Hadron Collider involves cutting-edge technology in these magnets. The country's light sources are developing superconducting undulators. Superconducting magnet technology can also be applied in an electron-ion collider. The advancements in this area could be immediately industrialized for MRI technologies and medical cyclotrons and will have applications in coherent light sources such as FELs and ERLs.

Demonstration projects for particle sources will benefit many projects, such as electron-ion colliders, ERL light sources and FELs.

Examples of successful accelerator R&D for discovery science

As mentioned in the earlier section entitled “Changing the Landscape,” good examples of successful accelerator R&D for discovery sciences are superconducting magnets, SRF acceleration, and niobium-3-tin superconductors.

Superconducting radio-frequency technology was first investigated in 1962. Since then it has been industrialized, and is now used for discoveries in many light sources, in spallation neutron sources and in colliders.

Superconducting magnets developed for Fermilab’s Tevatron were originally an aid for a cutting-edge high-energy physics programs, but their spin-off application was immediate. Most notably, they were transferred to MRI technology. Now they are used in superconducting cyclotrons in hospitals, as well as in colliders and light sources.

The development of stochastic DC cooling in the 1980s led to a Nobel Prize in physics. The technology has since been developed to bring about high luminosity for Brookhaven’s RHIC facility. Developing this cooling technique required fast electronics, which was another technology developed with wide-ranging applications.

DOE-National Laboratory-Industry-Other Government Agencies Collaborations: Learning from Success and Overcoming the Hurdles

Leveraging Federal Funding: SBIR/STTR Programs (R. Hamm)

The stated mission of the US Small Business Innovation Research (SBIR) program is “to support scientific excellence and technological innovation through the investment of Federal research funds in critical American priorities to build a strong national economy.” It has become a highly competitive program that encourages domestic small businesses to engage in programmatic federal research and R&D that also has the potential for commercialization. Through competitive grant awards, the SBIR program enables small businesses to explore the technological potential of doing this work and provides the incentive to profit from its commercialization. It has proven to be one of the most effective methods for leveraging taxpayers’ money to get the most benefit for the programmatic R&D needs of the nation.

The SBIR/STTR program has seen a significant transformation in US technical innovation over the almost 30 years it has been in place. Currently there are more scientists and engineers working in small companies than in any other technical employment sector. In 2005 this number was 38%, compared to only 6% in 1978 before the SBIR program began. In comparison, in 2005 27% of US scientists and engineers worked for large companies, 16% for universities, 13% for government, and 6% for nonprofit organizations.

In addition, the Information Technology and Innovation Foundation recently analyzed the past lists of the 100 most technologically important innovations, as selected annually by a panel of judges for *R&D Magazine* for the performance of SBIR companies. The authors of this report wrote: “The results show that these SBIR-nurtured firms consistently account for a quarter of all R&D 100 award winners—a powerful indication that the SBIR Program has become a key force in the innovation economy of the United States.”

Finally, it is well known that small businesses are the most important sector of our economy in creating net new jobs. Office of Advocacy data show that small businesses, particularly those the size of SBIR companies, have created more than two-thirds of the net new jobs over the past 15 years. In the area of accelerator technology, almost every new company started in the US during the last two decades has been initially supported at least partially, if not fully, by the SBIR program.

SBIR companies also provide financial leverage to the federal R&D dollars they receive. The SBIR program can provide an important stimulus to jumpstart the commercialization of the technologies of the companies awarded contracts. The SBIR grants and awards are non-dilutive to shareholders’ equity and are not loans that detract from a company’s balance sheet. In fact they are looked upon with considerable favor by both equity investors and banks and other financial lending institutions.

Each year, federal agencies with extramural research and development (R&D) budgets that exceed $100 million are required to allocate 2.5% of their R&D budget to the SBIR program. Currently, eleven federal agencies participate in the program with a total funding of $2 billion. Each agency administers its own individual program within guidelines established by Congress. These agencies designate R&D topics in their solicitations and accept proposals from small businesses. Awards are made on a competitive basis after proposal evaluation. With the passage of HR1540 in December 2011, the SBIR program has been extended for six more years and the portion of each participating agency's extramural R&D budget earmarked for these grants will be increased gradually to 3.5%.

Within the mission of this program, the DOE could direct more of its SBIR funds to the R&D of accelerator technology with significant commercial potential to better address US society's needs and contribute to a strong national economy. Input from industrial representatives could be sought in order to help identify accelerator solicitation topics that would meet these goals.

Due to the complexity and cost of the technology, a new accelerator company has to go through a number of SBIR grants to fully develop its technology into commercial products. This can result in a long development cycle that contributes to many of the failures of these companies in the "valley of death." The new higher funding limits on grants and faster response time to proposals will certainly help this process but will still not match the level of government support of new companies seen in other competing countries.

Finally, the additional requirements for Phase III commercialization readiness are not seen as an impediment to almost all new accelerator companies in the US. This is because they are all in the manufacturing business and are allowed to submit their own plan of how they will market and produce the products they develop on Phase II SBIR grants. This provision is generally only detrimental to R&D companies who do not intend to produce any products but rather hope to license their technologies to other companies. However, some of these companies have become "SBIR mills" that are very good at writing SBIR proposals but produce few if any commercial products on their own. This in effect keeps the small manufacturing companies that are not as clever at writing applications from winning SBIR grants, even though they have good technology.

A brief summary taken from the testimony of Jere Glover, Executive Director of the Small Business Technology Council, at recent Congressional hearings on HR1540 shows the documented success of the SBIR program. See Appendix 5.

Access to National Laboratories, User Facilities, and Infrastructure (J. Clayton, M. White)

Providing industrial companies with easier access to laboratories has the potential to foster innovation and technological advancements for accelerators, yet conducting this partnership in a way that preserves intellectual property and commercial advantages for industry while leaving enough time free for other users is sometimes problematic.

Problems facing industry-laboratory partnership

With small businesses especially, the disincentives to collaborate with the laboratories are not only the costs and sense of urgency and risk, but also the lack of resources to take an idea from inception to market. Laboratories could benefit from the sharing of these ideas, but in the absence of a marketing catalyst, good ideas could easily fall by the wayside. The industry-government relationship should take this into account.

Part of the problem of sharing risk and reward is a cultural gap between industry and laboratory, where the latter is viewed by the former as lacking focus and accountability when it comes to the market. Often laboratory researchers are unfamiliar with market-directed research and feel little urgency to advance R&D in a timely fashion, whereas industrial companies must follow a market-oriented, time-critical schedule. It is not always certain that the lab will be available to develop a particular project if other R&D activities take priority.

In short, businesses need to have assurances that the contracted resources that are shared with the laboratory are adequately represented and not diverted to other projects without notification. Should this happen, there should be a plan for mitigation.

Financial and research risks are not the only barrier to advancing accelerator R&D. Complicated processes and red tape also discourage expeditious R&D collaborations. Executing a non-disclosure agreement may take several months. The Cooperative Research and Development Agreement process is almost prohibitively complicated. Though such contracts are intended to encourage innovative research, the very act of applying to enter into a contract is viewed not as an opportunity, but as a hurdle.

Hurdles of intellectual property are similar in nature: they discourage partnerships between governmental and private sectors when they should be protecting involved parties. Difficulties surround the question of the origin and ownership of intellectual property. Many of these questions can be addressed through the implementation of standardized contacts with laboratories.

Finally, industry is aware that the national lab system provides fairly open access to their foreign competitors, from which it follows that any of their ideas or developments could easily be exported overseas by means of international lab users. In a roundabout way, US taxpayer money may be used against the very thing it is intended to support. It would be useful to implement measures to protect against unintentional dissemination of technology and knowledge.

General Partner, User Partner model

Prospective experimenters, including those from industry, could follow one model in which they access a laboratory facility either as a General User or a Partner User. If the capability or technique already exists on a current beamline, individuals can submit proposals to use this capability through the competitive peer-review General User process (see, for example, http://www.aps.anl.gov/Users/Scientific_Access/General_User/). Proposals and requests for user time against these General User proposals could be evaluated each cycle and allocated time according to their scores.

Partner Users, on the other hand, would be those who need a capability that does not currently exist and want guaranteed access to that capability for a period of time. If a research group wants to create a new capability in an existing facility, it could submit a Partner User proposal, which would be evaluated by the same process used for General User proposals. Approved PUPs may have a prescribed fraction of the available beam time on a specific beamline for up to a set number of years as determined by the laboratory.

For example, groups that wanted to build an entirely new beamline could submit a Letter of Intent (LOI) to be reviewed by the appropriate committee. If the LOI were approved, a full proposal would be requested and would undergo rigorous scientific and technical review. The group would then raise construction and operating funds. Once documentation of funding commitments is received, the group would be assigned a location and construction could begin.

The major advantage of this method is guaranteed access to some fraction of the available beam time, renewable on a set basis as long as the group remains productive. The remainder of the beam time would be allocated through the General User process.

Alternatively, the facility and the team proposing the development work could collaboratively design, construct, and fund the project. During commissioning, the group members have access to the majority of the beam time, but once the beamline is fully functional, it would transition to the facility after which some fraction of the time is available through the General User access mode.

If the research to be conducted is non-proprietary (freely available and published in open scientific literature), there would be no charge for beam time, but users would be responsible for their own experimental costs. Proprietary research carries, in addition, an hourly charge for the time used. Proprietary research could be carried out as either a General or Partner User, but a pre-funded proprietary user account must be established in advance.

The National User Facility Organization (NUFO) represents the interests of all users who conduct research at US national scientific user facilities, as well as scientists from US universities, laboratories, and industry who use facilities outside the United States. NUFO facilitates communication among users, user organizations, facility administrators and other stakeholders. Discussion topics include the benefits and significance of research conducted at user facilities as well as their operational needs. NUFO seeks to provide a unified message at the national level on issues of resources for science, economic competitiveness, and education for the next-generation scientific workforce. It is organized into two major branches: User Organization Representatives and User Administrators. User Organizations focus primarily on outreach activities, whereas User Administrators focus on streamlining processes to facilitate access.

Industry as developer

The industry developer of accelerator technology has a different perspective from the industrial user of accelerator technology. Facility users have developed a process for working with the specific laboratories. For accelerator developers, however, the path is more challenging and less refined.

Accelerator technology development is often used as an informational tool or stepping stone in an industrial company's development process. Examples of accelerator developers are companies such as Varian Medical Systems, Best Medical and Applied Materials.

It would benefit the US economy to identify synergies between laboratory and industry so the two sectors could work collaboratively on problems both inside the DOE and outside in the industrial world. For example, laboratories could work with industry to develop accelerator technologies that could dramatically reduce the cost of radiation therapy for hospitals and patients. This would be a large boost for the US, enhancing its bottom line and security.

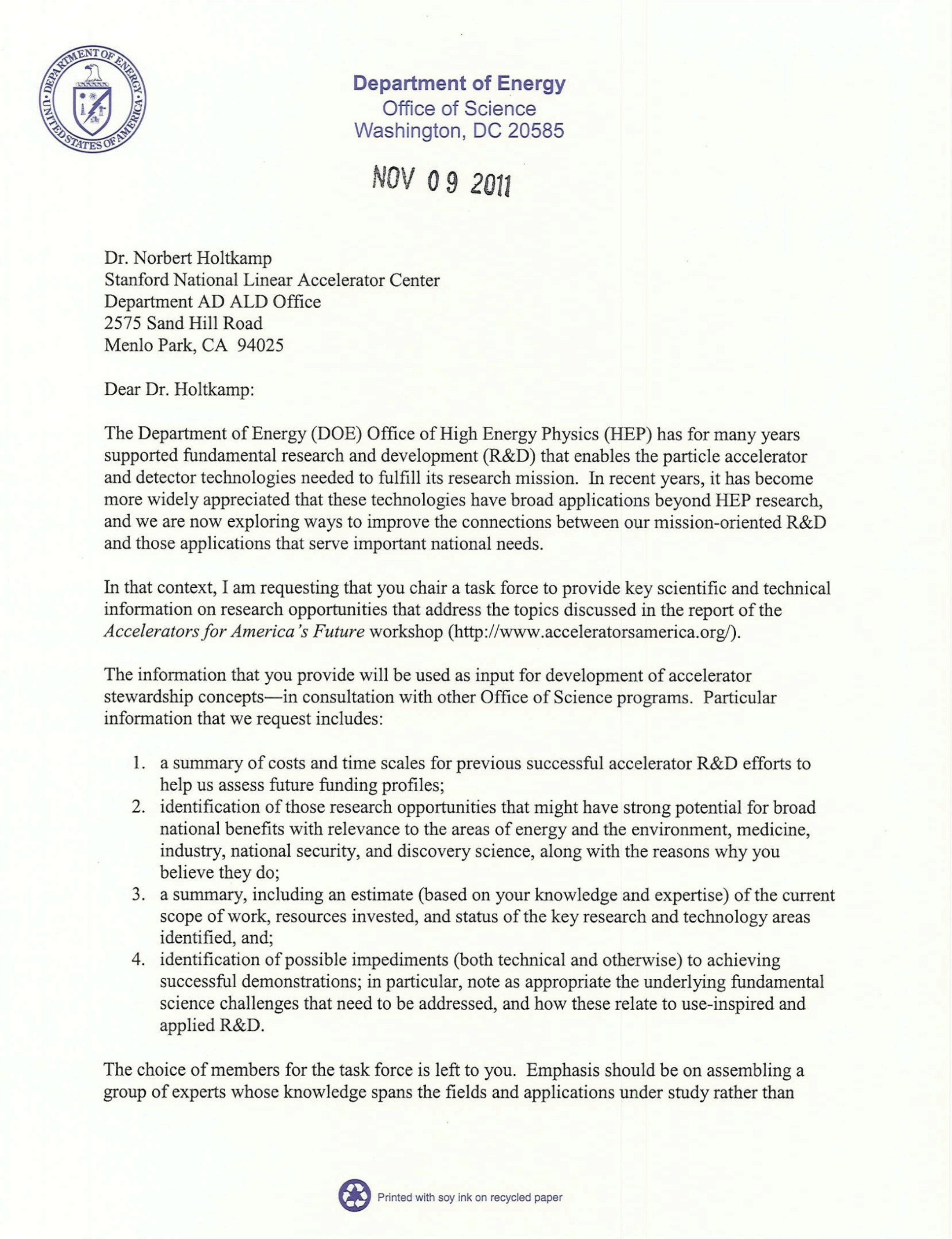
Another example is found in the semiconductor industry. Developing new methods to create the next generation of integrated circuits, even smaller than today's chips at 45 nanometers, will involve new accelerator technologies. Having this equipment developed in the US by US firms and laboratories enhances the nation's bottom line and security. Reaching out to the major equipment semiconductor manufacturers such as Applied Materials, KLA-Tencor or LAM Research, to name a few, would not only to make them aware of laboratory technology but would also help obtain feedback on what technologies are required to make the jump to smaller faster chips.

Impediments within other DOE programs

The DOE's Small Business Innovation Research (SBIR) program is a well known example of government-industry partnership, but as the name states, it is intended to promote small businesses, which cannot carry the risk or generate the funds to support larger projects, for instance, those related to accelerators in medicine. A comparable program for large businesses should be explored and be put in place. This process needs to undergo peer review by internal and external groups for technical and business acumen.

The Work for Others program, while a viable conduit for industry participation in accelerator research, still does not provide sufficient motivation for industrial companies to become involved in accelerator R&D. Industry may be more encouraged to participate in accelerator R&D if some of the financial burden could be alleviated, in particular, the commitment for fully funding the program in advance, which hampers cash flow substantially. Also, the full indemnification that is often required can be a problem for some commercial companies. The risks for industry are too steep, and there is little security or incentive in it for them to participate in large accelerator development programs.

Appendix 1: Charge letter



Department of Energy
Office of Science
Washington, DC 20585

NOV 09 2011

Dr. Norbert Holtkamp
Stanford National Linear Accelerator Center
Department AD ALD Office
2575 Sand Hill Road
Menlo Park, CA 94025

Dear Dr. Holtkamp:

The Department of Energy (DOE) Office of High Energy Physics (HEP) has for many years supported fundamental research and development (R&D) that enables the particle accelerator and detector technologies needed to fulfill its research mission. In recent years, it has become more widely appreciated that these technologies have broad applications beyond HEP research, and we are now exploring ways to improve the connections between our mission-oriented R&D and those applications that serve important national needs.

In that context, I am requesting that you chair a task force to provide key scientific and technical information on research opportunities that address the topics discussed in the report of the *Accelerators for America's Future* workshop (http://www.acceleratorsamerica.org/).

The information that you provide will be used as input for development of accelerator stewardship concepts—in consultation with other Office of Science programs. Particular information that we request includes:

1. a summary of costs and time scales for previous successful accelerator R&D efforts to help us assess future funding profiles;
2. identification of those research opportunities that might have strong potential for broad national benefits with relevance to the areas of energy and the environment, medicine, industry, national security, and discovery science, along with the reasons why you believe they do;
3. a summary, including an estimate (based on your knowledge and expertise) of the current scope of work, resources invested, and status of the key research and technology areas identified, and;
4. identification of possible impediments (both technical and otherwise) to achieving successful demonstrations; in particular, note as appropriate the underlying fundamental science challenges that need to be addressed, and how these relate to use-inspired and applied R&D.

The choice of members for the task force is left to you. Emphasis should be on assembling a group of experts whose knowledge spans the fields and applications under study rather than representing particular constituencies. Individual task force members should provide their own independent written input addressing the request above, but you can assign members to comment on particular topics as needed to ensure proper coverage of the relevant issues. Please supply the information you gather in writing to us by February 1, 2012. Dr. Michael Zisman from our office will be our liaison to the task force and will lead integration of the committee input into the DOE report.

Sincerely,

James Siegrist

James Siegrist
Associate Director of Science
for High Energy Physics

cc:
Persis Drell, SLAC
Pier Oddone, FNAL
David Nygren, LBNL
Harry Weerts, ANL
Steve Vigdor, BNL
Stuart Henderson, FNAL
Stephen Gourlay, LBNL

Appendix 2: Membership and Affiliation

Sandra Biedron	Colorado State University
Lester Boeh	Varian Medical Systems
James Clayton	Varian Medical Systems
Stephen Gourlay	Lawrence Berkeley National Laboratory
Robert Hamm	R&M Technical Enterprises, Inc.
Stuart Henderson	Fermi National Accelerator Laboratory
Georg Hoffstaetter	Cornell University
Norbert Holtkamp	SLAC National Acceleratory Laboratory
Lia Merminga	TRIUMF
Stephen Milton	Colorado State University
Satoshi Ozaki	Brookhaven National Laboratory
Fulvia Pilat	Jefferson Lab
Marion White	Argonne National Laboratory
George Zdasiuk	Varian Medical Systems
Michael Zisman	DOE Office of High Energy Physics

Appendix 3: William Barletta, Accelerator Education in America

Appendix 4: More university courses on accelerator-related fields

Appendix 5: Testimony of Jere Glover, Executive Director of the Small Business Technology Council

Appendix 6: AES – Examples of Lab and Industry Collaboration Funded by Government

Appendix 7: Meyer Tool, Inc. – Prioritizing the Advancement of Basic Science and Research

Appendix 8: Niowave, Inc. – DOE's Role in Commercialization of Particle Accelerators: An Industry Perspective

Appendix 9: Lawrence Berkeley National Laboratory – Ion Beam Technology

Appendix 10: Lawrence Livermore National Laboratory – MEGa-ray Technology

Appendix 11: Los Alamos National Laboratory – National Security and Defense

Appendix 12: Sandia National Laboratories – SPARC proposal

Appendix 13: National Nuclear Security Administration – Technology Roadmap

Appendix 14: National Nuclear Security Administration – Radiation Sensors and Sources Roadmap

Appendix 15: DTRA – Accelerator Technology for Long-Range Detection of Nuclear Material

To view Appendices 3-15, visit
http://acceleratorsamerica.org/report/accelerator_task_force_report_appendices.pdf