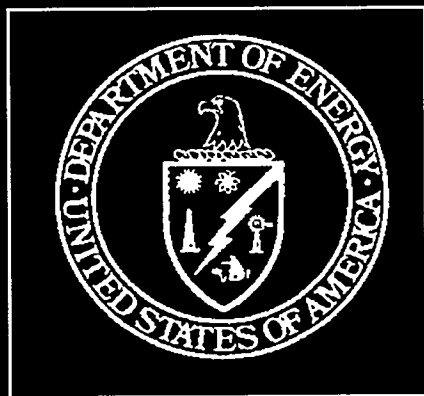


High Energy Physics Advisory Panel's Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology

May 1996



U.S. Department of Energy
Office of Energy Research
Division of High Energy Physics

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May 17, 1996

Dr. Martha Krebs
Director
Office of Energy Research, ER-1/FORS
U. S. Department of Energy
Washington, DC 20585

Dear Martha,

I am pleased to transmit to you the report of the "High Energy Physics Advisory Panel's (HEPAP) Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology" chaired by Dr. Jay Marx. This Subpanel has been formed in response to your letter to me dated November 17, 1994, requesting that a HEPAP subpanel be convened to examine these issues and that its membership be drawn also from, or through, the other four Energy Research advisory committees. HEPAP discussed this report initially at its February 26 and 27 meeting and after extensive discussions its members unanimously endorsed all six of the Subpanel's recommendations.

The HEPAP members were impressed by the broad spectrum of interests covered by the Subpanel membership, by the great effort expended in soliciting as wide an input as possible from all concerned scientific communities, by the Subpanel's extensive deliberations, and by the thoughtfulness of its recommendations.

The HEPAP feels that the Subpanel has done an excellent job of pointing out how the progress and developments in the accelerator science have been the engine driving progress in both particle and nuclear physics. In addition, accelerator advancements have had a major unanticipated impact on a variety of other scientific fields, such as chemistry, biology, medicine, and materials science. The HEPAP strongly endorses the idea that the Office of Energy Research (OER) should continue its strong support of accelerator science.

This Subpanel, albeit a HEPAP Subpanel, drew its membership from and through all five of the Office of Energy Research Advisory Committees. Mechanisms were set up to keep the other four committees apprised of the Subpanel's deliberations and to channel the other committees' views to the

May 21, 1996

Subpanel. I would like to summarize for you briefly, the actions of the other ER advisory committees regarding this Subpanel report. The letters to me from three other Chairs regarding their committees' reactions are attached to the report. The Fusion Energy Sciences Advisory Committee has been very much preoccupied during the last several months in formulating a new long range plan for fusion science in light of the drastically curtailed funding. Accordingly, it has not had the time to review and comment about the Accelerator Subpanel report.

There is a strong consensus among all the OER advisory committees that accelerator science and technology have had a major impact on all the fields they cover. They underscored that achievements in accelerator science have contributed greatly not only to the advancement of science but to the society as a whole, as clearly documented in the report. All the committees agree that the "stewardship of accelerator science and technology should be acknowledged as an explicit part of the overall DOE Energy Research Mission."

The Nuclear Science Advisory Committee (NSAC) has joined HEPAP in fully endorsing all of the Subpanel's recommendations. The other two committees expressed some reservations about Recommendation C (Basic Energy sciences Advisory Committee, BESAC) and Recommendations B and C (Health and Environmental Research Advisory Committee, HERAC). Both BESAC and HERAC expressed concern that the Subpanel's recommendations might be interpreted as mandated "set-asides" for accelerator science research. This was not the intention of the Subpanel, and the language in the final draft has been modified somewhat to try to alleviate those fears.

All the committees applauded the thorough work that the Subpanel has done in carrying out its mission. The Report should provide for you a comprehensive documentation of the past achievements of accelerator science and give useful guidance to the OER as it formulates its plans for future stewardship of the field of accelerator science and technology. On behalf of HEPAP and the other OER advisory committees, I would like to express deepest thanks to Dr. Jay Marx and the rest of the Subpanel members for their hard and dedicated work that was necessary to generate this excellent report.

Sincerely yours

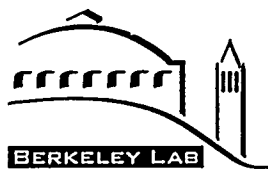


Stanley Wojcicki

HEPAP Chairman

SW/jlm

Enclosures



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Dear Stan:

On behalf of the HEPAP Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology, I am pleased to transmit our report.

This subpanel has carried out a broad assessment of the status and promise of accelerator physics and technology with respect to all five DOE Office of Energy Research (OER) programs. The subpanel drew its members from the scientific communities supported by the OER programs and included a liaison from each OER advisory committee as a full member. In meetings over a period of eight months we addressed the charge, and in doing so, sought input from all OER program offices, the accelerator physics community, representatives of those scientific communities supported by the OER programs, DOE laboratories and universities that host major accelerator facilities, and other DOE offices and federal agencies.

After extensive deliberations, the subpanel has concluded that the DOE and its predecessor agencies—primarily through their long-standing and sustained investments in accelerator science and technology development—have *de facto* held a national trust for the stewardship of accelerator science and accelerator-based technology development. This role has provided the foundation for essential capabilities needed both to fulfill the DOE mission and to address broader national interests.

We have also concluded that it is vital that the DOE and its OER programs explicitly acknowledge this national trust for accelerator science and technology, and that this trust and the resulting stewardship responsibilities should be an explicit part of the overall DOE OER mission.

The subpanel also undertook an extensive assessment of accelerator R&D in the OER programs. We conclude that the current approach for supporting short-term accelerator R&D, which is generally centered at facilities, is effective. The subpanel also endorses the present system of supporting medium-term accelerator R&D, which is generally directed at future facility capabilities, with funds from the

facility budgets. However, we believe that this approach could yield additional benefits if the BES and NP programs were to more explicitly recognize the value of such investments and evaluate the performance of their accelerator-based facilities accordingly.

The subpanel discussed at length the question of whether all OER offices should also support proposal-driven, peer-reviewed, long-term accelerator research and development, as the high energy physics program does now. As accelerators have become increasingly vital to research in NP, BES, OFE, and OHER, a similar need has emerged for such long-term accelerator R&D as an essential component of these OER programs. Accordingly, the subpanel believes that support for such R&D is necessary if these programs are to meet their scientific missions, impact national needs, fully benefit from the creativity of accelerator scientists and engineers at universities and national laboratories, and contribute to the education of the scientists and engineers who will be needed to build and operate facilities in the future. We conclude that these programs must include planning and funding for needed long-term accelerator capabilities. This conclusion was reached after consideration of input from the DOE OER program offices, from other parts of the agency, from the accelerator science community, and especially from a panel of highly regarded researchers whose collective vision spans the full range of the OER mission.

Finally, we wish to emphasize that during the deliberations of this subpanel, the essential contributions of accelerator science and technology to basic scientific research and to society as a whole were dramatically underscored. Accelerator science and technology is a vital and intellectually exciting field—one that has provided essential capabilities for the DOE OER research programs, has had an enormous impact on the nation's scientific research, and has significantly enhanced the nation's biomedical and industrial capabilities. Strong support of this field is essential to the continuing health of OER's scientific programs.

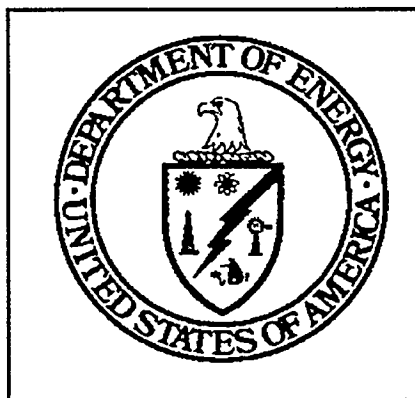
Yours sincerely,


Jay Marx for the

HEPAP Composite Subpanel for the Assessment of the
Status of Accelerator Physics and Technology
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High Energy Physics Advisory Panel's Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology

May 1996



MASTER

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CONTENTS

EXECUTIVE SUMMARY

Chapter I	Introduction	1
Chapter II	Department of Energy Office of Energy Research Stewardship Responsibilities for Accelerator Science and Technology	5
Chapter III	Contributions to the Office of Energy Research Scientific Missions	9
Chapter IV	Contributions to the Nation	23
Chapter V	Accelerator Science and Technology	31
Chapter VI	Management and Funding	35
Chapter VII	Conclusions and Major Recommendations	49

Appendices

- A. Charge to Subpanel
- B. Subpanel Membership List
- C. Subpanel Meeting Agendas and Acknowledgements
- D. Contributions of Accelerator Science and Technology to Office of Energy Research Programs
- E. Contributions to the Nation
- F. Accelerator Science and Technology in Support of Office of Energy Research Programs
- G. Letters to the HEPAP Chair from the other Energy Research Advisory Committees

EXECUTIVE SUMMARY

In November 1994, Dr. Martha Krebs, Director of the U.S. Department of Energy (DOE) Office of Energy Research (OER), initiated a broad assessment of the current status and promise of the field of accelerator physics and technology with respect to five OER programs—High Energy Physics, Nuclear Physics, Basic Energy Sciences, Fusion Energy, and Health and Environmental Research. Dr. Krebs asked the High Energy Physics Advisory Panel (HEPAP) to establish a composite subpanel with representation from the five OER advisory committees (HEPAP, Nuclear Science Advisory Committee [NSAC], Basic Energy Sciences Advisory Committee [BESAC], Fusion Energy Advisory Committee [FEAC], and Health and Environmental Research Advisory Committee [HERAC]) and with a balance of membership drawn broadly from both the accelerator community and from those scientific disciplines associated with the OER programs. The Subpanel was also charged to provide recommendations and guidance on appropriate future research and development needs, management issues, and funding requirements.

The Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology has sought information and advice using an open and participatory process. At three of its meetings, it heard presentations by OER program managers, by members of the accelerator physics community, and by leading scientists representing the major scientific fields that use accelerators. The Subpanel gathered information on accelerator R&D efforts from the national laboratories, university facilities supported by DOE and National Science Foundation (NSF), and DOE program managers.

The Subpanel finds that accelerator science and technology is a vital and intellectually exciting field. It has provided essential capabilities for the DOE/OER research programs with an enormous impact on the nation's scientific research, and it has significantly enhanced the nation's biomedical and industrial capabilities. Further

progress in this field promises to open new possibilities for the scientific goals of the OER programs and to further benefit the nation.

Sustained support of forefront accelerator research and development by the DOE's OER programs and the DOE's predecessor agencies—the Atomic Energy Commission (AEC) and the Energy Research and Development Agency (ERDA)—has been responsible for much of this impact on research. This report documents these contributions to the DOE energy research mission and to the nation.

This Subpanel believes that the DOE and its predecessor agencies—primarily through their long-standing and sustained investments in accelerator science and technology development—have *de facto* held a national trust for the stewardship of accelerator science and accelerator-based technology development. This has provided the foundation for essential capabilities needed both for the DOE mission and for addressing broader national interests. This Subpanel has concluded that it is vital that the DOE and its OER programs continue to hold this national trust and thus recommends that:

- A. Stewardship of accelerator science and technology should be acknowledged as an explicit part of the overall DOE Energy Research mission.**

These stewardship responsibilities are elaborated in Chapters 2 and 7.

The Subpanel examined the approach used by the five OER programs in managing and funding their R&D activities in accelerator science and technology to determine if each is carried out in a manner appropriate to the overall needs of that program. We identified three broad categories of accelerator R&D (short, medium, and long-term) that are useful for assessing the management of these activities. A principal focus of the Subpanel was long-term R&D that provides the scientific basis for the concepts and technologies that drive the development of important future

accelerator-based capabilities. Our assessment of long-term accelerator R&D led us to recommend that:

- B. Each OER program should have proposal-driven, peer-reviewed long-term accelerator R&D as part of its research portfolio.**
- C. The Director of Energy Research should charge the appropriate OER advisory committees with recommending the level of long-term accelerator R&D funding for each program.**

A more detailed discussion of these recommendations appears in Chapters 6 and 7.

The Subpanel found that the management of short-term (design, construction, operation, and improvement of existing or approved facilities) and medium-term (future capabilities of interest to a specific laboratory or facility) accelerator R&D is generally effective. Both types are conducted at a national laboratory or accelerator facility, where the management determines the scope of this R&D. We recommend that:

- D. The current approach to short-term, facility-directed accelerator R&D should be continued.**

The Subpanel endorses the present funding of medium-term accelerator R&D by facility budgets and Laboratory Directed R&D (LDRD) funds. However, additional benefits would be gained by each program office explicitly recognizing the value of such investments and evaluating the performance of its accelerator-based facilities accordingly. We recommend that:

- E. The present system of medium-term R&D directed at future capabilities of interest to laboratories, facilities or users of facilities should be strengthened.**

Associated with OER's stewardship of accelerator science and technology is a responsibility to encourage the timely dissemination of this knowledge and technology. To be effective this requires an environment that fosters communication and cooperation between the OER laboratories and grantees on one hand, and the industrial and commercial sectors on the other. We recommend that:

- F. OER program officers and laboratory managers who are responsible for the stewardship of accelerator science and technology should make a special effort to nurture societal applications.**

I. INTRODUCTION

In January 1994, representatives of the Division of Physics of Beams (DPB) of the American Physical Society (APS) approached Dr. Martha Krebs, Director of the Department of Energy (DOE) Office of Energy Research (OER), to propose that a study be done on the importance of accelerator physics and technology to the nation. After taking the proposal under advisement, Dr. Krebs decided to initiate an examination of accelerator science and technology as supported by five OER programs: High Energy Physics (HEP), Nuclear Physics (NP), Basic Energy Sciences (BES), Fusion Energy (OFE), and Health and Environmental Research (OHER). Dr. Krebs asked the High Energy Physics Advisory Panel (HEPAP) to assume executive responsibility for establishing a composite subpanel with representation from all five OER program advisory committees (HEPAP, Nuclear Science Advisory Committee [NSAC], Basic Energy Sciences Advisory Committee [BESAC], Fusion Energy Advisory Committee [FEAC], and Health and Environmental Research Advisory Committee [HERAC]) to perform the study, and she conveyed to the chairman of HEPAP a Charge to the Subpanel (Appendix A).

In her charge, Dr. Krebs requested that the composite subpanel carry out a broad assessment of the current status and promise of the field of accelerator physics and technology with respect to the five OER programs and provide recommendations and guidance to her on appropriate future research and development needs, management issues, and funding requirements. The Subpanel was given wide latitude in carrying out the study, but the following issues and questions were to be addressed:

- A. Review and summarize the role that accelerators, storage rings and colliding beam devices play in the OER research programs, providing also a brief summary of the R&D carried out within each program to support accelerator, storage ring, and colliding beam facility operations; for the

improvement of existing facilities; and for the development of new facilities.

- B. Provide an assessment of spin-offs and applications from the OER accelerator R&D activities with a focus on contributions to the productivity and competitiveness of American science, industry, and medicine in a world economy.
- C. Determine if the level of R&D for each OER program is appropriate, in terms of R&D content, activity level, and funding, to ensure the success of the scientific goals of that program and to assess future opportunities to meet national needs through accelerator science.
- D. Examine the approach used by the five individual OER program offices in managing their R&D activities in accelerator physics and technology to determine if each is appropriate to the overall needs of that program.

In response to Dr. Krebs' request, this Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology was set up with five members who also served as liaison representatives for each of the five advisory committees that advise OER. The balance of membership was drawn from both the accelerator community and from those scientific disciplines associated with the OER programs. Appendix B provides the full Subpanel membership.

An early response of the Subpanel to the charge was a decision to seek information and advice using an open and participatory process. Three meetings were held to gather information from OER program managers, accelerator physicists, and scientists representing the major scientific fields enabled by accelerators. The information addressed the long-range directions and needs of the OER programs and the scope, funding, and management of accelerator R&D within OER. The first

meeting, on June 28-29, 1995, included presentations by representatives of the five OER programs. It also included a session with Dr. Krebs on her expectations of the Subpanel. The second meeting was held August 2-3, 1995. Information was provided by members of the accelerator community whose names had been suggested by the executive committee of the APS DPB. Representatives from DOE's Defense Programs (DP) and the National Science Foundation (NSF) also spoke to the Subpanel. An "open mike" session provided opportunity for anyone to speak. The third meeting was held September 8-10, 1995, and consisted of input from sixteen eminent and visionary scientists selected by the five OER advisory committees as representative of the relevant scientific communities. Throughout the meetings, designated representatives of the five OER programs were invited to be present as observers and participants.

Appendix C provides the agendas for all three information-gathering meetings, including names and affiliations of those providing testimony to the Subpanel. The Subpanel also gathered information on accelerator R&D efforts from the national laboratories, university facilities supported by DOE and NSF, and DOE program managers. An acknowledgment of other sources of information is also provided in Appendix C.

This wealth of information provided the Subpanel with a broad perspective regarding the status of accelerator science and technology, the scope of current accelerator R&D, and future directions of scientific fields that use accelerator-based technology in support of the OER mission.

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II. DEPARTMENT OF ENERGY OFFICE OF ENERGY RESEARCH STEWARDSHIP RESPONSIBILITIES FOR ACCELERATOR SCIENCE AND TECHNOLOGY

Over the past 50 years or more, accelerator science and technology has provided essential capabilities for the Department of Energy Office of Energy Research (DOE/OER) research programs. It has had an enormous impact on the nation's scientific research and has significantly enhanced the nation's biomedical and industrial capabilities. Much of this impact can be traced to the support of forefront accelerator research and development as part of the DOE/OER programs and to the support of such activities by the DOE's predecessor agencies, the Atomic Energy Commission (AEC) and the Energy Research and Development Agency (ERDA). It is the view of this Subpanel that the DOE and its predecessor agencies—primarily through their long-standing and sustained investments in accelerator science and technology development—have held a *de facto* national trust for the stewardship of accelerator science and accelerator-based technology development. This stewardship has provided the foundation for essential capabilities needed both for the DOE mission and for addressing broader national interests.

Although many significant contributions to the accelerator field have been made by researchers supported by other government entities and by other nations, it is the high level of investment in accelerator science and technology by the AEC, ERDA, and DOE, the sustained level of commitment, and the number and impact of the developments resulting from this support that leads the Subpanel to this point of view. Appendices D and E document many of these contributions that have flowed from the investments made by AEC, ERDA, and DOE in the accelerator field over the past half century.

This Subpanel's recognition of the importance of DOE/OER's historical stewardship role emerged from hearing and considering detailed information from the DOE/OER program offices, from other parts of the agency, from the accelerator

science community, and especially from a panel of highly regarded researchers whose collective vision spans the full range of the OER mission.

The Subpanel strongly believes that it is vital that the DOE and its OER programs continue to hold accelerator science and technology as a national trust. This trust and the resulting stewardship responsibilities should now be an explicit rather than a de facto part of the overall DOE/OER mission to ensure that this activity will be effectively and consistently pursued. These stewardship responsibilities are essential if accelerator science and technology are to continue to support the DOE mission and the national interest.

This Subpanel has considered the range and depth of stewardship responsibilities that should be an explicit part of OER's portfolio and mission. In the Subpanel's view, the following are the important stewardship responsibilities:

- A. Design, construction, and improvement of accelerator-based facilities providing vital capabilities needed to carry out the mission of DOE's OER programs.
- B. Effective utilization and operation of these accelerator-based facilities.
- C. Support of the accelerator R&D required to provide facilities at the technological cutting-edge for the sciences that they serve.
- D. Appropriate investment in basic accelerator science and related technology R&D to form the foundation for capabilities needed in the future.
- E. Support of the training of the accelerator scientists and engineers required to provide the accelerator-based capabilities needed in future years.

- F. Support for the continued development and maintenance of the basic tools needed to stay at the cutting edge in the accelerator field (e.g., computer codes, essential stand-alone test facilities, and critical infrastructure elements at the accelerator-based facilities).

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III. CONTRIBUTIONS TO OFFICE OF ENERGY RESEARCH SCIENTIFIC MISSIONS

The Office of Energy Research (OER) provided approximately \$1.7B of support for basic research in FY1995. If the additional investment in instrumentation and the construction of major research facilities is included, OER ranks second only to the National Institutes of Health (NIH) in research investment. As stated in the OER Strategic Plan (DOE/ER-0656), OER supports "programs of basic and applied research that support the Department's energy, environmental, and national defense missions and that provide the foundation for technical advancement." The range of scientific fields supported by OER is consequently extensive, including: material and chemical sciences, geosciences, engineering, energy biosciences, fusion, high energy and nuclear physics, nuclear medical applications, environmental studies, and general life sciences, including the Human Genome Project. The research facilities and infrastructure developed and supported through OER enable key components of research in these many fields for thousands of researchers funded by the Department, other agencies, and industry.

In this section, we briefly summarize the extent and manner by which accelerator physics and technology play a critical role in making it possible for the United States to push forward the frontiers of research in this extensive array of scientific fields. More detailed descriptions of the scientific programs and the role played by accelerators in each of the five OER programs are given in Appendix D.

High Energy Physics

High energy physics studies the fundamental structure of matter and the laws governing the interactions of the basic constituents of the Universe. During the last decades, experiments on accelerators and colliders have enabled high energy physicists to develop a deep understanding of the basic constituents of matter and their interactions. As the energy and the intensity of accelerators and colliders increased,

new subatomic particles were discovered, and their interaction elucidated. Thus, the progress in high energy physics has been strictly paced by the progress in the physics and technology of accelerators, establishing a tight correlation between the two disciplines.

Major high energy physics accomplishments at U.S. accelerators during the past 25 years include:

- The discovery of the τ -lepton, and the charm, bottom, and top quarks. These discoveries led directly to the Standard Model of quarks and leptons that is the synthesis of the current understanding of fundamental particles and their interactions.
- Systematic studies of the properties of these new particles including measurements of masses and decay ratios. Much of our knowledge of the strong and electroweak forces comes from the results of these experiments.
- Experiments probing the structure of protons and neutrons, the particles that make up nuclei.
- Experiments that search for physics beyond the Standard Model. These include searches for rare or forbidden decays of elementary particles, and precision measurements of decay ratios, scattering probabilities, and beam polarization dependence.

High energy physics experiments are presently being done at Fermi National Accelerator Laboratory (Fermilab), Stanford Linear Accelerator Center (SLAC), Brookhaven National Laboratory (BNL), and Cornell in the United States, and also at laboratories in Europe, Japan, China, and Russia. The U.S. program is centered on fixed-target experiments at BNL (high-intensity proton beams accelerated to 30 GeV),

Fermilab (protons accelerated to 800 GeV), and SLAC (electrons accelerated to 50 GeV), and collider experiments at Fermilab (proton and antiproton beams accelerated up to 900 GeV per beam), SLAC (electron and positron beams accelerated up to 50 GeV per beam) and Cornell (electron and positron beams accelerated up to 6 GeV per beam). The Fermilab Tevatron collider is presently the highest energy collider in the world. The Stanford Linear Collider (SLC) at SLAC is the world's first linear collider. The Cornell Electron Storage Ring (CESR) at Cornell is the world's highest luminosity electron-positron collider. After the cancellation of the Superconducting Super Collider (SSC), the U.S. high energy physics community participation in the Large Hadron Collider (LHC) program at the European Laboratory for Particle Physics (CERN) has become a high priority.

Measuring top quark properties, exploring the particle-antiparticle asymmetry in nature, and elucidating the Higgs mechanism, the means by which particles obtain mass, are some of the most exciting scientific challenges for this field today. As in the past, progress on these scientific issues requires advances in the physics and technology of accelerators. The Fermilab Main Injector project will increase the Tevatron luminosity and the top quark production rate substantially. B-meson decay probes the particle-antiparticle asymmetry, and Positron-Electron Project (PEPII) (the SLAC asymmetric B-Factory now under construction) and the CESR luminosity upgrade are aimed at significant B-meson production rates.

Study of the Higgs mechanism requires higher energy than now available, and colliders with higher energy and luminosity are being designed and studied to further expand the high energy physics frontier. The LHC at CERN is a European project in which U.S. participation is being negotiated at the time this report is being written. The design of a next-generation, high-energy linear collider has advanced to a stage that includes engineering and cost considerations as well as prototypes and studies of underlying accelerator physics. Much of this work is being done in a large international collaboration involving the United States, Europe, and Japan. Other ideas

for future colliders are being studied although the work is not now as developed as that for a future linear collider. These ideas include: photon-photon colliders, TeV lepton colliders using unstable muons, and high-luminosity, multi-TeV proton colliders. Novel accelerator concepts, such as plasma-based acceleration in non-conventional structures, are being studied with the goal of further reductions in accelerator cost and size.

Nuclear Physics

The goal of nuclear physics research is to understand, at a fundamental level, the structure and dynamics of strongly interacting matter, its properties under a wide variety of conditions in the laboratory and the cosmos, and the forces that govern its behavior. Nuclear physics research depends, to a large degree, on the use of accelerators for its experimental investigation. Corresponding to the diversity of the field, a relatively large number of accelerator facilities of varying energy, type, and particle beams are employed. While early experiments were most frequently conducted at university-based small accelerators, the steadily increasing requirements in energy, intensity, and beam species have led to large, dedicated nuclear physics accelerator facilities.

Major nuclear physics accomplishments at U.S. accelerators during the past 25 years include:

- The exploration of the single-particle and the collective degrees of freedom and of the underlying symmetries in the strong-interaction nuclear many-body system.
- The rather complete description of the strong nucleon-nucleon interaction and its application to nuclei.

- The discovery of the parton structure of nuclei.
- The discovery of numerous new chemical elements up to element 111.
- The generation of hot, dense nuclear matter in the laboratory, allowing the study of hadronic matter under conditions approaching those present in neutron stars and at the origin of the universe.
- The study of nuclear reactions involving nuclei far from stability, which provide direct experimental information on important astrophysical processes, including those that fuel the Sun and determine nucleosynthesis.
- Precision measurements of the properties of the neutrino and the weak interaction, which help shape the Standard Model of fundamental particles and interactions.
- Development of accelerator mass spectrometry, the ultrasensitive detection method for long-lived radioisotopes, which has revolutionized archeological dating and found widespread application in various other areas of interdisciplinary research.

The present scientific objectives in nuclear physics can be grouped into four broad thrusts outlined in the 1996 Nuclear Science Advisory Committee Long-Range Plan.

The first objective is to explore the limits of nuclear structure and dynamics. In this area, nuclei are studied at the extremes of spin, temperature, and isospin, and in regions near the drip lines where nuclear binding comes to an end. An illustrative example is the study of the structures and symmetries governing the behavior of rapidly rotating, highly deformed nuclei. Most experiments in this field are performed

at smaller facilities that have been developed at both national laboratories and universities to provide unique capabilities in terms of beam species and characteristics.

The second broad thrust in nuclear physics is directed at the quark structure of matter. Here the field strives to understand nuclei and nuclear forces in terms of quantum chromodynamics (QCD), that is, the interactions of the underlying fundamental constituents, quarks and gluons, and to establish a bridge from this new understanding to descriptions in terms of nucleons and mesons. Beams of electrons, photons, and protons are essential tools. A major new facility, the Continuous Electron Beam Accelerator Facility (CEBAF) in Virginia, is aimed at this area of nuclear physics research.

Strongly interacting nuclear matter is expected to undergo phase transitions when exposed to extreme conditions. This defines a third major thrust of nuclear physics research, which attempts, through heavy-ion collisions at intermediate and very high energies, to explore the equivalent of a liquid-gas phase transition for quantum systems and the transition from hot, dense nuclear matter to a quark-gluon plasma. Producing this latter state of matter, in which quarks and gluons are deconfined, will be the objective of research at the Relativistic Heavy Ion Collider (RHIC), now under construction at BNL. At present, the heavy ion physics program at Brookhaven utilizes the AGS for fixed-target experiments aimed at exploration of nuclear matter under extreme conditions.

The fourth objective concerns fundamental symmetries and tests of the Standard Model at low energies, and their connection to nuclear astrophysics. Precision experiments (focusing, for example, on parity violation) with the techniques of nuclear physics (for example, electron scattering of nucleons and nuclei) can shed light on the limitations of the Standard Model in ways complementary to high energy physics. A major component in this area of research is the study of neutrino properties, involving both accelerators and non-accelerator facilities.

CEBAF and RHIC are currently the major investments of nuclear physics in forefront accelerator facilities. In the long term, their operation and the research efforts of their university-based users, will occupy more than half of the planned Department of Energy (DOE) nuclear physics budget.

A number of smaller accelerator facilities at universities and national laboratories around the country have unique characteristics and capabilities. These facilities are supported by both DOE and the National Science Foundation (NSF) and provide training for graduate students in a direct, hands-on manner. They constitute an important component in the nuclear physics program. Brief descriptions of the nuclear physics facilities are given in Appendix D.

Some nuclear physics research also utilizes high energy physics accelerator facilities, such as the program at the Alternating Gradient Synchrotron (AGS) at BNL, which uses both heavy-ion and proton beams in a fixed-target mode. Other experiments are being carried out at Fermilab and at Deutsches Elektronen Synchrotron (DESY) in Germany.

With the operation of CEBAF, the completion of RHIC, and new radioactive beam facilities, accelerators and accelerator technology developments are defining many of the forefront opportunities in nuclear physics research.

Basic Energy Sciences

The mission of Basic Energy Sciences (BES) is to expand scientific knowledge and technical skills needed to aid long-term economic growth and to develop new and existing energy resources. BES has sub-programs in materials science, chemical science, biosciences, and earth sciences. A component of the research performed for the BES materials science and chemical science programs is done at a suite of major accelerator-based facilities operated by BES—four of the nation's eight synchrotron

light sources (the Advanced Light Source [ALS] at Lawrence Berkeley National Laboratory [LBNL], the Advanced Photon Source [APS] at Argonne National Laboratory [ANL], the National Synchrotron Light Source [NSLS] at BNL, and Stanford Synchrotron Radiation Laboratory [SSRL] at SLAC) and the two U.S. pulsed neutron sources (the Intense Pulsed Neutron Source [IPNS] at ANL and Los Alamos Neutron Scattering Center [LANSCE] at Los Alamos National Laboratory [LANL]). At present, no additional light sources or neutron sources are under construction. However, beam lines are being added at existing light sources, and a design study is underway for a state-of-the-art pulsed spallation neutron source. BES also supports programs at national laboratories and universities using electron microscopes and ion-implantation facilities for characterization and modification of a wide variety of materials. All of these BES-supported accelerated-based research facilities are used by thousands of basic and applied scientists supported by the DOE, other Government agencies, and industry (see Appendix D).

Neutron Scattering. Neutron sources have provided capabilities which have led to important advances in basic science and technology. The following are some examples:

- Ever since the discovery of the high-T_c ceramics, neutrons have been the principal contributors to the knowledge of their structures because of the sensitivity of neutrons to light atoms (here, importantly, oxygen) in the presence of heavy ones.
- Chopper spectrometers at pulsed neutron sources have made possible measurements of the Bose condensate fraction in superfluid helium.
- Neutrons have thrown new light on the conformations and interactions of polymeric materials in bulk and solution. Using proton/deuteron substitution, individual molecules or segments of molecules can be labeled.

- Because neutrons penetrate centimeter depths in many materials, high resolution neutron diffraction can probe the strain distribution in bulk materials. Measurements of residual stresses in welded sections and plastically deformed specimens, and temperature dependence of stresses in fiber-reinforced composites provide the basis for new understanding of engineering materials.
- Neutron radiography finds many technical applications, such as in the inspection of aircraft structures for evidence of corrosion and in the radiography of turbine blades.
- The recently-developed technique of neutron reflectometry provides a way to determine the variation of chemical composition and (using polarized neutrons) the magnetization density in films, multilayers, and bulk material surfaces.

Increases in neutron flux, such as would be provided by next-generation spallation neutron sources, would lead directly to increased capability for these and other studies.

Synchrotron Radiation. The increasing availability and capability of synchrotron radiation has provided major benefits to many fields of research relating to BES programs—including chemistry, materials science, and surface science—as well as to technology. Examples include:

- High-resolution, angle-resolved photoemission experiments have generated new understanding of highly correlated and magnetic materials, including high temperature superconductors.
- In-situ studies of organometallic vapor phase epitaxial growth using X-ray diffraction have contributed vital information on this technique, which is

used commercially to produce high quality GaAs, CdTe and other important semiconductors.

- Nondestructive measurement of silicon wafer cleanliness with linearly polarized synchrotron radiation has achieved about a factor of 20 improvement in the detection limits with a technique called total reflection X-ray fluorescence. Such improvements in sensitivity will be critical to the development of the next generation of integrated circuits.
- Circularly polarized soft X-rays have been used to study magnetic materials, including the magnetic and magneto-optic recording materials that underlie data storage in the computer industry. X-rays avoid the diffraction limit of laser light and can penetrate coatings to image the shape and properties of magnetic recording bits.
- The high brightness and tunability of synchrotron radiation from the IR to hard X-rays has led to major advances in spectromicroscopy. A variety of chemically selective imaging techniques are used, including scanning transmission and photoelectron imaging, to study many different materials, ranging from semiconductors to radioactive materials to materials of forensic interest.
- The selective ionization made possible by tunable synchrotron radiation has been used, together with lasers and molecular beams, to study processes relating to combustion and photochemistry in general, including the dynamics of ozone dissociation in the atmosphere.

The performance of synchrotron radiation light sources has increased greatly with advances in accelerators and insertion-device technology. For example, X-ray source brightness has increased by about 11 orders of magnitude during the past 25

years. Since we are still far from fundamental limits on source performance, ideas for next-generation light sources are now being developed. These include storage rings with lower electron beam emittance and short wavelength free electron lasers (FELs). The latter would offer X-ray beams with full transverse coherence and with a peak brightness about 10 orders of magnitude higher than that available today.

Health and Environmental Research

The Office of Health and Environmental Research (OHER) develops and supports fundamental science that underpins the strategic goals of the DOE in areas related to health and environmental effects. The program mission is to "develop the knowledge needed to identify, understand, and anticipate the long-term health and environmental consequences of energy production, development, and use." Accelerator-based technologies contribute to several OHER strategic objectives: using unique national laboratory facilities for structural studies at the molecular and cellular level, developing advanced medical technologies and radiopharmaceuticals, and contributing to environmental cleanup by developing advanced remediation tools.

Operations and direct support of accelerator facilities are not part of the direct mission orientation of OHER, nor is R&D on them. Some accelerator operations are supported as part of research programs on isotope production at accelerators. The Office does support R&D at accelerator-based *user* facilities in areas relevant to achieving the above strategic objectives. In some of these cases, OHER cooperates closely with other Offices such as BES or other Federal agencies (NIH and NSF) to achieve its goals most effectively and to best meet the needs of the national scientific user community.

A particularly important example is OHER's program to enable the effective use of synchrotron radiation for structural molecular biology research. Structural molecular biologists use information on biological structure at atomic resolution to

gain fundamental insights into function (such as muscle contraction), into biological processes (like cell division and cancer), and to provide the means to design new drugs to correct malfunction or disease (like viral and bacterial infections). During the past decade synchrotron radiation has become recognized as an extremely powerful tool enabling state-of-the-art research in this area, leading to a rapidly growing user community and a need for more beam time.

In the environmental area, synchrotron radiation studies of the electronic structure and speciation of actinides in weapons plant waste products provides vital information relevant to developing strategies for remediation and long-term storage.

National user facilities developed and supported by OHER at the synchrotron facilities operated by BES are the primary means by which OHER program needs are being met. OHER supports R&D activities on the development of new beam lines, insertion devices (wigglers and undulators), and optical systems tailored to produce radiation optimized for the study of biological and environmental samples. Other areas to which OHER provides support include the development of: specialized sample manipulation instrumentation, advanced detectors for both synchrotron and neutron applications, and advanced computational methodologies.

In nuclear medicine, OHER supports the development of new target designs for the efficient production of radioisotopes at accelerators, with current emphasis on modeling of heat transfer properties to permit the handling of deposited beam power. The program also funds identification and development of procedures for production at accelerators of new isotopes for medical research, including nuclear cross-section studies, targetry research, development of radioanalytical methodologies, and neutron therapy for brain tumors.

Fusion Energy

Fusion is the process that powers the Sun and the stars. The oceans and other waters contain vast quantities of the fuel needed to power fusion reactions, and the goal of fusion energy research is the production of controlled fusion energy for electric power generation. This is a daunting goal. Worldwide, the total continuing investment for fusion research is approximately \$1B per year. After more than 40 years of research, fusion devices have only recently begun producing megawatts of power, and commercialization will still require several decades of research.

There are two principal approaches to fusion energy, magnetic and inertial, and OER supports research on both. In addition, DOE's Office of Defense Programs (DP) supports the Inertial Confinement Fusion Program for defense applications.

Accelerators play three principal roles and several subsidiary roles in the OER fusion program. The principal roles are discussed below.

Plasma heating for magnetic fusion energy. The neutral-beam accelerators for plasma heating recently enabled the Tokamak Fusion Test Reactor (TFTR) at Princeton to achieve a world-record fusion power level of approximately 10 MW.

Drivers for inertial fusion energy. Accelerator drivers for inertial fusion have demanding requirements on beam current and beam brightness. While some of the accelerator technology has already been developed by other OER programs, the study of these requirements has been an important factor in the creation of a new subfield of accelerator science, the physics of high-current beams. The combination of research into high-current beams with research into target physics supported by DOE/DP makes inertial fusion energy potentially a cost-effective development path to a commercial power plant. In addition to fusion, high currents are essential for many of the other new applications of accelerator technology such as destruction of radioactive waste, isotope production, food treatment, energy production, and defense.

Materials testing. The ultimate attractiveness of magnetic fusion energy depends on the development of low-activation materials that behave well under irradiation by neutrons. The Rotating Target Neutron Source accelerator has already provided important information regarding the behavior of materials, including optical materials, under neutron irradiation. The Fusion Energy Advisory Committee has concluded that it will be necessary to build a new, high-fluence neutron source for magnetic fusion energy materials development to continue these studies in the future and that an accelerator-based source is the system of choice.

Each of these roles could be critically important to fusion research, but support has not been steady. This is discussed in more detail in Appendix D.

IV. CONTRIBUTIONS TO THE NATION

Maintaining our nation's premier status in accelerator science and technology is necessary not only for the Office of Energy Research (OER) to fulfill its mission but also to provide broader benefits to the overall national interest such as keeping our economy vital through contributions to industrial innovation and advancement of medical and other applications. Many technologies that have evolved directly from developments in accelerator science over roughly the past 50 years have found significant applications in arenas of importance to the nation. A number of these applications, including medicine and health care, energy, and the environment, overlap the mission of the U.S. Department of Energy (DOE), while many others, such as industrial processing, directly benefit society at large. The DOE can be proud of the technical applications that benefit society and enhance U.S. competitiveness in the world market. In this section, we highlight the wide range of beneficial contributions that stem from accelerator concepts and discuss the mechanisms by which DOE technical achievements are spun off to industry (Appendix E provides a more complete description of these benefits).

Major Benefits to the Nation

There are well established applications of accelerator science and technology in diagnostic and therapeutic medicine for research and routine clinical treatments. A significant fraction of the radioisotopes used in treatment, diagnostics, and research are produced by accelerators. Beams of X-rays, neutrons, protons, and ions that are derived from particle accelerators are currently used in the treatment of cancer and other disease, while accelerators are used in many biomedical research programs to explore both beam-related treatment modalities and to develop other approaches to therapy. An example of the latter is the use of synchrotron radiation sources and high-

resolution X-ray crystallography to characterize the structure of viruses. If the link between structure and function can be determined, it may be possible to develop designer drugs that can subtly alter the viral structure so as to interfere with its functional ability to cause disease. Researchers are also using accelerator-based X-ray sources to develop approaches to non-invasive angiography in hopes of significantly reducing the risks associated with this important diagnostic tool.

Accelerators and associated technologies have various important uses in industry for R&D, manufacturing, testing, and process control. Industrial researchers, in common with materials scientists in universities and national laboratories, use synchrotron radiation, neutron scattering, and other accelerator-based techniques as important tools in their R&D activities. In industry, the R&D is often undertaken to develop new products—for example, high-density magnetic storage media. In manufacturing, beams from accelerators are used to alter material composition (e.g., ion implantation); to improve important characteristics of a product (e.g., sterilization of medical equipment and the hardening of surfaces for greater wear resistance); as a basic part of the production process (e.g., ion implantation and X-ray lithography in silicon wafer production, or X-ray micromachining); to improve industrial processes (e.g., curing epoxies and plastics); and to provide information about manufacturing processes (e.g., wear studies of materials or characterization of impurities in semiconductors).

Accelerator systems are important tools in fundamental and applied research. In addition to those uses mentioned elsewhere in this report, accelerators are used for accurate, nondestructive dating of archeological samples and art objects, and by National Aeronautics and Space Administration (NASA) for simulation of cosmic rays to determine the impact of this radiation on astronauts. Electron microscopes use electron beams to provide the detailed

images that permit researchers to understand the structure of biological and other materials. Developments in the understanding of beam dynamics and control hold promise for advancing electron microscopy capabilities.

Accelerators hold promise for impacting a number of critical societal problems, including energy production, waste treatment, and defense applications. Accelerators are a significant part of the fusion energy program and could be used to burn radioactive waste while generating useful energy. Food sterilization with beams could have significant benefits for food storage and distribution. Though still in its infancy, an accelerator-based, antiballistic missile system continues to be pursued. Finally, the use of accelerators to produce tritium for thermonuclear weaponry is now being considered as a leading approach in the coming decade.

These and other benefits are discussed in greater detail in Appendix E.

Interaction with the Private Sector

In this section, we briefly describe two Federal programs that involve accelerator R&D and provide economic benefit to the private sector. These are the Small Business Innovation Research (SBIR) program and the Cooperative Research and Development Agreement (CRADA) program.

By law, every Government agency that funds more than \$100M in extramural R&D must set aside a percentage of its R&D funds (2% in FY1996) to conduct an SBIR program. Small businesses submit research proposals and compete for awards once a year. Awardees receive up to \$75K in Phase I, then within a year compete for Phase II awards, which provide up to a total of \$750K for two years.

In the DOE, SBIR proposals are thoroughly peer-reviewed and the award process is quite competitive. SBIR proposals can only be submitted for specified research topics chosen by DOE programs. The current list of 41 topics includes several with direct relevance to accelerator physics, including *Technology and Instrumentation for High Energy Accelerators*, *Nuclear Physics Accelerator Technology*, and *Technology and Instrumentation for Heavy Ion Fusion Accelerators*. Other topics such as *Medical Applications* and *Fusion Energy Systems* frequently involve some degree of accelerator R&D. There are additional technical topics on instrumentation, data processing, and detector technology of interest to OER scientific programs. Award decisions are made by a combination of SBIR managers and appropriate DOE program office technical managers, after proposal review.

Examples of past successful projects include advances in superconducting wire and cable fabrication, development of new radiofrequency sources, target development for isotope production, and numerous improvements in electronic instrumentation. The SBIR program provides a significant source of additional funds for accelerator R&D, supporting OER scientific and technical goals as well as technology transfer to industry. Current Phase I SBIR programs include:

- Development and fabrication of superconducting wire (six projects)
- Advanced microwave concepts (seven projects)
- Electronic instrumentation, data acquisition, control, and new detectors (seven projects)
- Other projects involving innovative solutions to specific problems and needs (seven projects).

In contrast to SBIRs, CRADAs require a negotiated agreement between a laboratory and a commercial entity. They began as a result of Federal legislation passed during the 1980s to assist in commercializing spinoffs so that society can benefit from the extensive funds invested in science and technology.

Generally, collaboration between laboratories and the private sector for technology transfer has had mixed success because: (1) rigid procedural requirements, including intellectual property issues, make cooperative research between the labs and the private sector difficult; and (2) organizational cultures differ in perspectives and value systems, especially with regard to views on cost, schedules, the concept of deliverables, and optimization strategies for generic technology development.

Within the last year, three important studies involving the role of Federal research in fostering economic vigor and competitiveness have been completed:

- *Alternative Futures for the Department of Energy National Laboratories* (the so-called Galvin Committee Report), DOE, February 1995
- *Energy R&D: Shaping Our Nation's Future in a Competitive World* (the so-called Yergin Panel Report), DOE, June 1995
- *Allocating Federal Funds for Science and Technology*, National Academy of Sciences, December 1995.

All three reports recognize that there is only a limited role for Federal science to contribute to industry; however, they also recognize that private sector R&D is concentrating on shorter and shorter time horizons. Thus, Federal research

facilities can make a contribution if the particular technology is closely related to a core mission of the laboratory and if it is not something that industry would fund on its own anyway. The last two reports acknowledge that there are areas in which the national interest is not served by the market alone, such as new enabling or broadly applicable technologies.

In analyzing industry-laboratory interaction, the Subpanel has reached the following conclusions. First, some (perhaps many) national laboratory R&D activities are not relevant to industrial technology commercialization. Second, the highest probability of successful technology transfer occurs when there is user (industry) pull, as opposed to technology push from the laboratories, i.e., a perceived need should be the focus for identifying a commercialization opportunity. Third, the critical interface necessary for successful transfer and adoption of the technology involved is people-to-people contact. With these findings in mind, we offer the following suggestions for improving the impact of accelerator technology on society.

- A. Laboratory technologies should be better publicized to industry.
Experience with the Fermilab Industrial Affiliates Association and similar organizations elsewhere indicates that industry will make an effort to understand the technologies.
- B. Protocols for laboratory-industry interaction should be designed to minimize administrative and funding delays in the execution of cooperative projects.
- C. Laboratory managers should increase emphasis on the transition of laboratory technologies to the private sector and encourage scientists and engineers in their organizations to assist in transferring technology.

These issues must be addressed if DOE is to become more effective in contributing to U.S. competitiveness. In addition, the Subpanel believes that more attention should be paid within the DOE to providing an environment in which emerging technologies that do not fit into mainstream programs can be nurtured and possibly develop into new mainstream programs or into spinoffs.

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V. ACCELERATOR SCIENCE AND TECHNOLOGY

Advances in accelerator physics and technology have driven fundamental scientific research programs and led to significant societal impact during roughly the past 50 years. The field of accelerators began as an appendage to the fledgling fields of high energy physics (HEP) and nuclear physics (NP), providing these fields with essential experimental tools. Over the years, accelerator physics has matured into a scientific field in its own right. This new status is evidenced by sophisticated mathematical and computational tools for modeling beam behavior, experimental programs to study the basic physics of beams and the technology for producing beams, and journals and graduate level degree programs dedicated to accelerator physics. The American Physical Society (APS) has acknowledged the scientific status of the field by creating a Division of Physics of Beams (DPB).

The invention of the cyclotron in 1930 can be viewed as the start of the field of accelerator physics. This was followed by the discovery of phase stability and the invention of alternating-gradient focusing. These and other advances in accelerator technology have led to a million-fold increase in particle beam energy. We are now at the point where R&D on accelerator science leads in the medium-term to the construction of facilities and to facility upgrades that greatly expand the potential for scientific research. At the same time, long-term accelerator R&D is likely to make possible new capabilities that will benefit an ever-wider realm of science.

Accelerator physics and technology as a scientific discipline is practiced in universities as well as at the national laboratories, thus accessing the talent of university researchers and providing a training ground for students, who will become the next generation of scholars in this field and will also contribute to other scientific and technological fields.

Each Office of Energy Research (OER) program uses accelerators to a different extent. Appendix F details the frontiers of accelerator science and technology and the potential advances of further medium and long-term R&D in each program. These frontiers and potential advances indicate that specific long-term R&D is likely to have an impact in more than one OER program. For example, production and acceleration of high brightness electron beams will help both HEP, through the development of future linear colliders, and Basic Energy Sciences (BES), through increased brightness photon beams and free electron lasers (FELs). This translates into extension of our knowledge of the subatomic world and new tools for materials and biological research. Continued R&D on superconducting rf structures and the use of new superconducting materials can lead to improved accelerator capabilities for high energy and nuclear physics as well as for advanced FEL drivers. In addition, particle beams are one of the best tools for studying nonlinear physics. This field has applications all the way from celestial mechanics to biology and chaos theory. Finally, R&D on the production and transport of high intensity ion beams will make important contributions in HEP, NP, Fusion, BES, and other U.S. Department of Energy (DOE) programs outside OER, such as radioactive waste processing and tritium production. Other examples of such beneficial accelerator research can be found in Appendix F and include:

- beam stability and feedback
- storage ring quality magnets
- new superconducting materials
- novel lattices and beam optics
- high efficiency rf sources and accelerating structures
- beam polarization
- beam cooling
- targeting
- beam instrumentation and diagnostics

- beam control
- particle sources
- computer codes

It is important to recognize that unless the basic scientific knowledge is created to extend the reach of these generic areas, the field of accelerators will not continue to be as fruitful as it has been in the past in giving new tools to the DOE and to the nation to accomplish new goals. Unless new basic research is done, the old boundaries will restrict us to old levels of accomplishment.

Short, medium, and long-term accelerator R&D activities in individual OER programs were reviewed by the Subpanel (see Appendix F). Strong short-term and medium-term R&D programs exist at major accelerator facilities. To a lesser extent, long-term R&D programs are supported at some facilities. Only HEP has a major proposal-driven peer-reviewed program that supports medium and long-term R&D at universities and DOE facilities. This program has been successful with important contributions to superconducting wire development, to accelerator theory, to high-gradient acceleration, and to the support of accelerator education.

A strengthened long-term R&D program will have significant positive impact with regard to future facilities and the potential for scientific research in all OER programs.

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VI. MANAGEMENT AND FUNDING

The Subpanel examined the approach used by five Office of Energy Research (OER) programs in managing and funding their R&D activities in accelerator physics and technology to determine if each is appropriate to the overall needs of that program. A summary of that analysis and the conclusions drawn from it are presented in this section.

Management Approaches of Five Office of Energy Research Programs

The Subpanel identified three broad categories of accelerator research and development that are pertinent to accelerator-related activities supported by OER programs. Although these R&D categories sometimes overlap, they provide useful distinctions for commenting on the management of accelerator R&D activities by the five OER program offices.

- *Short-term R&D* is focused on the design, construction, operation, and improvement of existing or approved facilities. Such R&D is generally conducted at a national laboratory or accelerator facility where management determines the scope of this R&D.
- *Medium-term R&D* is related to future capabilities of interest to a specific laboratory or facility. Such R&D is most frequently conducted at a national laboratory or accelerator facility where management determines the scope of this R&D.
- *Long-term R&D* provides the scientific basis for the enabling concepts and technologies that drive the development of important future accelerator-based capabilities. It furthers the fundamental understanding of accelerators and maintains the vitality of

accelerator science as a science. As such, it is the basic research component of accelerator R&D. Examples of high impact past activities of this type are the successful development of superconducting rf cavities, high-current superconducting wire, and laser-driven, low-emittance photocathode electron sources. Long-term R&D involves the broader intellectual base available in the universities and the accelerator community.

The Office of Health and Environmental Research (OHER) funds specialized facilities for biological and environmental research at accelerators constructed and operated by Basic Energy Sciences (BES). OHER policy is that accelerator operations and R&D are not part of its direct mission, and it does not support accelerator R&D of any type above. It does support R&D in areas that directly enhance accelerator utilization, such as beamlines, instrumentation, and support facilities. OHER and closely related National Institutes of Health (NIH) activities are one of the growth areas in synchrotron radiation based sciences, and the presentations the Subpanel heard from OHER users were among the most demanding and the most creative in terms of future accelerator capabilities.

The OHER policy means that accelerator R&D needed for operational improvements and to pursue future directions will not be performed unless there is overlap with the interests of other OER programs and the relevant R&D is initiated and funded by those programs. For short-term and possibly medium-term R&D there is a substantial shared interest between OHER and BES. For long-term R&D (and for some medium-term research) there may or may not be such overlap with other OER programs. When there is overlap in these needed developments, they will be pursued with the schedule and priority of the other OER program rather than those of OHER. When there is no

overlap, there is some risk that accelerator capabilities needed for future OHER research will be unavailable.

Basic Energy Sciences (BES), High Energy Physics (HEP), and Nuclear Physics (NP) operate accelerators for scientists supported by these programs, by related programs such as OHER at BES facilities, and by other Federal agencies, including the National Science Foundation (NSF) and the NIH. They have a common approach to short-term accelerator R&D. The accelerator program is managed by the facility using resources provided to it by the DOE. The priority of a particular activity within the accelerator program itself and within the broader program of the facility is determined by the facility managers working within their budget constraints. The overall scientific program of the facility is reviewed by laboratory visiting committees, by DOE committees, or both, and the accelerator activities are reviewed primarily in the context of that overall program.

These three programs manage medium-term accelerator R&D with somewhat different emphasis. In BES and NP, facility managers can and do devote resources provided to the facility for development of future capabilities. Current examples include free electron laser (FEL) development for BES at the National Synchrotron Light Source (NSLS) and the Stanford Synchrotron Radiation Laboratory (SSRL) and radioactive beams for nuclear physics at Lawrence Berkeley National Laboratory (LBNL), Argonne National Laboratory (ANL), and Oak Ridge National Laboratory (ORNL). Facility directors are given freedom to allocate resources between accelerator development and other activities.

For a number of reasons the development of future accelerator capabilities has generally been given lower priority in BES and NP than in HEP, which is the only program that has a specific budget category for funding

accelerator R&D and other technology development. These reasons include less program office encouragement for proposals addressing accelerator development, tight budgets, user community pressure, and lower expectation by the DOE that money be spent on this. Many NP and BES facilities are part of larger, multipurpose laboratories that have Laboratory Directed Research and Development (LDRD) funds that can be used for proposal development, and this has been done successfully in a number of cases.

The response of BES to the recent National Research Council (NRC) study on FELs gives an example of the opportunities that can be missed absent a clear long-term accelerator research policy. The NRC study contained a number of recommendations related to accelerator R&D. Synchrotron radiation facility directors have the freedom to respond to these recommendations, but BES has no expectation that they will and no policy about the appropriate nature or level of response. In addition, university and national laboratory researchers who are not associated with synchrotron radiation facilities have no clear way of securing funding for research in these directions. A promising program for developing a low-cost infrared FEL, initially supported by the Strategic Defense Initiative Office, was discouraged from applying for BES funding. Work on short wavelength FELs is minimally supported. Leadership in this field is in danger of moving from the United States to Europe and Japan where such FEL facilities are planned and user communities are growing.

High Energy Physics. The distinction between HEP and the other programs is the expectation by the HEP program management and the user community that some money be spent on long-range, risky accelerator development even if it comes at the expense of running time, construction of experimental apparatus, or other laboratory services. Development for future accelerator capabilities has a priority comparable to other laboratory goals, and pursuing these developments is evaluated on par with other goals when

reviewing a facility. As in BES and NP, directors of HEP facilities are also given freedom to allocate resources between accelerator development and other activities.

High Energy Physics is the only program that supports long-term accelerator R&D as a matter of policy. The High Energy Physics Advisory Panel (HEPAP) Subpanel on Accelerator Research and Development (M. Tigner, chair) concluded in 1980 that support for long-range accelerator development was critical for the future of high energy physics. This was reaffirmed in 1994 by the Subpanel on Vision for the Future of High Energy Physics. This support manifests itself in two ways: (1) long-term accelerator development at major high energy physics laboratories, and (2) a proposal-driven, peer-reviewed program in accelerator physics that supports long-term R&D activities relevant to HEP by investigators at universities, national laboratories, and industry. This policy is strongly supported by the DOE Division of High Energy Physics.

Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (Fermilab), Argonne National Laboratory (ANL), and Stanford Linear Accelerator Laboratory (SLAC) have high energy physics accelerator R&D supported as part of the annual funding of the laboratory by the DOE. These programs have varying combinations of support for specific (present and future) projects and for more general research. In addition, a program administered through the HEP division accepts proposals for accelerator R&D and evaluates them through the peer review process. This program has been effectively managed, and it significantly broadens the opportunity for innovative developments that will have substantial long-range impact. Some of the research at ANL, LBNL, and BNL is also evaluated and funded through this peer review process. In total, about 2.5% of the FY1995 HEP operating budget was devoted to this program.

The HEP support of accelerator R&D follows from the link between advanced accelerator capabilities and HEP scientific frontiers. The expectation that HEP laboratories pursue future facilities aggressively follows from this close link. The centrally administered program leads to accelerator activities outside of the national laboratories, particularly at universities, and activities within national laboratories but outside those relating to operating or developing facilities.

Universities are a central element of the basic research enterprise in the United States. The combination of academic freedom and education has proven to be a creative force that is an effective way to train future leaders. The proposal-driven, peer-reviewed program that HEP runs is an important way for a university scientist to obtain accelerator research support, and for accelerator physics to have the creativity and leadership needed for the future. The program is a major source of funding for accelerator physics research and graduate student training at universities.

The Office of Fusion Energy (OFE) supports R&D in fusion science and technology to achieve its principal mission, fusion energy production. Accelerators play important roles in fusion research as energy and neutron sources. OFE also has stewardship for basic plasma science, which has significant synergism with long-term accelerator research.

The OFE funding of accelerator R&D is predominantly driven by its programmatic needs. Because fusion research has a significant technology development component, much of the effort funded by OFE can be properly considered R&D. Short-term R&D is managed by the individual facilities using resources provided to them by the OFE. Medium-term research to develop future accelerator capabilities and long-term research has traditionally been managed and funded by separate technology development branches within

OFE. In addition, OFE has a proposal-driven peer-reviewed program of long-term accelerator R&D in support of inertial fusion.

In recent years OFE has suffered from a series of funding crises. This situation has had serious consequences for its accelerator based programs and ultimately, perhaps, for the nation. As a result, several promising R&D efforts have fallen victim to erratic funding and shifts in program priorities. For example, OFE developed neutral beam accelerators for plasma heating which were later discontinued. Since the United States no longer has a program in this field, leadership has moved to Japan. Similarly, the development of accelerators for fusion materials testing was stopped a decade ago but is now being resumed in an international collaboration.

The history of the Heavy Ion Fusion (HIF) Program provides an example of the difficulty of nurturing spin-off accelerator technology programs that may hold great promise for the nation. Although HIF has been strongly endorsed by the Fusion Energy Advisory Committee (FEAC), the National Academy of Sciences (NAS), and the Fusion Policy Advisory Committee, the DOE has found it difficult to find a hospitable long-term home. HIF has been transferred back and forth between OER and Defense Programs (DP), ultimately landing in OER, where it has been shuffled between HENP, BES, and OFE. Clearly, more coherent management is essential for efficient progress in an R&D program.

Assessment of Management of Short and Medium-Term Accelerator R&D

The heads of OER accelerator facilities are responsible to the DOE and the facility users for providing the capabilities needed for their experiments (short-term R&D). They must also develop future accelerator-based capabilities envisioned as important to the evolution of the facility and host laboratory

(medium-term R&D). The current approach to short-term accelerator R&D in which the program is managed by the facility is effective. The Subpanel agrees with the DOE approach that facility managers are best able to choose the most appropriate R&D for construction, operations, and improvement within their overall budgets determined by DOE/OER program management.

In general, accelerator facility managers can and do devote resources for development of future capabilities (medium-term R&D), particularly in HEP. In the face of tight budgets, user pressure, and less encouragement by the DOE, the development of future accelerator capabilities has generally been given lower priority at BES and NP facilities. Where these facilities are part of a larger, multipurpose laboratory, the availability of LDRD funds can and has offset this limitation.

The Subpanel endorses the present system of accelerator R&D directed at future capabilities, which is supported by funds from facility budgets. However, we believe that this approach could yield additional benefits if the BES and NP programs were to more explicitly recognize the value of such investments and evaluate the performance of their accelerator-based facilities accordingly.

Assessment of Management of Long-Term Accelerator R&D

Based on the Subpanel's work, it is clear that long-term generic R&D is vital to the future advances in accelerator technology required to fulfill some critical aspects of the scientific mission of OER. While this statement is generally accepted in principle, the realities of funding and of the OER management structure can lead to problems. Accelerator R&D efforts that are perceived as of no immediate benefit for the core mission are often handled on an ad hoc basis and are most susceptible to funding uncertainties in times of

financial stress. Generic accelerator R&D which spans the OER offices or does not have direct relevance to a mainstream program may be orphaned and not receive the consideration it deserves. As a result, the OER programs may fail to capitalize on opportunities for tapping innovative ideas, for developing new long-range technologies and for training and education of the next generation of accelerator scientists and engineers.

The importance of this long-term research presents a particular dilemma to facility directors who already bear responsibility for short and medium-term R&D. Examples of major DOE user facilities and centers and those sciences they serve are:

- Fermilab, SLAC, and the Alternating Gradient Synchrotron (AGS) at BNL for high energy physics.
- Continuous Electron Beam Accelerator Facility (CEBAF) and the Relativistic Heavy Ion Collider (RHIC) at BNL for nuclear physics.
- SSRL, the Advanced Photon Source (APS) at ANL, the Advanced Light Source (ALS) at LBNL, and the NSLS at BNL for materials science, chemistry, biology, etc.

Do the directors of those facilities and laboratories bear some responsibility for the development of accelerator technologies for the future of these scientific fields? We believe that they do and note that the National Research Council FEL study has argued similarly for the specific case of FELs. Moreover, the intellectual challenges and research opportunities associated with longer-term developments are important for attracting and keeping the most creative engineers and scientists. The Subpanel believes that facility directors

will continue to address some aspects of long-term R&D, but that a broader based effort is required.

The 1980 Tigner HEPAP Subpanel recognized the importance of accelerators to HEP research and recommended a coherent program of long-term R&D in accelerators. The Subpanel report led to the creation of the HEP Advanced Technology R&D program which has successfully demonstrated the benefits of such an approach. *Our composite Subpanel discussed at length the question of whether OER offices beyond HEP should fund accelerator research and development other than that at facilities. Such funding is necessary if these programs are to meet their scientific missions, impact national needs, benefit from the creativity at universities and national laboratories other than those hosting specific facilities, and contribute to the education of the scientists and engineers who will be needed to build and operate future facilities. As accelerators have become increasingly vital to research in NP, BES, OFE, and OHER, there is a similar need for long-term accelerator R&D as an essential component to carry out the mission of these OER programs. Such research supports both the scientific goals of the program and the health of the accelerator technology required for the future. It is essential that these programs include planning and funding for needed long-term accelerator capabilities if they are to accomplish their mission.*

The Subpanel recommends several modifications to the present OER management approach for long-term accelerator R&D to assure that each program includes it as part of its research portfolio. The Subpanel has considered a number of mechanisms to enhance the level of long-term accelerator R&D and has identified the following characteristics that are essential for successful broadening of such activities within OER programs:

- A) The funding process should be proposal driven and peer reviewed and be open to all qualified researchers based at universities, in industry and at the national laboratories.
- B) Proposals should explicitly include the potential impact on the OER missions and the benefit to the nation.
- C) Proposals should be reviewed by peers with appropriate knowledge of accelerators and by scientists from the relevant office in OER who have vision and understanding of the long-range directions and needs of OER and of the nation.
- D) Each program office should have expertise on accelerator issues to assure appropriate management input. This expertise could come from detailees with accelerator experience when the program office has a limited staff size and accelerators are a relatively small part of the office activities.
- E) Each program office should develop and update regularly a broad list of accelerator research and development topics relevant to future aspects of the program mission and other national needs.
- F) OER and its programs should publicize their intention to consider accelerator research and development proposals to be evaluated within these guidelines.

The Subpanel strongly believes that each OER program should have or participate in a proposal-driven, peer-reviewed process to encourage, evaluate, and fund long-range accelerator R&D that is relevant to its mission and to broader national needs. We believe that the Director of the OER is in

the best position to determine the most effective management approach to implementing this long-term accelerator R&D program and should do so.

Funding

To estimate present levels of funding for accelerator R&D, the Subpanel gathered information from the major DOE, NSF, and university accelerator facilities, and from DOE program managers. Short-term R&D on existing facilities is so closely connected with on-going operations that it is difficult to quantify. Similarly, R&D on approved construction projects frequently includes some small-scale, longer-term R&D efforts. Because of these ambiguities, the Subpanel has not attempted to estimate funding for short-term R&D. In FY1995, funding for medium-term accelerator R&D was approximately \$32M from OER programs and \$10M from DP. OER funding for long-term accelerator R&D totaled approximately \$16M with \$12M from HEP, \$2M from OFE, and less than \$1M each from NP and BES. OHER funded no accelerator R&D.

This Subpanel believes that enhancing long-term accelerator R&D is in the best interests of the DOE OER programs and the nation. The appropriate level of investment for this activity will vary from program to program depending on overall priorities, funding level, and other program dependent considerations. The Subpanel views the OER advisory committees as the appropriate mechanism to determine the optimal level of investment in long-term accelerator R&D. Hence, we recommend that the Director of Energy Research charge the OER advisory committees with recommending the appropriate level of funding for each program. For this to be effective, each advisory committee should include or consult accelerator experts. This recommendation should be taken by each advisory committee in view of the totality of the program for which it is responsible. Thus, each advisory

committee, with input from its OER office, would take into account the evolving nature of each program and its mission within budget constraints and requirements for balance. Such advice has already been provided by HEPAP in the form of the Tigner Subpanel recommendation.

This Subpanel would like to provide a guideline for the advisory committees indicating the level of investment in proposal-driven, peer-reviewed long-range accelerator R&D that the Subpanel believes would assure that OER continues to meet its accelerator related stewardship responsibilities in all program areas. We suggest that HEP continue to use the Tigner report, which recommended an investment of 4% of the HEP operating budget as a healthy goal. This investment has been as high as 3.2% and is currently about 2.5%. Recognizing that different OER programs need different levels of long-range accelerator R&D, we suggest the following as a funding basis for the NP, BES, and OHER investments in accelerator-based research: (1) for Nuclear Science Advisory Committee (NSAC) and Basic Energy Sciences Advisory Committee (BESAC), respectively, the NP and BES accelerator operations budgets, and (2) for Health and Environmental Research Advisory Committee (HERAC), the OHER budget for development and support of experimental facilities at the BES accelerators. Even though it is the belief of the Subpanel that the ultimate level of funding in this area has to be determined by each Advisory Committee in view of the totality of the program for which it is responsible, the Subpanel suggests that roughly 1% of this annual basis is a reasonable initial level of investment for long-term accelerator R&D. If this investment is made, U.S. science and technology will benefit in the long-term.

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VII. CONCLUSIONS AND MAJOR RECOMMENDATIONS

The study and assessment conducted by this composite Subpanel has focused on the role of accelerator science and technology in enabling critical capabilities to support the mission of the U.S. Department of Energy (DOE) Office of Energy Research (OER) programs and to contribute to important national interests. Accelerator science and associated technologies nurtured by DOE's OER programs continue to be an essential part of DOE's energy research mission, especially in the fields of high energy and nuclear physics. In the basic energy sciences accelerator-based facilities and techniques are playing increasingly vital roles in the characterization and modification of materials. Accelerator-related technologies have played an essential role in fusion research. The health and environmental sciences make use of accelerator-based facilities for the study of biological structures and other significant research. These trends will continue. High energy and nuclear physics will continue to rely on state-of-the-art accelerator facilities, and the basic energy sciences and health and environmental research programs increasingly will use accelerator facilities to expand their scientific and technical horizons. For fusion energy, the use of accelerator-based drivers is one of the promising roads to commercial power in the next century.

This Subpanel believes that the DOE and its predecessor agencies—primarily through their long-standing and sustained investments in accelerator science and technology development—have *de facto* held a national trust for the stewardship of accelerator science and accelerator-based technology development. This role has provided the foundation for essential capabilities needed both to fulfill the DOE mission and to address broader national interests. Although there have been many, very significant contributions to this field made by researchers supported by other government agencies and by other nations, the Subpanel was led to this point of view by:

- the high level of investment in accelerator science and technology by the Atomic Energy Commission (AEC), Energy Research and Development Agency (ERDA), and DOE,
- the sustained level of commitment, and
- the number and impact of the developments that have resulted from this support.

This Subpanel has concluded that it is vital that the DOE and its OER programs explicitly acknowledge that they hold a national trust for accelerator science and technology, and that this trust and the resulting stewardship responsibilities should be an explicit part of the overall DOE OER mission. This conclusion was formed and strengthened by our hearing and considering detailed information from the DOE OER program offices, from other parts of the agency, from the accelerator science community, and especially from a panel of highly regarded researchers whose collective vision spans the full range of the OER mission.

Given the vital role that OER's programs have and should continue to play in the nurturing of accelerator science and technology, the Subpanel has formulated the following recommendations:

Recommendations

- A. Stewardship of accelerator science and technology should be acknowledged as an explicit part of the overall DOE OER mission.**

This stewardship entails:

- 1. Design, construction, and improvement of accelerator-based facilities needed to carry out the mission of DOE's energy research programs.**
- 2. Effective utilization and operation of these accelerator-based facilities.**
- 3. Support of the accelerator R&D required to provide facilities at the technological cutting edge for the sciences that they serve.**
- 4. Appropriate investment in basic accelerator science and in related technology R&D to form the foundation for capabilities needed in the future.**
- 5. Support for the training of the accelerator scientists and engineers required to provide the accelerator-based capabilities needed in future years.**
- 6. Support for the continued development and maintenance of the basic tools needed to stay at the cutting edge in the accelerator field (e.g., computer codes, essential stand-alone test facilities, and critical infrastructure elements at the accelerator-based facilities).**

B. Each OER program should have proposal-driven, peer-reviewed long-range accelerator R&D as part of its research portfolio.

The following guidelines are essential for the success of this approach:

1. The funding process should be open to all qualified researchers based at universities, in industry, and at the national laboratories.
2. Proposals should explicitly include the potential impact on the missions of OER programs and the benefit to the nation.
3. Proposals should be reviewed by peers with appropriate knowledge of accelerators and by scientists from the relevant office in OER who have vision and understanding of the long-range directions and needs of OER and of the nation.
4. Each program office should have expertise on accelerator issues to assure appropriate management input. This expertise could come from detailees with accelerator experience when the program office has a limited staff size and accelerators are a relatively small part of the office activities.
5. Each program office should develop and update regularly a broad list of accelerator research and development topics relevant to future aspects of the program mission and other national needs.

6. OER and its programs should publicize their intention to consider accelerator research and development proposals to be evaluated within these guidelines.

The Director of the Office of Energy Research is in the best position to determine the most effective management approach to implementing this long-term accelerator R&D program and should do so.

To assure that this R&D is well targeted, program managers should actively consult both their scientific communities and the accelerator community about the long range opportunities that could be enabled by forefront development in accelerator science and technology.

- C. **The Director of the Office of Energy Research should charge the appropriate OER advisory committees with recommending the level of long-term accelerator R&D funding for each program.**

This recommendation should be taken by each advisory committee in view of the totality of the program for which it is responsible. Thus, each advisory committee, with input from its OER office, would take into account the evolving nature of each program and its mission within budget constraints and requirements for balance. These advisory committees should include or consult accelerator experts.

D. The current approach to short-term, facility-directed accelerator R&D should be continued.

Facility management is best able to choose the most appropriate R&D for the construction, operation, and improvement of facilities within overall facility budgets determined by DOE/OER program management.

E. The present system of medium-term R&D directed at future capabilities of interest to laboratories, facilities or users of facilities should be strengthened.

The Subpanel endorses the present funding of medium term accelerator R&D by facility budgets and Laboratory Directed R&D (LDRD) funding. However, additional benefits would be gained by each program office explicitly recognizing the value of such investments and evaluating the performance of their accelerator-based facilities accordingly. In the DOE reviews of accelerator laboratories and facilities, the charge should include assessment of the medium and long-term accelerator R&D.

In all accelerator R&D improvements suggested in the above recommendations, informal coordination among OER program offices should be fostered.

F. OER program officers and laboratory managers who are responsible for the stewardship of accelerator science and technology should make a special effort to nurture societal applications.

Associated with OER's stewardship of accelerator science and technology is a responsibility to encourage the timely distribution and diffusion of this knowledge and technology. To be effective this requires an environment which fosters communication and cooperation between OER-funded research institutions and the industrial and commercial sectors.

A related issue is the treatment of long-term spinoff technology development that does not fit the DOE program structure. For example, the management of the Heavy Ion Fusion program has been a thorny issue for years, primarily because of indecision regarding its home within the DOE. Our concern is that crucial opportunities for the DOE and the nation could be missed unless the management structure is capable of sustained commitment to such long-term technology developments.

From the information gathering process and during the deliberations of this Subpanel the very important contributions of this field to basic scientific research and to society as a whole were again underscored in a dramatic way. While the areas mentioned in the recommendations presented above need attention, the Subpanel finds that accelerator science and technology is a vital and intellectually exciting field. It has provided essential capabilities for the DOE/OER research programs with an enormous impact on the nation's scientific research, and it has significantly enhanced the nation's biomedical and industrial capabilities. Further progress in this field promises to open new possibilities for the scientific goals of the OER programs and to further benefit the nation.

APPENDIX A



Department of Energy
Washington, DC 20585

NOV 17 1994

Professor Stanley Wojcicki
Department of Physics
Stanford University
Stanford, California 94305


Dear Professor Wojcicki:

I would like to request that the High Energy Physics Advisory Panel form a composite subpanel for the assessment of the status of accelerator physics and technology. In addition to HEPAP, the subpanel should draw its membership from, or through, the other four ER advisory committees; i.e., the Basic Energy Sciences Advisory Committee, Fusion Energy Advisory Committee, Health and Environmental Research Advisory Committee, and Nuclear Science Advisory Committee. The charge for this subpanel is contained in the enclosed document.

The subpanel report should be completed, reviewed by HEPAP, and transmitted to DOE no later than August 1, 1995.

Thank you for your assistance in this important matter.

Sincerely,


Martha A. Krebs
Director
Office of Energy Research



**Charge for the
Composite Subpanel for the Assessment of the Status of
Accelerator Physics and Technology**

I. Introduction

Particle accelerators have become central to many areas of modern science and technology. They have always defined the frontiers of particle and nuclear physics and are now beginning to play the same role for important parts of materials sciences, chemistry, biology and medicine. Because of these strong scientific roles, applications of accelerators are also expanding into industry, medical treatment, and defense. It is very likely that trends toward greater use in science and wider applications in industry and other areas will continue, and that farther in the future, particle accelerators will play an ever-increasing role in addressing some pressing societal needs, among them the safe production of electrical power and restoration of the environment, applications only dimly envisioned today.

Accelerator physics and engineering address the means by which particle beams are produced, and how these beams can be tailored for application in scientific research, industry, medicine, and defense. Accelerator science evolved from early studies in nuclear physics, where the design and construction of early particle beam devices were an integral part of the research, to the very complex applications of modern high energy, high current accelerators in particle physics, nuclear physics and materials sciences on the one hand, and sophisticated but inexpensive mass-produced instruments with numerous applications in industry and medicine on the other. To design and build a modern accelerator or colliding beam facility requires a multidisciplinary amalgam of classical physics (mechanics, electricity and magnetism, and thermodynamics) and advanced engineering (civil, structural, vacuum, radiofrequency, cryogenic and magnetics). The result has been a rich development of technologies, some very unique to accelerator building and some--for example, superconducting magnets--with wide spin-off benefits. Several years ago, the American Physical Society (APS) gave formal recognition to accelerator physics as an emerging, intellectual discipline in its own right by the formation of the Division of Physics of Beams (DPB). This follows a historical tradition set with the much earlier establishment of the Optical Society of America and the American Vacuum Society. The DPB gives recognition to the maturity and sophistication of accelerator physics (and engineering) and the importance of this technology to physics, in particular, and science, in general.

Accelerators have been an important element in the Department of Energy (DOE), Office of Energy Research (ER) programs for many years, as they were in similar basic research programs in the two predecessor agencies, the Atomic Energy Commission and the Energy Research and Development Administration. In fact, much of the development of modern accelerator physics and technology was carried out under the auspices of these earlier agencies. Accelerator Physics and Technology is today a core competency of the DOE Office of Energy Research. The use of accelerators, storage rings, and colliding beam facilities as diverse and flexible sources of radiation and particle beams for scientific research are important for all ER programs. Although the principal R&D activity in accelerator physics and technology has been, historically, supported through the ER Division of High Energy Physics, Technology R&D Branch, there are accelerator R&D programs tailored to specific objectives in Nuclear Physics, Basic Energy Sciences, and Fusion Energy. There are also strong research needs for accelerators in the sciences and applications supported by the Office of Health and Environmental Research. Recently, representatives from the Division of Physics of Beams proposed to DOE that the Division conduct, through the National Academy of Sciences (NAS), a national

assessment of beam physics as a scientific field in the U.S.: its history; current status; contributions to applications in industry, medicine, and defense; the future promise to basic science and for new practical applications; and the funding health. Although, DOE decided not to fund the DPB/NAS study, many of the issues and questions raised in the proposal are important to the future of ER programs; in particular, the need to look at this important core competency in a unified way, integrated across all five ER programs.

II. Formation of a Composite Subpanel under HEPAP

An integrated assessment of the ER activities in accelerator physics and technology requires input from all the ER-supported scientific communities. For this reason, ER believes a Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology should be established. Although formed under the High Energy Physics Advisory Panel (HEPAP), the Subpanel also draws membership from, or through, the other four ER Advisory Committees: Basic Energy Sciences Advisory Committee (BESAC), Fusion Energy Advisory Committee (FEAC), Health and Environmental Research Advisory Committee (HERAC), and Nuclear Science Advisory Committee (NSAC). The Composite Subpanel will receive staff support from all five of the involved ER program offices as required.

III. Charge to the Subpanel

The Director of the Office of Energy Research requests that the subpanel carry out a broad assessment of the current status and promise of the field of accelerator physics and technology with respect to all five ER programs--High Energy Physics, Nuclear Physics, Basic Energy Sciences, Fusion Energy, and Health and Environmental Research--and provide recommendations and guidance to the Director on appropriate future research and development needs, management issues, and funding requirements. The committee should exercise wide latitude in carrying out the study, but the following issues and questions should be addressed:

1. Review and summarize the role that accelerators, storage rings and colliding beam devices play in the ER research programs, providing also a brief summary of the R&D carried out within each program to support accelerator, storage ring and colliding beam facility operations; for the improvement of existing facilities; and for the development of new facilities.
2. Provide an assessment of spinoffs and applications from the ER accelerator R&D activities with a focus on contributions to the productivity and competitiveness of American science, industry, and medicine in a world economy.
3. Determine if the level of R&D for each ER program is appropriate, in terms of R&D content, activity level, and funding, to ensure the success of the scientific goals of that program and to assess future opportunities to meet national needs through accelerator science.
4. Examine the approach used by the five individual ER program offices in managing their R&D activities in accelerator physics and technology to determine if each is appropriate to the overall needs of that program.

We request that the subpanel complete its study and provide its assessment and recommendations to the Director of the Office of Energy Research by August 1, 1995.

APPENDIX B

High Energy Physics Advisory Panel

Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology

Jay Marx, Chairman
Lawrence Berkeley National Laboratory

Roger Bangerter
Lawrence Berkeley National Laboratory

Klaus Berkner
Lawrence Berkeley National Laboratory

Bruce Brown
Argonne National Laboratory

Robert Gluckstern
University of Maryland

Terry Godlove
FM Technologies

Michael Harrison
Brookhaven National Laboratory

Don Hartill
Cornell University

Walter Henning
Argonne National Laboratory

Keith Hodgson
Stanford University

Steve Holmes
Fermi National Accelerator Laboratory

Christoph Leemann
**Continuous Electron Beam Accelerator
Facility**

Arlene Lennox
Fermi National Accelerator Laboratory

Robert Macek
Los Alamos National Laboratory

Leonard Mausner
Brookhaven National Laboratory

Dale Meade
Princeton University

Bruce Miller
**Titan Advanced Innovative
Technology**

Claudio Pellegrini
University of California at Los Angeles

Nan Phinney
Stanford Linear Accelerator Center

Robert Pollock
Indiana University

Robert Siemann
Stanford Linear Accelerator Center

Herman Winick
**Stanford Synchrotron Radiation
Laboratory**

Non-Member Representatives

Stanley Schriber
Los Alamos National Laboratory

John Lightbody
National Science Foundation

Executive Secretaries

Henry Rutkowski
U.S. Department of Energy

Joseph McGrory
U.S. Department of Energy

Appendix C

AGENDA

HEPAP Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology

The Bethesda Ramada Hotel, Ambassador I
8400 Wisconsin Avenue
Bethesda, Maryland

Wednesday, June 28, 1995

9:00 a.m. Introduction/Welcome

J. O'Fallon/J. Marx

Talks by Energy Research Programs

9:15 a.m. High Energy Physics

D. Sutter

10:15 a.m. Break

10:30 a.m. Nuclear Physics

D. Hendrie

11:30 a.m. Basic Energy Sciences

W. Oosterhuis

12:30 p.m. Lunch

1:30 p.m. Fusion

M. Wilson

2:30 p.m. Health and Environmental Research

R. Hirsch

3:30 p.m. Break

3:45 p.m. Discussion of Issues

6:00 p.m. Adjourn

Thursday, June 29, 1995

9:00 a.m. Organization of Study

10:00 a.m. Break

10:15 a.m. Organization of Study (cont.)

11:00 a.m. Administrative Issues

12:00 Noon Lunch

1:15 p.m. Discussion of Charge

M. Krebs

2:15 p.m. Executive Session

3:00 p.m. Adjourn

AGENDA

HEPAP Composite Subpanel for the Assessment of the Status of Accelerator Physics & Technology

Holiday Inn-O'Hare International
Chicago, Illinois

Wednesday, August 2, 1995

- | | | |
|-------|--|-------------------------------------|
| 08:00 | Overview of Day's Program | R. Siemann, SLAC |
| 08:15 | High Brightness Electron Beams | J. Rosenzweig, UCLA |
| 09:15 | Physics and Technology of the Energy Frontier | R. Palmer, BNL |
| 10:30 | BREAK | |
| 10:45 | High Intensity Proton Beams | G. Lawrence, LANL |
| 11:25 | Industrial Applications of Accelerators | G. Neal, CEBAF |
| 12:05 | LUNCH | |
| 1:00 | Medical Applications of Accelerators | J. Alonso, LBNL |
| 1:40 | Accelerator Physics and Technology Education | M. Month, BNL |
| 2:10 | Accelerator Physics and Technology Research
at Universities | M. Reiser, MD |
| 2:50 | BREAK | |
| 3:00 | Accelerator Physics and Technology Research
at National Labs | G. Jackson, FNAL |
| 3:40 | Radioactive Ion Beams | J. D'Auria, Simon Fraser University |
| 4:20 | <u>"OPEN MIKE" AVAILABLE FOR COMMENTS FROM THE FLOOR</u>
(EACH SPEAKER WILL BE GIVEN <u>ONLY 5 MINUTES</u> AT THE MIKE) | |
| 6:00 | DINNER (note: <u>subgroup chairs have dinner with Jay Marx</u>) | |
| 7:30 | Meetings of the Subgroups | |

Thursday, August 3, 1995

08:30 Briefing by NSF Representative
09:15 Briefing by DOE Defense Programs

J. Lightbody, NSF
S. Schriber, DOE/LANL

10:15 BREAK

10:30 Brief Progress Reports by 5 ER Advisory
Committee Representatives

11:00 Progress Reports by Subgroup Chairs

12:30 LUNCH

1:30 Subpanel Business and Discussion
(where we go from here, plans for future meetings, etc.)

3:30 Adjourn

AGENDA

HEPAP Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology

Radisson Suite Hotel, O'Hare Airport
Chicago, Illinois

Friday, September 8, 1995

6:00 p.m. Working Dinner (Subpanel, Staff, Program Representatives)
Status of EM and NIH Input
Questionnaire Results H. Rutkowski
Discussion of Issues

Saturday, September 9, 1995

8:15 a.m. Welcome and Introduction J. Marx

HERAC Speakers

8:30 a.m. Stanford University G. Brown, Jr.

9:10 a.m. University of Chicago K. Moffat

9:50 a.m. BREAK

10:00 a.m. Massachusetts Institute of Technology J. Yanch

10:40 a.m. Health and Environmental Research Discussion

HEPAP Speakers

11:00 a.m. Yale University C. Baltay

11:40 a.m. Yale University M. Zeller

12:20 p.m. LUNCH

1:30 p.m. Fermi National Accelerator Laboratory A. Tollestrup

2:10 p.m. High Energy Physics Discussion

Saturday, September 9, 1995 (cont.)NSAC Speakers

2:30 p.m.	Argonne National Laboratory	W. Henning
3:10 p.m.	BREAK	
3:20 p.m.	California Institute of Technology	R. McKeown
4:00 p.m.	Indiana University	S. Vigdor
4:40 p.m.	Nuclear Physics Discussions	
7:00 p.m.	Subgroup Meetings, except #4	

Sunday, September 10, 1995FEAC Speakers

8:30 a.m.	Stanford Linear Accelerator Center	W. Herrmannsfeldt
9:10 a.m.	Lawrence Berkeley National Laboratory	J. Kwan
9:50 a.m.	BREAK	
10:00 a.m.	Los Alamos National Laboratory	R. Macek
10:40 a.m.	Fusion Energy Discussion	

BESAC Speakers

11:00 a.m.	Oak Ridge National Laboratory	J. Roberto
11:40 a.m.	Cornell University	J. Silcox
12:20 p.m.	LUNCH	
1:30 p.m.	University of Washington	E. Stern
2:10 p.m.	Argonne National Laboratory	J. Carpenter
2:50 p.m.	Basic Energy Sciences Discussion	
3:10 p.m.	BREAK	
3:25 p.m.	Subpanel Business and Discussion	
5:00 p.m.	Adjourn	

AGENDA

HEPAP Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology

Lawrence Berkeley National Laboratory
Building 50 Room 5132
Berkeley, California

Monday, October 23, 1995

8:30 am	Coffee and Bagels	
9:00 am	Goals and Format of this Meeting	J. Marx
9:30 am	Presentation of White Paper #1	C. Pellegrini
10:30 am	Coffee Break	
10:45 am	Discussion of White Paper #1	ALL
11:15 am	Presentation of White Paper #2	A. Lennox
12:15 pm	Lunch	
1:30 pm	Discussion of White Paper #2	ALL
2:00 pm	Presentation of White Paper #3	K. Berkner
3:00 pm	Coffee Break	
3:15 pm	Discussion of White Paper #3	All
3:45 pm	Presentation of White Paper #4	D. Hartill
4:15 pm	Discussion of White Paper #4	ALL
5:30 pm	Are Subgroups Finished?	J. Marx
6:00 pm	Jay's Strawman Report	J. Marx
	Dinner	
8:00 pm	Subgroup Meetings (If Needed)	

Tuesday, October 24, 1995

8:30	am	Coffee and Bagels	
9:00	am	Summary of Issues, Recommendations	J. Marx
10:00	am	Discussion/Debate leading to Consensus	ALL
10:30	am	Coffee Break	
10:45	am	Continuation of Discussion	ALL
12:00	noon	Lunch	
1:30	pm	Continuation of Discussion	ALL
3:00	pm	Coffee Break	
3:15	pm	Continuation of Discussion	ALL
4:30	pm	Where We Go From Here - Editorial Committee, Format of Next Meeting, End Game	J. Marx
6:00	pm	Adjourn	

Acknowledgments

The Subpanel would like to thank the directors of the following laboratories, university facilities, and offices for providing valuable information to aid the Subpanel in its deliberations:

DOE Laboratories

Ames Laboratory
Argonne National Laboratory
Brookhaven National Laboratory
Continuous Electron Beam Accelerator Facility
Fermi National Accelerator Laboratory
Los Alamos National Laboratory
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Oak Ridge National Laboratory
Pacific Northwest Laboratory
Princeton Plasma Physics Laboratory
Stanford Linear Accelerator Center

DOE-funded University Facilities

Duke University–Triangle Universities Nuclear Laboratory
Massachusetts Institute of Technology–Bates Linear Accelerator Center
Texas A&M–Cyclotron Institute
University of Washington–Nuclear Physics Laboratory
Yale University–A.W. Wright Nuclear Structure Laboratory

DOE Offices

Office of Scientific and Technical Information
Small Business Innovation Research

NSF Facilities

Cornell University–CESR

Indiana University–Cyclotron Facility

Michigan State University–National Superconducting Cyclotron Laboratory

University of Wisconsin–ALADDIN

APPENDIX D

Contributions of Accelerator Science and Technology to Office of Energy Research Programs

D. 1. Accelerator Physics—A Brief Overview

Particle beams are essential tools of modern science and technology. From the early experiments of Roentgen and Rutherford to present times, X-rays, gamma-rays, electrons, protons, neutrons, and alpha particles have been used to explore the structure of matter, to probe the interactions among the components of matter, and to further numerous medical and technological applications. Advances in the development of particle accelerators and continuing progress in particle-beam physics underlie the ever-increasing utility of these tools.

A particle beam is a particular state of matter, consisting of a large ensemble of particles having nearly the same momentum. The average direction of the momentum defines the direction of propagation of the beam, and usually all the particles are of the same type—for example, they are all electrons or they are all protons.

Historically, the idea of a beam derives from light optics, where the physical properties of light rays have been studied for centuries. Many of the basic concepts for particle beams are carried over from the optics of light beams. As in optics, accelerator science is the study of beam sources, beam propagation and the systems used to focus and bend beams, and the interaction of beams with matter. In most cases, however, the particles in a beam are electrically charged; this introduces many new properties not found in light beams. Charged-particle beams can interact with electromagnetic fields ranging from the fields of a resonant cavity to those of a laser beam. Particles can gain energy through this interaction and thereby be accelerated to high energies. This property has led to the development of particle accelerators that serve to greatly increase the velocity and therefore the energy of particle beams.

The development of particle accelerators during the last roughly 50 years has been striking. From the first electrostatic accelerators, which accelerated particles to a few hundred keV, to present TeV colliders, particle energies have increased by seven orders of magnitude. Experiments are now exploring matter at a scale length of about 10^{-18} m, which is about one-thousandth the size of a proton. Synchrotron radiation sources based on electron or positron storage rings are producing X-ray beams with more than one trillion times the brightness of X-ray tubes, thus leading to new insights into the structure of materials and biological molecules. Intense low-energy neutron beams, produced by high-current proton accelerators, are being used to study the structure of materials, and extensions of these accelerators are being considered for defense applications.

This progress has been made possible by research into the physical properties of particle beams and the development of accelerator technology. Most of this research and development is applied work, done in a context established by the anticipated use.

Dealing as it does with unique states of matter and physical configurations, accelerator research often has much broader implications than suggested by the original applied motivation. Spin-offs and applications based on accelerator technology have significant impact on the U.S. Department of Energy (DOE) programs, biomedicine, industry, and the national economy. Examples include applications to medical diagnostics and therapy using electron, proton, and X-ray beams; to structural molecular biology studies; and to heavy-ion fusion and plasma heating in the fusion program.

Another, quite different consequence of accelerator physics research has been its seminal contributions to an entirely new field of research. Studies of the motion of charged particles in nonlinear electromagnetic fields (that is, fields that vary rapidly with position) contributed to the discovery of one of the most active fields of modern

physics, nonlinear physics, whose implications range from the motion of planets and stars to biology—anywhere there are questions of long-term stability and the onset of chaotic behavior. Even today, particle beams remain one of the best systems for pursuing combined, detailed theoretical and experimental studies of single-particle and multiple-particle nonlinear dynamics.

Studies of the nonlinear behavior of beams are an example of basic research that uses beams and their properties outside a context set by an anticipated use. Far less effort and funding is devoted to such basic research than to applied accelerator research, but for several reasons, it is an important contributor to the health and vitality of accelerator physics and technology. First, basic research encourages creativity by removing boundaries set by an anticipated use. In addition, it offers a broadened perspective that research can have long-range impacts even when no short-term benefit is envisioned. And finally, since basic research is naturally pursued in universities, it assures the benefits of the free-ranging inquiry typical of academia, together with the vitality and new ideas that students bring to the field.

The Office of Energy Research (OER) high energy physics program has supported this type of basic research, and it has led to many important results, including the development of superconducting materials, magnets, and RF cavities; very-high-gradient accelerating structures; and methods for studying the nonlinear dynamics of particle beams. More details of these results are given in Appendix F.

The role that accelerators play is different for each of the five OER research programs. In the following sections, we describe the role of accelerator science and technology in each of these programs.

D. 2. High Energy Physics

High energy physics studies the fundamental structure of matter and the laws governing the interactions of the basic constituents of the universe. Recently, experiments in underground laboratories have studied solar neutrinos, the long-term stability of the proton, and related phenomena, but the great majority of high energy physics experiments have been and are still done with high energy accelerators.

During the 1950s and 1960s, all high energy physics accelerator-based experiments relied on scattering primary or secondary beams from a fixed target. During this period, the development of strong-focusing accelerators led to a large increase in beam energy, from a few GeV at the Cosmotron and Bevatron in the 1950s, to 30 GeV at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) and the Proton Synchrotron (PS) at the European Laboratory for Particle Physics (CERN) in the early 1960s. There followed the multihundred-GeV Main Ring at Fermi National Accelerator Laboratory (Fermilab) and the Super Proton Synchrotron (SPS) at CERN; the development of GeV-level lepton colliders in Europe, the U.S., and the Soviet Union; and a 30-GeV proton collider, the Intersecting Storage Ring (ISR), at CERN. The colliders soon reached a luminosity that allowed them to explore small-cross-section events, leading to an ever-increasing use of colliding-beam experiments in place of fixed targets.

The next phase, beginning in the 1980s, has been characterized by the construction of very-high-energy colliders: the Tevatron at Fermilab, the Stanford Linear Collider (SLC) at the Stanford Linear Accelerator Center (SLAC), and the Large Electron-Positron Project (LEP) at CERN and by the development of very-high-luminosity lepton colliders, such as the Cornell Electron Storage Ring (CESR) at Cornell. The present phase continues this trend with the construction of B-factories in the U.S. and Japan, substantial upgrades of the Tevatron and CESR, and construction of the Large Hadron Collider (LHC) at CERN.

Currently, the U.S. high energy physics program centers on fixed-target experiments at BNL, Fermilab, and SLAC, and on collider experiments at Fermilab, SLAC, and Cornell. A description of the basic characteristics and performance of these facilities is given below.

Major U.S. High Energy Physics Facilities

	<u>Fixed-target Facilities</u>		<u>Colliding-beam Facilities</u>	
BNL	AGS (p)	30 GeV		
	AGS (polarized p)	22 GeV		
SLAC	Linear accelerator (polarized e^-)	50 GeV	SLC (e^+/e^-)	50 GeV/beam
			(polarized e^-)	
			B-Fact. (3-GeV e^+ on 9-GeV e^-)*	
Fermilab	Tevatron (p)	800 GeV	Tevatron (p/pbar)	900 GeV/beam
Cornell**			CESR (e^+/e^-)	8 GeV/beam

* Under construction; expected to be completed in FY1998.

** National Science Foundation supported; majority of outside users are DOE supported.

The Fermilab proton-antiproton collider, where the top quark was recently observed for the first time, is currently the highest-energy collider in the world, and it will remain so until the LHC at CERN starts to operate around 2005, at an energy of about 7 TeV per beam. The SLC at SLAC was the world's first linear collider and has been used to study the Z particle using polarized beams. To bring the SLC to the luminosity level needed to study the Z has required the development of new accelerator physics and technology, which will be essential for future TeV-class linear colliders. CESR at Cornell is the world's highest-luminosity electron-positron collider. It has been used to study the properties of B particles and, at the same time, develop the accelerator physics and technology needed for the next generation of very-high-luminosity colliders, which will be used for the study of Charge Conjugation Parity (CP) violation in the decay of B particles and phi particles. At Brookhaven, following

a period of extensive and innovative improvements to the AGS, the facility now provides proton beams at the highest intensity available in the world. These intense beams are being utilized for experiments studying very rare decays of K mesons, the anomalous magnetic moment of the muon with high precision and for many other precise measurements.

In the last 15 years, it has become widely accepted that lepton colliders based on storage rings cannot exceed the LEP energy in a cost-effective manner because of synchrotron radiation losses. The solution to this problem is the linear collider, which was developed initially at SLAC, and whose development continues now in a large international collaboration involving the U.S., Japan, and Europe. Two main approaches to linear colliders are being pursued, one based on high-frequency, room-temperature accelerating structures (being studied mainly at SLAC and the National High Energy Physics Laboratory of Japan [KEK]), and a second based on lower-frequency superconducting structures (being pursued by the TESLA collaboration involving Deutsches Elektronen Synchrotron [DESY], other European laboratories, and Fermilab).

The next-generation proton colliders (for example the LHC) are still based on storage rings, using high-field superconducting magnets. Synchrotron radiation will reach a significant level in this collider and would certainly be very important in colliders with energies above 50 TeV. In the long run, circular hadron colliders will also be limited by synchrotron radiation losses.

This process of developing ever-larger accelerators with ever-larger energies—and at ever-higher costs—has been accompanied by a dramatic decline in the number of operating accelerators and high energy physics laboratories. In fact, most present research is concentrated in four laboratories in the U.S., two in Europe, and one in Japan. This trend will likely continue in the next decades.

Since high energy physics depends so strongly on the development of higher-energy and higher-intensity accelerators and colliders, accelerator R&D has always been an important part of this DOE program. In 1962 the Division of Physical Research of the Atomic Energy Commission (AEC) set up a formal program in accelerator R&D, and, as a result, the AEC/Energy Research Development Agency (ERDA)/DOE Division of High Energy Physics has always had a budget line item for accelerator physics and technology. A High Energy Physics Advisory Panel (HEPAP) subpanel (the Tigner Panel) was established in 1980 to review accelerator R&D and to look at the future of accelerators and colliders. The Tigner Panel recommended establishment of a separate effort within the DOE high energy physics program for long-term accelerator R&D. This program funds research groups at national laboratories, universities, and industry and provides the main support for training graduate students in accelerator physics. This is described in more detail in Appendix F.

D. 2. 1. Funding and Users

Research in high energy physics is supported mainly by the DOE, with additional support from the National Science Foundation (NSF). Fermilab, SLAC, and BNL are DOE laboratories, while Cornell is supported by the NSF. DOE funding for high energy physics is approximately \$600M (in 1995 dollars). In recent years, funding has decreased for accelerator operations, with consequent reductions in personnel and accelerator running time at the DOE laboratories.

Numbers of users from U.S. universities, national laboratories, and foreign institutions of the three major U.S. high energy physics facilities are given in the following table:

Users of U.S. High Energy Physics Accelerator Facilities

	<u>U.S. Universities</u>	<u>U.S. Laboratories</u>	<u>All Foreign</u>	<u>TOTAL</u>
BNL	295	98	120	513
Fermilab	1227	171	647	2045
SLAC	<u>332</u>	<u>186</u>	<u>280</u>	<u>798</u>
TOTALS	1854	455	1047	3356

In addition, DOE's High Energy Physics program supports Brookhaven's Accelerator Test Facility (ATF) and Argonne's Advanced Accelerator Test Facility (AATF) and its direct successor, the Argonne Wakefield Facility (AWF), which are user-oriented facilities that focus on studies of new acceleration concepts. Presently, the ATF has a total of about 40 users and the AWF about 12.

D. 3. Nuclear Physics

The goal of nuclear physics research is to understand, at a fundamental level, the structure and dynamics of strongly interacting matter, its properties under a wide variety of conditions in the laboratory and the cosmos, and the forces that govern its behavior. Nuclear physics depends largely on the use of accelerators for its experimental investigations. Corresponding to the great diversity of the field, a relatively large number of accelerators are employed, of greatly varying size, age, and type. Nuclear physicists use beams of ions from protons to uranium nuclei, radioactive beams, and secondary beams such as pions or kaons, as well as electrons.

During the 1950s and 1960s, nuclear physics experiments relied on small accelerators at universities, such as cyclotrons and Van de Graaffs. As the requirements for beam energies, intensities, and, especially beam species grew, additional larger dedicated facilities were built at universities and at the national laboratories. The Los Alamos Meson Physics Facility (LAMPF) was the premier

nuclear physics facility in the U.S. for many years. At the same time, the use of high energy physics facilities played a significant role: The Lawrence Berkeley National Laboratory (LBNL) Bevatron was modified to become the Bevalac, the first high energy heavy-ion accelerator, and SLAC accommodated some nuclear physics experiments, as did Fermilab.

Recently, two of nuclear physics' key scientific objectives—understanding the quark structure of nucleons and nuclei and the search for the quark-gluon plasma—have demand higher currents and duty factors for electrons, and higher currents and energies for heavy ions. This motivated the construction of two large facilities designed specifically for nuclear physics at these research fronts: the Continuous Electron Beam Accelerator Facility (CEBAF) in Virginia, a continuous wave (CW), high-current electron accelerator of moderately high energy, which has recently become operational, and the Relativistic Heavy Ion Collider (RHIC), a dedicated high energy heavy-ion collider.

CEBAF is a superconducting, recirculating linac designed to deliver continuous electron beams of up to 200 mA of current, polarized and unpolarized, simultaneously to three experimental areas. CEBAF's design energy is 4 GeV, but operational experience with the superconducting cavities indicates that an energy of up to 6 GeV may be possible within a few years and that a push into the 8- to 10-GeV range will be possible at modest expense. Research at CEBAF is aimed at understanding nuclei and nuclear forces in terms of quantum chromodynamics (QCD), which describes the interactions of the underlying fundamental constituents, quarks and gluons.

Now under construction at BNL, RHIC is the first colliding-beam facility specifically designed to accommodate the requirements of heavy-ion physics. When completed in 1999, RHIC will provide heavy-ion collisions for a range of ion species up to gold, with beam energies of 30 to 100 GeV/nucleon. Collisions between unlike ion species will also be possible at constant nucleon energies. Projected luminosities

vary with ion species and range from about $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ for gold beams to $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ for protons. The facility will support up to six interaction regions, with two major detectors and two smaller experiments approved for initial operation. Research at RHIC will attempt to explore the equivalent of a liquid-gas phase transition for quantum systems where hot, dense nuclear matter becomes a quark-gluon plasma.

A number of smaller accelerator facilities with unique characteristics and capabilities constitute an important component in the nuclear physics program. The DOE supports programs at Massachusetts Institute of Technology (MIT), Argonne National Laboratory (ANL), LBNL, BNL, and Oak Ridge National Laboratory (ORNL). The Bates Laboratory at MIT uses a pulsed electron linac and stretcher ring for experiments with internal polarized targets and polarized electrons. The ATLAS heavy-ion linear accelerator at ANL is based on low-velocity superconducting cavities and provides high-quality heavy-ion beams from hydrogen to uranium for nuclear structure research. The 88-Inch Cyclotron at LBNL provides heavy-ion beams for nuclear structure research from a state-of-the-art high-charge-state electron cyclotron resonance ion source. A fixed-target heavy-ion experimental program at BNL uses the AGS proton synchrotron in an incremental fashion around the long-running high energy physics program. A first-generation Isotope On-Line (ISOL)-type radioactive beam facility (now under development) is based on the ORIC cyclotron and 25-MV folded tandem at ORNL.

Nuclear physics facilities at Michigan State University (MSU) and Indiana University are supported primarily by the NSF. MSU has three superconducting cyclotrons at National Superconducting Cyclotron Laboratory (NSCL). The K500 was the world's first superconducting cyclotron. The K1200 is the world's highest-energy (~10 GeV) CW cyclotron and has been used in support of the nuclear physics program since 1988. The MSU cyclotrons and the DOE-supported cyclotron at Texas A&M are used for research on nuclear fragmentation, the nuclear liquid-gas phase transition, and in-flight radioactive beams.

The Indiana University Cyclotron Facility (IUCF) is active in areas of beam-cooling technologies and polarized proton beams. Two cyclotrons provide protons with energies up to 200 MeV for direct beams, as well as serving as the injector complex for the Cooler Ring. This ring can accelerate protons to an energy of 500 MeV. The distinguishing characteristic of this facility is the availability of polarized beams in all machines. The Cooler Ring has a state-of-the-art electron-cooling system capable of providing very dense beams, which are used for dedicated accelerator physics experiments related to the intensity frontier.

Several smaller accelerators at universities do important experiments in nuclear structure and nuclear astrophysics, and provide training for graduate students in a direct, hands-on manner: Triangle Universities Nuclear Laboratory (TUNL), University of Washington, and Yale (all DOE supported), and Florida State, Texas A&M, Notre Dame, Princeton, and SUNY Stony Brook (all NSF supported).

With two new major accelerator facilities under construction (RHIC) or coming into operation (CEBAF), limited effort is going into new nuclear physics facility initiatives. CEBAF has a development effort in superconducting RF technology and engineering with a goal of reliably achieving accelerating gradients of 10 to 15 MV/m for an eventual boost in CEBAF energy. The NSCL facility at MSU has proposed to couple the K500 and K1200 cyclotrons to increase the output beam currents by orders of magnitude. The recent Nuclear Science Advisory Committee (NSAC) long-range plan recommended the development of ongoing radioactive ion beam capabilities through the immediate upgrade of the MSU facility, together with a design study for and future construction of a next-generation radioactive beam laboratory based on the ISOL technique. In addition, they encouraged support for a Light Ion Spin Synchrotron facility based on the existing IUCF infrastructure.

D. 3. 1. Funding and Users

The recently completed long-range plan for nuclear physics in the United States is based on outyear projections of funding for nuclear physics by the DOE of \$325-\$350M (in 1997 dollars) and by NSF of a constant level of effort starting from the FY1994 budget. The FY1996 DOE budget for nuclear physics is \$304.5M.

Numbers of users from U.S. universities, national laboratories, and foreign institutions (for most recent year reported) are given in the following table:

	<u>U.S. Universities</u>	<u>U.S. Laboratory</u>	<u>All Foreign</u>	<u>TOTAL</u>
RHIC	225	120	377	722
AGS	256	94	119	469
CEBAF	287	87	168	542
ATLAS	173	55	82	310
Bates	199	16	49	264
IUCF ¹	292	81	60	433
MSU ²	290	79	138	507
HRIBF	123	66	74	274 ³
88-Inch	<u>71</u>	<u>96</u>	<u>46</u>	<u>237⁴</u>
TOTALS	1916	694	113	

1-Users reported for period 1990-93.

2-Users reported for period 1988-95.

3-Eleven industrial users included in total.

4-Twenty-four industrial users included in total.

D. 4. Basic Energy Sciences

The mission of DOE's Basic Energy Sciences (BES) program is to expand the scientific knowledge and technical skills needed to aid long-term economic growth and to develop new and existing energy resources. The role of accelerators in BES programs in Materials Sciences, Chemical Sciences, Engineering and Geosciences, and Energy Biosciences has increased greatly during the past two decades. Twenty years ago, no accelerator-based user facility was supported by BES. The first synchrotron

light source to be supported by BES was the National Synchrotron Light Source (NSLS), for which construction began in 1978. The first accelerator-based neutron source was the Intense Pulsed Neutron Source (IPNS), which began operation in 1982.

In carrying out its mission, BES now supports activities at the DOE national laboratories to design, construct, and operate major accelerator-based user facilities. These include four of the nation's eight synchrotron light sources (the Advanced Light Source [ALS] at LBNL, the Advanced Proton Source [APS] at ANL, the NSLS at BNL, and Stanford Synchrotron Radiation Laboratory [SSRL] at SLAC) and the two U.S. pulsed neutron sources (the IPNS at ANL and the Los Alamos Neutron Scattering Center [LANSCE]). The 7-GeV APS synchrotron light facility at ANL is now being commissioned. BES also supports two reactor-based neutron sources not included in the scope of this report. In addition, DOE supplied most of the funding to construct the light source at Louisiana State University (LSU), the CAMD facility, but DOE supplies no operating funds for this facility.

At present, no new light sources or neutron sources are under construction; however, beamlines are being added at existing light sources. In addition, BES supports programs using electron microscopes and ion-implantation facilities. In FY1996, BES will support the development of a conceptual design for a 1-MW spallation neutron source.

The other four light sources in the U.S. (the NSF-supported CHESS facility at Cornell University, the SURF II facility at the National Institute of Standards and Technology [NIST], the NSF-supported Aladdin facility at the University of Wisconsin, and the CAMD facility at LSU) are all smaller than any of the BES/DOE facilities. In addition, a 1-GeV ring has recently begun operation at Duke University, which will be used as a VUV free-electron laser driver, as well as a source of synchrotron radiation. Among possible future resources is a 2.5-GeV light source, proposed at North Carolina State University. Proposals for linac-based, short-

wavelength free-electron lasers have been developed at BNL ($\lambda > 750 \text{ \AA}$) and SLAC ($\lambda > 1.5 \text{ \AA}$).

Over the past two decades, BES has acquired considerable experience and expertise in constructing, operating, and improving their accelerator-based user facilities. The broad, multidisciplinary research at these facilities is conducted by scientists supported by BES, other OER programs (particularly the Office of Health and Environmental Research [OHER]), other DOE programs (for example, Environmental Management [EM] and Defense Programs [DP]), other agencies (including the NSF and the National Institutes of Health [NIH]), and industry. BES experience with user facilities has broadly benefited OHER, which funds beamlines (including the insertion device source) optimized for its user community at BES-supported facilities. In some cases, the funding for a beamline is shared by OHER and BES, where it is relevant to the missions of both programs.

D. 4. 1. Neutron Scattering

Neutron scattering is an important tool for R&D in condensed-matter science, including the life sciences, materials science, and chemistry. Experimental possibilities are limited by the intensity of the neutron sources, which fundamentally determines the achievable signal-to-noise ratio in any experiment. One of the major strengths of neutrons as probes of structure, dynamics, and magnetic properties is the fact that they are indirectly ionizing and hence nondamaging to many materials of interest. Thus, all gains in intensity are gains in capability. As accelerator R&D moves forward, thereby providing the technology for more powerful neutron sources, new opportunities are sure to emerge in applying neutron scattering to biological, materials, and chemical research.

For many years, reactors have been the mainstay of neutron beam applications. However, the development of high-flux reactors has reached a level where further

enhancement of source fluxes has become very difficult. The Advanced Neutron Source (ANS) proposed a factor of five increase in neutron flux beyond that achieved in present sources. This step proved to be extremely technologically challenging and costly, contributing to the demise of this proposal.

Beginning about 25 years ago, high-current, medium-energy proton accelerators were built which could drive spallation sources of sufficient intensity to compete favorably with reactors. In particular, pulsed sources could provide peak fluxes exceeding that available in reactors. However, such sources required development of time-of-flight techniques if they were to be effective in scientific applications. Pulsed-source and instrumentation development has since proceeded apace. Four very effective pulsed spallation sources are now operating worldwide (two in the U.S.), and efforts are under way in the U.S., Europe, and Japan to design even more powerful sources.

In the early years, the pulsed sources were viewed as unique in providing high instantaneous fluxes and short pulses of epithermal (0.05–10 eV) neutrons, especially useful in diffraction and high-energy transfer spectroscopy. Experience rapidly showed that cryogenic moderators at pulsed sources are highly effective sources of cold neutrons, while also advantageous at the epithermal energies. As a consequence, thermal and cold neutron time-of-flight methods have been developed that parallel capabilities at reactors and compete advantageously or even excel them in many scientific applications. New accelerator-based sources have been considered that could provide time-average slow neutron fluxes comparable to the reactor fluxes. Some facility concepts are simultaneously adaptable to providing intense, short pulses and high-time-average fluxes.

At present there are four operating pulsed spallation sources and one nearly complete steady-state spallation source as described in the table below:

Accelerator-Based Neutron Sources

<u>Facility</u>	<u>Location</u>	<u>Beam parameters</u>	<u>Power</u>	<u>1st Year of Operation</u>
SINQ	PSI/Switz.	600 MeV \times 1300 μ A	780 kW	1996
ISIS	RAL/U.K.	800 \times 200	160	1985
LANSCCE	LANL/U.S.	800 \times 60	48	1985
IPNS	ANL/U.S.	450 \times 15	6.8	1981
KENS	KEK/Japan	500 \times 7	3.5	1980

In the U.S., site-specific studies of 1-MW pulsed spallation sources, begun in 1992 at ANL and Los Alamos National Laboratory (LANL), have been documented and reviewed. BNL has documented a preliminary study of a green field 5-MW source, and LANL has begun a study of a 1-MW long-pulsed spallation neutron source to be based on the LAMPF beam. In early 1995, DOE designated ORNL as the preferred alternative site for a 1-MW pulsed spallation source, on which design studies are to begin in FY1996. Europe, Russia, and Japan also have ongoing studies of comparable sources at various stages of completion.

D. 4. 2. Synchrotron Light Sources

The increasing availability of synchrotron radiation has revolutionized many fields of basic research, including chemistry, materials science, and structural molecular biology. It has also had major benefits for applied research, such as the development of techniques for lowering detection limits of contaminants on silicon chips. In medicine, clinical studies are under way on coronary angiography without the conventional, invasive arterial catheter.

Some specific fields of study include IR and X-ray microscopy, surface science, atomic and molecular physics, magnetic circular dichroism, spin-polarized photoemission, lithography and micromachining, diffraction, EXAFS, magnetic scattering, liquid surfaces, standing waves, angiography, structural biology (crystal

structures and EXAFS), resonant nuclear scattering, trace element analysis for semiconductors, environmental science, photoelectron diffraction, spectromicroscopy, electronic structure (band structure, semiconductors, superconductors), and X-ray crystallography (materials and proteins).

Synchrotron light source performance has increased greatly with advances in accelerator and insertion device technology. The increase has been particularly dramatic for the flux (number of photons/s \cdot mrad \cdot 0.1% bandwidth), brightness (number of photons/s \cdot mm² \cdot mrad² \cdot 0.1% bandwidth), and coherence (proportional to brightness) of VUV and X-ray beams. X-ray source brightness has increased by about 11 orders of magnitude during the past 25 years.

The first major increase in brightness, of about five orders of magnitude, occurred in the 1970s with the parasitic use of synchrotron radiation from the bending magnets of storage rings developed for high energy physics research—the so-called first-generation rings. Subsequently, fully dedicated light sources, the second-generation rings, were brought on line in the 1980s. These offered many beamlines, primarily from bending magnets, in facilities designed from the start as light sources. With the implementation of insertion device sources on first- and second generation rings, starting in 1979, it became clear that the brightness could be significantly increased if the electron beam emittance were reduced. This led to the design and construction of the third-generation rings, with many straight sections for insertion devices and with lower emittance than earlier rings. Third-generation rings are now coming on-line around the world. BES now supports one first-generation facility (SSRL), one second-generation facility (NSLS), and two third-generation facilities (ALS and APS).

In addition, major new source capabilities, leading to new scientific opportunities, have emerged with the very active development of insertion devices. These include higher flux at high photon energies with superconducting wigglers,

higher brightness at high photon energies with small-gap, short-period undulators, and circularly polarized beams with switchable helicity. Major progress has also been made in developing compensation schemes to permit the undulator on an individual beamline to be tuned without adverse effects on other beamlines.

Nonetheless, as powerful as third-generation sources are, fourth-generation sources with even higher performance appear achievable, since we are far from fundamental limits such as the diffraction limit, particularly at X-ray wavelengths. The ease with which this generation of sources has been commissioned has led to consideration of fourth-generation light sources at several laboratories. These include designs for advanced storage rings with lower emittance, shorter bunches, and/or longer straight sections.

D. 4. 3. Free-Electron Lasers (FELs)

FEL user facilities, primarily in the near-IR, are now in operation in several laboratories around the world, including four in the U.S. These have proved to be extremely capable sources, opening up new scientific opportunities with bright, coherent IR beams. Since these are still relatively new sources, many ideas have been proposed for extending their performance and spectral range.

A study done by the National Research Council in 1994 concluded that "the most compelling case for a free-electron laser facility is in the far-infrared, the region between 1000 and 10 μm ." This report also recommended that "the development of technology for a vacuum ultraviolet free-electron laser should be supported" and that "the research and development necessary for the possible construction of an X-ray free-electron laser should be supported." This report repeatedly stressed the need for R&D to develop more compact FELs and to reduce their cost. (See *Free-Electron Lasers and Other Advanced Coherent Light Sources*, report available from the Board

on Chemical Sciences and Technology, National Research Council, 2101 Constitution Avenue, Washington, DC 20418.)

Around the world, activities are under way at accelerator laboratories to extend FEL operation to wavelengths shorter than the 240 nm reached to date. Duke University, Dortmund University, and the Photon Factory group at the KEK laboratory in Japan are pursuing oscillator configurations in which an optical cavity is used to build up the intensity of the radiation. However, because of the lack of suitable reflecting materials, it is difficult or impossible to make such a cavity with high enough reflectivity at wavelengths below about 150 nm.

This has led to the development of the single-pass, high-gain amplifier approach in which laser operation is achieved in a single pass of a bright electron beam from a linear accelerator through a long undulator. With advances in accelerator technology, it now appears possible to use high-energy linacs to extend FEL operation down to wavelengths in the angstrom range. These advances include the development of high-brightness electron sources, initially at LANL; advances in the understanding and control of emittance degradation effects in the acceleration and compression of high-brightness beams, initially at SLAC; and the development of precision undulator magnets, initially at LBNL. These sources would deliver sub-picosecond X-ray pulses with coherent power and instantaneous brightness many orders of magnitude higher than that available from third-generation rings. However, such linear light sources would have a slower repetition rate and serve a smaller number of users than light sources based on storage rings.

Proposals for linac-based short-wavelength FELs have been developed at BNL ($\lambda > 750 \text{ \AA}$, using a 210-MeV linac) and SLAC ($\lambda > 1.5 \text{ \AA}$, using a 15- to 20-GeV linac). The DESY laboratory in Hamburg, Germany, is constructing a single-pass FEL that would reach about 60 \AA using the TESLA Test Facility 0.5- to 1.0-GeV

superconducting linac. Short-wavelength FELs are also being considered at CERN and at several laboratories in Japan.

D. 4. 4. Funding

The total BES budgets for FY1995 and 1996 are \$705.3M and \$738.1M, respectively, including funding for Applied Mathematical Sciences and Advanced Energy Projects. The corresponding operating budgets are \$601.1M (FY1995) and \$660.0M (FY1996). Of the total, 30% was devoted to accelerator-based facilities in FY1995; 26% is projected for such facilities in FY1996.

D. 4. 5. Users Of Synchrotron Radiation and Spallation Neutron Facilities

The BES-funded accelerator-based synchrotron radiation and neutron-scattering user facilities support a large number of users from universities, industry, government laboratories, and foreign institutions. Details are given in the table below. These users receive support from many sources, including BES and other DOE offices, other agencies, industry, and foreign sources. Most of the BES support comes through the BES Divisions of Materials Sciences and Chemical Sciences. Of all the individual research projects supported by the former division, about 25% use accelerators in some form, including electron microscopes. For the Division of Chemical Sciences, this number is about 10%.

The user community for neutron sources has not grown significantly in recent years, not because of limited demand, but rather because of static funding for the operation of existing facilities. Where user programs exist and where the program of utilization is through a proposal-and-review system, the facilities are always oversubscribed by factors of two or three. This frustrating situation has been recognized recently, and measures to rectify it are reflected in the Scientific Facilities Initiative, now approved by the Congress and the President. This Initiative will

provide sorely needed increases in operations support for synchrotron light and neutron sources operated by the DOE, as well as for high energy and nuclear physics facilities.

Light source and neutron source experiments are "small science" efforts. A typical team consists of two or three scientists, who bring an experiment to the facility. Measurements last a few hours, a few days, or in some cases, a few weeks. Several classes of users can be distinguished: (i) specialists, typically resident at the facilities, who provide, care for, and operate instruments for users and who may team up with incoming users or carry out scientific programs of their own; (ii) experts who are thoroughly conversant with the techniques and instruments being used and who usually carry out measurements and analyses independently; and (iii) occasional users, less familiar with the techniques but requiring data from the facilities that cannot be provided by other methods. User support, particularly for this last category of user, is an important service provided by each facility, or by the research team responsible for the beamline.

All three categories of users typically take advantage of other spectroscopies in their scientific programs, so that the neutron or light source represents only one of several research methods available, others of which are accessible at home installations. Users travel from one large installation to another, as science demands, to capitalize on special features available in different places. Since, to a large extent, light source and neutron source experiments are "scattering" measurements, the same scientists often use both types of facilities in their programs.

**User Community for BES-Supported Synchrotron Light
and Pulsed Neutron Sources**
(Data for FY1994)

	<u>University</u>	<u>Industry</u>	<u>Labs</u>	<u>Other</u>	<u>Total</u>
<u>Light Sources</u>					
NSLS	1097	317	449	368	2231
SSRL	324	58	155	50	587
ALS*	<u>(61)</u>	<u>(5)</u>	<u>(72)</u>	<u>(25)</u>	<u>(163)</u>
Subtotal	1482	380	676	443	3073
<u>Pulsed Neutron Sources</u>					
IPNS	63	15	62	32	172
LANSCÉ**	<u>15</u>	<u>5</u>	<u>36</u>	<u>17</u>	<u>73</u>
Subtotal	78	20	98	49	245
Total	1560	400	774	492	3318

* ALS is still in a start-up mode, with new beamlines being implemented. Figures in parentheses refers to the latest 12-month period. APS is currently being commissioned.

** LANSCE operated for only 1 month in 1994.

D. 4. 6. Electron Microscopy

In support of its mission, the DOE also funds electron microscopy centers. Electron microscopy plays a major role in materials research, including research on energy-related materials. More than a third of all papers published in materials sciences journals involve electron microscopy in some way. Because electron microscopes are based on accelerator technology, we included a brief description of this activity here.

The DOE funds four electron microscopy user facilities: the National Center for Electron Microscopy (NCEM) at LBNL, the Electron Microscopy Center for Materials Research (ECM) at ANL, the Shared Research Equipment (SHaRE) program at ORNL, and the Center for Microanalysis of Materials at the University of Illinois, all with annual operating budgets under \$2M. Together, these four facilities provide

specialized facilities for forefront research projects and serve a user community of more than 800 scientists a year. A far larger number of researchers, not requiring state-of-the-art facilities, make use of thousands of small, commercially available electron microscopes in individual research labs.

The major new directions in instrumentation are concerned with electron optics, computer image reconstruction, and the development of stages and detectors. The facility most closely involved with accelerator technology is the one at ANL, where a tandem accelerator is interfaced with an electron microscope for in situ ion irradiation experiments.

D. 5. Health and Environmental Research

The program mission of the Office of Health and Environmental Research (OHER) is to develop and support fundamental science that underpins the strategic goals of the DOE in areas related to health and environmental effects. The OHER program “develops the knowledge needed to identify, understand, and anticipate the long-term health and environmental consequences of energy production, development, and use.” Accordingly, OHER pursues three overall strategic objectives:

- To contribute to human health by: sequencing the human genome by 2005; developing advanced medical technologies and radiopharmaceuticals; and using unique national laboratory facilities for structural studies at the molecular and cellular level.
- To contribute to cleaning up the environment by developing advanced remediation tools and risk assessment technologies.
- To understand global environmental change by understanding the role of energy production.

Explicit operations support for accelerator-based facilities and R&D support for related technologies are not parts of the mission orientation in OHER (as they are, for example, in BES in its operation of synchrotron light sources). However, the long-term strategic directions of OHER are problem-oriented, and accelerator-based technologies offer a *means* to help solve specific problems. In particular, OHER supports the development of specialized capabilities at national laboratories that enable researchers to make use of these unique facilities. These capabilities take the form of beamlines and/or instruments at the DOE synchrotron light sources and accelerator-based neutron sources (and also reactors). Key components of OHER's strategy include support of scientific and technical personnel to construct, operate, and provide user support for the specialized instrumentation. An additional important component is the provision of funding for advanced R&D, especially detector R&D. The shared facilities supported by OHER are used by hundreds of scientists from the national laboratories, universities, and industry. Funding for the individual research projects conducted at those facilities often comes from other agencies, especially the NIH and the NSF. In some cases, close cooperation between OHER and the NIH has led to the development of complementary resources at the facilities, to the direct benefit of the user community.

D. 5. 1. Structural Molecular Biology

The area of structural molecular biology is of central importance in sequencing the human genome and in understanding how this information can be used for improving health. Obtaining an in-depth knowledge of molecular-structure is closely coupled to understanding the function (and malfunction) of biological processes. Such structural knowledge comes primarily from studying how biological molecules interact with electromagnetic radiation or neutrons.

As noted earlier in this appendix, synchrotron radiation provides remarkably intense X-rays broadly applicable to the study of condensed matter. In the field of

structural molecular biology, synchrotron radiation offers the means to solve more challenging problems (for example, the study of larger structures and assemblies) with higher resolution (even at the level of individual atoms) and to do it more rapidly than is possible with conventional sources. For scientists to make use of synchrotron radiation, however, specialized facilities must be developed and supported for studying biological systems. Accordingly, OHER is funding ongoing programs at NSLS and SSRL and has initiated projects (currently in the construction phase) at the ALS and the APS.

Growth in the demand for access to synchrotron radiation facilities for structural biology research has been remarkable. In the early 1980s, synchrotron radiation was little used for such studies; it was applied primarily to specialized problems being studied by a few small groups. From 1980 to 1990, however, the use of synchrotron radiation grew rapidly, revolutionizing several areas, including time-resolved investigations of biological structure and high-resolution studies of very large biological assemblies such as viruses. By 1991 a survey of biological users of synchrotron radiation revealed that existing facilities were oversubscribed and "a threefold increase in the need by U.S. scientists for synchrotron radiation is projected through the year 2000, based on current growth rates."

Because of the unique capabilities at the national laboratories for synchrotron radiation-based science and because of the direct relevance of these technologies to the OHER mission, OHER proposed and initiated a program to develop the resources and to provide support for access by the biological community. This approach was strongly endorsed and supported by the 1992 review of structural biology by a subcommittee of the Health and Environmental Research Advisory Committee (HERAC). This endorsement was reaffirmed in a more recent review (September 1995) of the OHER instrumentation programs (which includes synchrotron user facility support) by another HERAC subcommittee. Nonetheless, it is by no means clear that

the new beamline developments currently funded by OHER at SSRL, the APS, and the ALS will meet the continually increasing user demand.

Compared with studies using synchrotron radiation, neutron scattering and neutron crystallography serve a complementary and, in some ways, more specialized role in studies of biological systems. Hydrogen atoms (which are involved in hydrogen bonds common in biological structures) can be located precisely with neutrons, but not with X-rays. Neutrons also provide special capabilities for enhancing contrast of a selected component in a large biological assembly. OHER therefore supports development of neutron-scattering expertise and capabilities for the study of biological macromolecules at the LANSCE pulsed neutron-scattering facility at LANL. (It also supports similar efforts at the steady-state reactor facilities at BNL and ORNL.) In all of these cases, OHER again supports specialized facilities and staff for R&D and user support, not facility operations and accelerator development.

D. 5. 2. Environmental Sciences

There is an increasingly pressing need to study and understand the chemical and physical forms of toxic and radioactive contaminants and pollutants in soils, sediments, man-made waste forms, natural waters, and the atmosphere. This information is important in understanding why contaminants do (or do not) migrate and in helping to develop sound remediation strategies for removing these materials from the environment. Techniques using synchrotron X-rays (especially X-ray absorption spectroscopy and X-ray scattering techniques) have significant potential to provide the needed scientific information. Existing synchrotron facilities at NSLS and SSRL are already being used in this regard, and development of new specialized facilities is being considered by OHER to support basic research in this area. As these endeavors utilize BES-operated synchrotrons and are of direct interest to the mission of EM, coordination across these offices is essential. This area was examined in a DOE workshop held in July 1995, entitled "Molecular Environmental Science:

Speciation, Reactivity, and Mobility of Environmental Contaminants—An Assessment of Research Opportunities and the Need for Synchrotron Radiation Facilities.”

D. 5. 3. Nuclear Medicine

Nuclear medicine is the practice of using radioactive isotopes for diagnostic imaging, the measurement of physiologic processes, and the treatment of disease. Radionuclide imaging has been widely used for diagnosing brain and heart disease, and for diagnosing and treating many types of cancer. Nuclear medicine has applications in practically every organ system in the body, and is also useful in evaluating patient response to therapy. An estimated one-third of hospital patients in the U.S. undergo nuclear medicine procedures, and even more nuclear medicine procedures are performed on outpatients.

More than 50 different types of diagnostic tests involve nuclear medicine. These include radioisotopes administered to patients with disorders affecting bone, heart, lung, brain, thyroid, kidney, liver, gall bladder, and the colon. In all cases, accelerators and reactors produce the radioisotopes used to perform the tests. Most accelerator-produced isotopes used in clinical practice are supplied by commercial sources using relatively low-energy cyclotrons (30 to 50 MeV). Isotopes requiring higher energies (greater than 50 MeV) are obtained from DOE accelerator facilities such as BLIP, LAMPF, and TRIUMF (the last of these in Canada). Most isotopes produced with these higher-energy accelerators are used in research, with only a few used in clinical medicine. In addition, a few of the medical centers around the country own and operate small, low-energy cyclotrons (10 to 15 MeV) to supply very-short-lived isotopes for their positron emission tomography (PET) programs. OHER does not directly fund the operations of any of these accelerator facilities except a contribution the BLIP program makes to the operation of the AGS's linac injector. It does, however, support R&D on the fundamental aspects of radiopharmaceuticals and radionuclides. OHER also provided the construction funding for upgrading the BLIP

complex at BNL in 1994 and funded an R&D effort emphasizing target development for high-intensity operation and optimized radioisotope processing.

D. 5. 4. Funding and Users

The total OHER budget for FY1995 was \$431M. Of this total, about 7% was devoted to activities that relied on accelerator-based capabilities for structural biology and nuclear medicine.

The users of OHER-supported beamlines and instruments are included in the table summarizing users of BES-funded synchrotron light and neutron sources in Section D.4.5.

D. 6. Fusion Energy

The goal of fusion energy research is the production of controlled fusion energy for electric power generation. Accelerators play important roles in fusion research supported by the OER and in the inertial confinement fusion (ICF) program supported by the DOE Office of Defense Programs. The three principal roles in OER are: plasma heating for magnetic fusion energy (MFE), drivers for inertial fusion energy (IFE), and materials testing. All three have the potential of being critically important to the fusion program, but support has not been steady.

D. 6. 1. Plasma Heating

Neutral-beam accelerators for plasma heating enabled the Tokamak Fusion Test Reactor (TFTR) at Princeton to achieve a world-record fusion power level of approximately 10 MW. Despite this success, the Office of Fusion Energy (OFE) recently terminated the U.S. neutral-beam research program. The U.S. fusion community is a collaborator in the proposed construction of the International

Thermonuclear Experimental Reactor (ITER). The plans for ITER are still evolving, and neutral beams may yet be needed. Japan has maintained a large neutral-beam research program and is likely to supply any neutral beams needed for ITER.

D. 6. 2. Inertial Confinement and Heavy-Ion Fusion

Defense Programs sponsors the inertial confinement fusion program primarily for its applications to weapons physics and nuclear stockpile stewardship. In ICF intense laser or ion beams will be used to implode and ignite millimeter-sized capsules containing thermonuclear fuel. The burning fuel will produce many times the amount of energy used to implode and ignite the capsule. To achieve ignition, however, the beams must deposit several megajoules of energy in about ten nanoseconds. These numbers correspond to a beam power of several hundred terawatts. Lasers can readily produce high beam power and are, therefore, well suited to near-term research on the physics of the fusion capsules. Accordingly, the DOE and Congress recently approved construction of the National Ignition Facility (NIF) which is a billion-dollar laser facility for defense-related ICF research. The NIF schedule calls for demonstration of thermonuclear ignition in the year 2005.

The NIF and other existing lasers do not have some important capabilities needed for commercial power production. They do not have the pulse repetition rates, the lifetime, the reliability, or the efficiency needed for economical power production. Review panels have consistently identified high-energy heavy-ion accelerators as the most promising driver technology to solve these problems. Heavy ions, in contrast to light ions, give the appropriate depth of penetration at ion kinetic energies achievable by conventional accelerator technology. The principal new issue for heavy-ion inertial fusion is the production of very high beam power while maintaining adequate beam quality for focusing. Theory, numerical simulation, and scaled experiments indicate that it should be possible to produce beams with adequate power and quality, but further progress requires experiments with full-scale beams.

LBNL has proposed the construction of a series of such experiments, known collectively as ILSE (Induction Linac Systems Experiments). Multiple beams of ions such as potassium or cesium would be accelerated to a kinetic energy of about 10 MeV. Elise, a 5-MeV accelerator using electrostatic focusing is the first phase of the ILSE program. In December 1994, OFE approved the construction of Elise, with construction scheduled to begin in FY1996, but Congress did not approve any new OER fusion projects. At this point, the future of the Elise project is unclear. It would be desirable to complete the accelerator research program by 2005 so that the combination of data from NIF and the accelerator research program could be available to make a sound decision about the feasibility of heavy-ion fusion.

Heavy-ion fusion is a good example of (i) a benefit that has emerged unforeseen from accelerator developments undertaken for high energy physics and (ii) strong synergism among DOE programs. If successful, heavy-ion fusion will provide an important source of energy for future generations. One of the most critical issues facing OER is the projected cost of developing fusion science and technology. The development of heavy-ion fusion is expected to be relatively inexpensive, because other accelerator programs have developed much of the technology, for example, superconducting magnets, high-power switching technology, and accurate alignment systems, and because Defense Programs has developed much of the target science. Ongoing developments in these areas will undoubtedly continue to benefit heavy-ion fusion.

D. 6. 3. Materials Testing

Materials testing, the third major role of accelerators in OER's Fusion Program, has a long history. Fusion researchers have recognized for more than two decades that the development of advanced materials is needed to make magnetic fusion environmentally and economically attractive. One critical issue is the behavior of

these materials under bombardment by fusion-spectrum neutrons (14 MeV for deuterium-tritium fuel).

In 1992, OER asked the Fusion Energy Advisory Committee to review OFE's Neutron-Interactive Materials Program. The resulting report (DOE/ER-O593T), issued in April 1993, emphasizes the need for a neutron source to test fusion materials and concludes that an accelerator-based system provides the most direct route to the needed capability. The report states that preparation for building a demonstration power plant "requires that both ITER and a high-flux 14-MeV neutron source proceed on similar schedules. Two concepts have been proposed: a 35-MeV deuterium beam impinging on a liquid lithium target, and a 120-keV deuterium beam impinging on a mirror-plasma target. While the proposed accelerator technology for a D-Li neutron source will be challenging (especially if superconducting RF cavities are chosen), the beam current exceeds existing room-temperature CW systems by only a factor of two and appears feasible. Although the design of the lithium target system will be difficult, much was accomplished in the earlier FMIT Project. This approach appears to be the most direct route to attaining the needed materials testing capability."

Funding for the Fusion Material Irradiation Test (FMIT), mentioned in the quotation above, reached a peak of nearly \$31M per year in FY1981. The DOE had hoped for foreign contributions to FMIT, but these contributions did not materialize, and construction was canceled. The international fusion community is now developing plans to design and build a new facility, usually called the International Fusion Materials Irradiation Facility (IFMIF) for materials testing. The probable cost is near \$1B.

D. 6. 4. Other Aspects of Accelerators and Fusion Research

Apart from these three main applications of accelerators to fusion, the nuclear data obtained from accelerators are an indispensable part of the foundation of fusion

research. These data include cross-sections for fusion, for tritium production, for the activation of materials, and for the interaction of heavy ions with matter. In addition, accelerator technology is the basis for some speculative approaches to fusion, such as colliding-beam machines, and accelerator spin-off technologies such as superconductivity, RF power production, and diagnostics all find important applications in fusion research.

Other accelerator programs provide important contributions to the OER fusion program. Examples include the Rotating Target Neutron Source (RTNS) facility at Lawrence Livermore National Laboratory (LLNL), Defense Programs' light-ion fusion research, and U.S. Department of Defense accelerator research. The RTNS is a high-current, continuous-beam deuteron accelerator producing D,T neutrons in a rotating, tritiated metal target; it has provided important data for Defense Programs' fusion effort. Light-ion fusion research is strongly related to the heavy-ion fusion program through beam physics, target physics, and pulsed-power technology. The work sponsored by the Defense Department is related through beam physics, precise focusing systems, and the development of advanced accelerator concepts.

D. 6. 5. Funding and Users

Funding for magnetic fusion energy in FY1996 is approximately \$236M; this is about \$120M below the FY1995 appropriation. FY1996 funding for inertial fusion energy is \$8M.

Unlike the situation in High Energy Physics, Nuclear Physics, BES, and OHER, fusion accelerators have not yet become large user facilities. In the case of beam heating, the accelerators are essential parts of larger devices. The larger device, for example, the Tokamak Fusion Test Reactor (TFTR) or Doublet III-D (DIII-D), may serve a number of users, but this practice is not as common as in the other fields. At the present time, the issues for heavy-ion inertial fusion are related to the accelerator

itself, and the accelerator designers and builders are themselves the users. Ultimately, a full-scale heavy-ion driver would be capable of serving a large user community doing research on targets, target chambers, materials, etc. A fusion materials test facility would, from its inception, be a user facility.

APPENDIX E

Contributions to the Nation

Developments in accelerator science and technology during the past 50 years have spawned a number of applications which have improved the quality of life for the general population. In most cases these improvements are taken for granted, and the average citizen is unaware of the connection between accelerators and the benefit he or she is receiving. This Appendix describes significant medical, industrial, military, and energy production applications which depend on accelerator technology.

E.1 Medical Applications

Many of the most advanced techniques in medical imaging and radiation therapy are direct spinoffs of accelerator development. Historically, there has always been a close relationship between physics and medicine, which has led to rapid transfer of technology from basic physics research to practical medical applications. The U.S. Department of Energy (DOE) can be particularly proud of the contributions it has made to medicine.

Radioactive Isotopes—DOE and its predecessor agencies have long supported the development and medical application of radioactive isotopes. This was an early and extremely successful example of technology transfer, which has allowed the creation of both the radiopharmaceutical and nuclear medicine instrumentation industries. In diagnostic nuclear medicine, radioactive chemicals at tracer levels are administered to patients and gamma rays emitted from the radioactive tracer are detected by a gamma camera, which uses computer techniques to reconstruct an image of the distribution of tracer in the body. Such imaging provides information about organ function and metabolism. At present one out of every three hospitalized patients in the United States undergoes a nuclear medicine procedure. In excess of 36,000 diagnostic medical procedures that utilize radioisotopes are performed daily in

the United States, and a growing number of therapeutic procedures as well (approximately 200,000 annually). The total value of this use is estimated at \$7-10B per year. In addition, there are close to 100 million laboratory tests annually that use radioisotopes to measure constituents of biological samples.

Approximately 20% of radiopharmaceuticals are based on accelerator produced isotopes. The most important and widely used of these is thallium (Tl)-201, which was originally developed at Brookhaven National Laboratory (BNL) in the 1970s. It is used to measure blood flow in heart muscle during exercise and is now produced commercially by proton irradiation of Tl-203 in a cyclotron at 28 MeV. Another important DOE development is the radiopharmaceutical F-18 deoxyglucose (FDG), which uses the accelerator-produced radioisotope fluorine-18. Originally developed at BNL in 1978, it is now the most widely used tracer for Positron-Electron Therapy (PET). FDG is a sugar analogue that can be used to study glucose metabolism in the brain, heart, and other organs. Many applications already exist in oncology (detection of tumor location and type, assessment of tumor response to surgical, drug or radiation therapy), neurology (early diagnosis of Alzheimer's disease, location of seizure foci in epilepsy prior to surgical treatment, differential diagnosis of Parkinson's disease, and brain function research), and cardiology (assessment of heart muscle viability). It is the only PET agent approved by the Food and Drug Administration for clinical rather than experimental use.

In addition, BNL and Los Alamos National Laboratory (LANL) have significant radioisotope production programs serving both the nuclear medicine research community and industry. The Brookhaven Linac Isotope Producer (BLIP) has used a 200-MeV, 45-microampere proton beam for this purpose since 1972, and is presently upgrading to 145 microamperes. The Los Alamos Meson Physics Facility (LAMPF) has delivered 800-MeV, 600-microampere protons for radioisotope production since 1975. Several unique, hard-to-make

isotopes have been developed and are now distributed by these facilities. For example, strontium-82 is the parent in a generator system for creating the short-lived potassium analogue rubidium-82. This FDA-approved radioisotope system is used to assess cardiac function. The long-lived, positron-emitting germanium-68 is used to calibrate PET cameras throughout the world. Also, copper-67 is one of the most attractive radioisotopes for tumor therapy when attached to a tumor-specific monoclonal antibody.

Conventional Radiation Therapy—Over the past 25 years cobalt therapy machines for treating malignant tumors have been replaced by electron linear accelerators, which provide better and more flexible penetration of the therapy beams into the body. This allows the physician to raise the dose to the tumor while keeping the side effects comparable to those incurred during cobalt therapy. The linacs produce 4-25 MeV electron beams which strike a tungsten target to generate photons for treating cancer with radiation therapy. In some cases the electron beam is used to treat superficial tumors directly. The linac is typically one to two meters long and mounted on a gantry so it can rotate around a supine patient. A dipole magnet bends the beam perpendicular to the linac and the patient is positioned so the beam strikes the tumor. These linacs cost \$1-2M and are used to provide radiation therapy at most large hospitals throughout the United States and other technologically advanced countries. About five major corporations dominate the competitive market, including Varian Associates and General Electric in the United States.

Proton Cancer Therapy—This promising therapy uses the proton Bragg peak to minimize unwanted dose to healthy tissue. For many types of cancer, it has the same probability of tumor control as photons, but with significantly fewer side effects. For harder-to-control tumors it allows the physician to prescribe a much higher tumor dose than would be possible with conventional photon radiation therapy. Pioneering work was done at Lawrence Berkeley National

Laboratory (LBNL) using the 184-Inch Synchrocyclotron, and the research has been continued at the Harvard Cyclotron. The first hospital-based synchrotron for proton therapy was built by Fermi National Accelerator Laboratory (Fermilab) and installed at Loma Linda University Medical Center in the late 1980s. Use of the first commercially manufactured radiofrequency quadrupole (RFQ) linac substantially reduced the size and cost of the Loma Linda accelerator. A 70- to 300-MeV variable-energy proton therapy synchrotron has been commercialized in United States by Elektus, and a 235-MeV cyclotron can be purchased from Ion Beam Applications in Belgium. A superconducting cyclotron for proton therapy is being developed at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL).

Fast Neutron Cancer Therapy—This is the first form of hadron therapy to be investigated. Early initiatives at Berkeley revealed the importance of the concept of Relative Biological Effectiveness in understanding neutron dosimetry. The high reliability and favorable dose rate of the 66-MeV proton beam from Fermilab's injector linac enabled Fermilab to set the standard for the beam qualities required for effective fast neutron therapy. This therapy is superior to photon therapy for some radioresistant tumors, including salivary tumors, soft tissue and bone sarcomas, adenocarcinoma of the lung, and advanced prostate cancer. AccSys Technology has developed a hospital-based linac for neutron therapy, and the NSCL has developed a hospital-based superconducting cyclotron.

Heavy-Ion Cancer Therapy—Heavy ion therapy combines the advantages of the Bragg peak seen in proton therapy with the biological effectiveness seen in fast neutron therapy. This combination makes heavy ion therapy a very attractive option for many types of tumor. Pioneering work was done at LBNL's Bevalac. Unfortunately, all clinical research with this therapy in the United States was terminated with the closing of the Bevalac, though the therapy is

available in Japan. Several European countries have plans to build heavy-ion therapy centers.

Pion Cancer Therapy—Pioneering work with pi mesons was done at Stanford using their high-energy electron linac and at LANL using the LAMPF linac. The most extensive clinical research with this therapy was done at Paul Scherrer Institute (PSI) in Switzerland using technology developed in the United States. The PSI clinical results were similar to those for fast neutrons, though the cost of producing pions is much greater. PSI terminated its pion research in favor of proton therapy research, but pion therapy is available at the TRIUMF accelerator in Canada.

Coronary Angiography—By using radiation from a synchrotron rather than conventional X-ray machines it is possible to inject the iodine contrast agent into a vein rather than an artery to obtain an image of the heart. Injection into a vein makes the procedure much safer for the patient and enables clinicians to image the hearts of patients who might not be candidates for the more dangerous conventional procedure. Use of synchrotron light for coronary angiography was pioneered at the Stanford Synchrotron Radiation Laboratory, and the technology was transferred to the National Synchrotron Light Source at BNL, where physicians and physicists are performing clinical trials and fine-tuning the technique. Coronary angiography using conventional X-rays is a \$2B per year industry.

Designer Drugs—High-resolution X-ray crystallography using synchrotron radiation has enabled researchers to understand the detailed structures of proteins, enzymes, and viruses. Using this knowledge, they are designing drugs which alter these structures to fight disease more effectively.

E.2. Industrial Applications

Besides the economic benefit derived from knowledge acquired in the many research uses of accelerators, there are applications that add direct value to industrial goods and services. A selected list of such applications is shown below. It is not a complete list but rather a sampling across a broad range of application categories that are now commercially successful or are close to being brought to market.

Ion Implantation for Semiconductor Devices—One of the most widespread and economically important applications of particle accelerators is for ion implantation, in which beams of doping or alloy materials are implanted into metals or semiconductors to selectively alter material properties. Major applications of ion implantation are in the manufacturing of semiconductors and in the improvement of surface hardness and corrosion resistance of metallic devices.

Thousands of ion-implanting systems have been used by the semiconductor industry to produce embedded layers in silicon wafers doped as needed for various semiconductor devices. In processes that are now totally automated, the doping material species, depth of implant, and doping concentration can be carefully controlled to meet the exacting requirements for mass-produced, high quality devices. For example, the uniformity of doping concentration can be controlled to better than 1% across the wafer.

The economic impact of the ion implantation is large. As direct measure of value, we note that several companies now manufacture the implanting systems, which cost about \$5M each. The multi-billion dollar per year semiconductor industry would be much different without the essential technology that makes many of their devices possible.

Ion Implantation for Surface Hardening—Surface hardening by ion implantation uses ion beams to alloy a thin surface layer with foreign atoms at concentrations hundreds of times the typical level used for semiconductor doping. This method is superior to the traditional thermal treatment and results in greatly enhanced surface hardness and resistance to wear and corrosion. Some examples include the surface treatment of prosthetic devices such as hip and knee joints to reduce wear of the moving parts while using biologically inert materials, surface hardening of high speed bearing surfaces, and the hardening of metal forming and cutting tools. Several DOE laboratories are currently involved in the continued development of these technologies.

Sterilization By Accelerator-Generated Radiation—Electron beams from a variety of low energy accelerators such as the Cockcroft-Walton, Dynamitrons or RF linacs are widely used for sterilization and other forms of industrial irradiation. As electrons penetrate materials they create radiation fields from showers of low energy electrons and photons. After many collisions the electrons have the proper energy to create chemically active sites. In sterilization, the radiation breaks down biological molecules to render them useless and, thus, kills the organism. Important applications include the sterilization of syringes, gloves, cosmetics, pharmaceuticals, and food. Accelerator beams have been used to sterilize sewage sludge so that it can be used safely as fertilizer. The compact electron linacs are a spinoff from linacs developed originally at Stanford Linear Accelerator Center (SLAC) and LAMPF for basic research.

Materials Irradiation—Radiation generated by electron beams can also be exploited to change material properties such as cross-linking a polymer to strengthen it, curing epoxies, production of shrink film and tubes, or radiolysis of toxic wastes to less toxic products. Other important applications include the removal of pollutants from utility stack gas and electron treatments to cure thin

films and coatings. For applications requiring the lower energies, 1-5 MeV, conventional high-voltage generators can be used. Above about 5 MeV, the size and cost of these generators makes them impractical, and compact linacs are the technology of choice.

X-Ray Lithography—Lithography refers to the technique of shadow or proximity printing to replicate fine patterns on various materials. The pattern on a mask is transferred to a photoresist coating on a wafer using optical radiation or low energy X-rays. This process is most extensively used in the manufacture of microchips and other semiconductor devices. In a deep-etch process it is also used to produce micromachines. The interest in X-ray lithography stems from the finer spatial resolution possible with the shorter wave-length X-rays. Higher resolution means more microelectronic circuits per unit area on a chip, a very important factor in the highly competitive semiconductor industry, which thrives on a fast pace of technological improvements that yield ever increasing capability per unit cost.

Pioneering development work in X-ray lithography was done at the DOE and the National Science Foundation (NSF) synchrotron light sources. Currently, multi-GeV electron synchrotrons and storage rings are still the best sources of intense X-ray beams for lithography R&D. Ultimately, commercial use of X-ray lithography will require compact X-ray sources appropriate for industrial settings.

Explosives and Contraband Detection—Effective, non-destructive, automated methods of explosives and contraband detection would be of great benefit to the traveling public and ease the burden on inspection agencies. Systems based on such methods would reduce the inconvenience to travelers and enhance the security of airports and other transportation hubs. The feasibility of two accelerator-based concepts has been established. In one concept, accelerator-

produced gamma rays and gamma-ray resonance absorption analysis are used to detect explosives. In the other, an accelerator-based inspection system employs pulsed fast neutron analysis (PFNA) for detection of drugs or explosives. At this time, further development is needed to achieve cost-effective, reliable systems that are likely to be commercially successful. Among DOE laboratories, LANL has been active in the development of accelerators for the gamma-ray resonance absorption technique. In industry, Science Applications International Corporation has developed, built, and is now testing a system using the PFNA concept.

Neutron Radiography Using Accelerator Sources—Neutron radiography is a well-established, nondestructive inspection technique used at reactor neutron sources. Major applications include inspection and checking of components such as turbine blades, reactor fuel components, small explosive devices, corrosion in aerospace parts, and hydrogen embrittlement in welds. Accelerator-produced neutron beams could meet the neutron beam requirements for commercial neutron radiography. Suitable beams could be produced by moderating and collimating neutrons produced by a few-MeV proton or deuteron beam striking a lithium or beryllium target. Transportability by truck is one advantage that an accelerator-based neutron radiography facility could have over a reactor-based facility. This opens up the possibility of inspecting objects too large or not transportable to a reactor hall. The RFQ accelerator technology could provide the proton or deuteron beams to meet the needs for low energy neutron radiography. (The RFQ was first developed at LANL for the DOE fusion energy program.) Neutron radiography also shows promise for the nondestructive inspection of nuclear weapon assemblies. This application requires a beam of several-hundred-MeV protons to produce neutrons using a spallation reaction.

E.3. Defense Applications

The U.S. continues to rely on its shrinking stockpile of nuclear weapons to deter strategic military threats to its national security. The strength of the deterrence is strongly tied to the reliability, safety and credibility of the aging stockpile.

Accelerators contribute in increasingly important ways to the maintenance of the stockpile. They currently provide important radiographic diagnostics in hydrodynamic, non-nuclear simulation/testing of weapon primaries. Pulsed-power accelerators are used in the simulation of weapons effects for testing defense systems survivability.

Tritium is a key weapons ingredient that has a limited lifetime and must be replenished over time. Accelerator-based production of tritium (APT) is judged feasible and has the potential to supply tritium with fewer safety and environmental problems than a new production reactor. Accelerator-based neutron and proton radiography also show promise as important tools for stockpile stewardship.

Other issues in the management of the nuclear weapons complex that accelerators can address include accelerator-based conversion (ABC) of excess weapons plutonium to non-fissile material and accelerator transmutation of radioactive or fissile defense wastes (ATW) to short-lived isotopes or non-fissile materials. Finally, it should be noted that an accelerator-based, antiballistic missile system is another potential defense application that has been intensively developed but is still in its infancy.

Pulsed Radiography in Hydrodynamic Testing—Hydrodynamic testing refers to the above-ground, non-nuclear experimental study of the implosion process in the primary initiator system in a nuclear weapon. Without underground testing, it is the program that comes closest to experimental verification of device performance. Data from hydrodynamic testing is used to validate computer

codes, study the effects of component aging, study sensitivity to environmental parameters, and assess weapons safety issues.

Accelerator-generated, very intense, short bursts of high-energy X-rays are used to radiograph the implosion. It is the one method capable of providing data from late in the implosion. The oldest pulsed radiographic linac in the weapons complex, PHERMEX at LANL, which dates from the 1960s, uses rf linac technology. To obtain much higher beam current, Lawrence Livermore National Laboratory (LLNL) built a radiographic induction linac, the FXR, and LANL is now constructing a dual-axis induction accelerator, DAHRT, for pulsed radiography. These induction linacs are capable of kiloampere electron beams at 15-20 MeV.

Weapons Effects Simulations—Pulsed power accelerators are a vital component in pulsed X-ray sources used to simulate the effects of nuclear explosions. For many years, above-ground simulators have supplemented underground testing of survivability and hardening of nuclear weapons and other defense systems. In the complete test ban environment, such non-nuclear studies assume much greater importance to maintaining the credibility of the U.S. nuclear deterrence. Sandia National Laboratories and various Department of Defense (DOD) labs have led in the development of nuclear weapons effects simulators.

Accelerator Production of Tritium—Replenishing the decaying tritium component of nuclear weapons is essential to maintaining any size stockpile. There is little doubt that accelerator production of tritium can meet the needs of the reduced stockpile planned for the future. The system design behind the proposed APT facility is based on well-established, existing technology in the areas of operational linear accelerators, tritium extraction and neutron production targets. The proposed APT facility has several advantages over reactor production of tritium in that APT uses no fissile materials, has no

chance of a criticality accident, produces no high-level radioactive waste, and can easily be scaled up or down to meet stockpile needs. In addition, the LANL concept for APT has continual extraction of tritium that avoids buildup and thereby avoids the risk of a large release. Capital costs of APT are estimated to be less than for a new production reactor. APT is a spinoff from the high-power proton linac technology developed at LANL and other DOE laboratories.

Accelerator Transmutation of Waste and Conversion of Plutonium—

Accelerator-driven transmutation of radioactive or fissile waste (ATW) is a concept that uses a high-intensity beam of protons up to 1.6 GeV to generate a very intense, high flux spallation neutron source. The spallation neutrons are thermalized in a moderating blanket and produce the flux needed to transmute long-lived actinide isotopes and fission products to stable isotopes or much-shorter-lived isotopes that decay to stable products. This ameliorates the very difficult technical and political problems of storing long-lived, high-level radioactive waste from nuclear weapons production and nuclear power plants.

Accelerator-based conversion of plutonium is a special form of ATW designed to convert weapons plutonium to a form that cannot be subverted for use in other nuclear weapons. It is aimed at converting excess plutonium from nuclear weapons dismantled as a result of stockpile reduction agreements. The immediate concern is to gain control of the material and prevent clandestine use in nuclear weapons.

The accelerator requirements for ATW are similar to those of APT, but the spallation neutron target requirements are more demanding. Both ATW and ABC are spinoffs from the high-power proton linac technology developed at LANL and other DOE laboratories.

Beam Weapons—Another potential application is accelerator-based anti-ballistic missile defense systems. They were studied and some received considerable development under the DOD Strategic Defense Initiative. The neutral particle beam project (NPB) and the free-electron laser projects were accelerator based and depended heavily on high-power rf linacs. The NPB project studied the use of neutral particle beams to perform several functions, including detecting the incoming missile, distinguishing it from decoys, and finally destroying the warhead before it could do harm. Many of the accelerator physics issues were resolved before the project was closed, but many engineering, operational, and cost issues remain. These applications were potential spinoffs from proton linac and free electron laser accelerator technology developed at DOE laboratories.

E.4. Energy Production

When deuterium and tritium atoms fuse, they release energy, which can be used for electrical power. It is important that the energy used to initiate the fusion reaction be less than the energy released in the reaction. Fusion has great long-term potential but is not yet commercially practical. Fission, on the other hand, has been proven practical, but concerns about safety and radioactive waste have limited construction of reactors. In this section, we describe two promising accelerator-based methods for energy production. These are heavy-ion fusion (HIF), a form of inertial fusion, and accelerator-based fission reactors. Research on the high-intensity accelerators required for both concepts is being pursued in the DOE.

Heavy Ion Fusion—This method of fusion uses intense beams of heavy ions to compress and ignite a small pellet of inertially confined deuterium-tritium fuel. The late Alfred Maschke first proposed using heavy ions in 1975, based on his experience with high-energy accelerators at Fermilab and BNL. Maschke recognized the advantages of heavy ions, since confirmed by a number of

national reviews, including a National Academy review. The current DOE program is centered at Berkeley with additional effort at LLNL. The research involves a series of experiments to validate methods for increasing the beam intensity while keeping costs down.

The HIF effort is coordinated with the inertial fusion research program in DOE's Defense Programs, which is based on lasers and light ion beams. Also, good interaction exists between the U.S. effort and European research, concentrated in Germany. The European effort is based on rf accelerators while the U.S. effort emphasizes induction linacs.

Accelerator-Based Fission—Use of an accelerator-based neutron source to initiate fission in a sub-critical reactor is inherently safer than the methods currently used in fission power plants. Use of a sub-critical assembly eliminates the possibility of a runaway chain reaction; if the linac is off, the fission reaction shuts down quickly. Other safety features include reduced after-heat, less production of high-level radioactive waste and the possibility of burning or transmuting its own radioactive waste. The rf linac needed for accelerator-based fission is similar to that required for accelerator-based tritium production (APT) for DOE's Defense Programs. LANL scientists and others have studied methods for achieving the required higher intensity, and currently LANL has a program to begin development of such a linac.

Many of the developments in both of the above programs regarding high intensity have spinoff potential to other DOE accelerator programs and illustrate the synergism of such programs.

APPENDIX F

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Accelerator Science and Technology in Support of Office of Energy Research Programs

Particle accelerators are the tools that support a significant component of the research programs overseen by the Office of Energy Research (OER). As such, advances in the research missions of OER are strongly coupled to advances in accelerator physics and technology. Over the years this reliance has been recognized, and accelerator R&D in support of OER missions has been an important component of the programs of the U.S. Department of Energy (DOE) and its predecessor agencies. This appendix reviews the underlying accelerator technology base supporting OER's research programs and identifies the technologies that will be required to support a continuation and expansion of research opportunities into the future.

High Energy Physics

High energy physics (HEP) research is aimed at identifying and understanding the most fundamental building blocks of matter and the forces that govern their behavior. HEP operates at the high energy frontier. The Tevatron currently operates at 1800 GeV in the center-of-mass, making it the highest energy collider in the world today. The Stanford Linear Collider (SLC) operates at 90 GeV, making it, along with the Large Electron-Positron Project (LEP) machine at the European Laboratory for Particle Physics (CERN), the highest energy electron colliders in the world. The goal of the HEP community over the next few decades is to advance the energy and luminosity capabilities of the collider facilities by at least an order of magnitude.

Current Accelerator R&D

The accelerator R&D program in support of HEP has been largely effective in addressing needs in the near to intermediate term future. Major achievements associated with this program over the past 20 years include, but are not limited to:

- Development of high luminosity electron-positron storage ring colliders
- Development of the first synchrotron/storage ring based on superconducting magnets
- Development of the first electron-positron linear collider
- Development of superconducting materials capable of supporting current densities of $>3000 \text{ A/mm}^2$ in an accelerator magnet application
- Development of rf sources and structures capable of supporting accelerator gradients of 50 MeV/m or more
- Development of high bandwidth (up to 8 GHz) stochastic cooling
- Development of an antiproton source capable of supporting high luminosity proton-antiproton collisions.
- Development of polarized proton sources and means for preserving polarization during acceleration
- Development of polarized electron sources to support high-luminosity operation in a linear collider
- Development of concepts for medium energy electron cooling
- Development of techniques for measurement of wakefield (or impedance) characteristics of accelerator components up to and beyond the GHz range
- Significant contributions to the field of non-linear dynamics.

These developments have allowed the U.S. HEP program to remain at the forefront of research worldwide. Effectiveness of the program results largely from recognition and acceptance on the part of the HEP laboratories, the DOE (and National Science Foundation [NSF]) program offices, and (most importantly) the user community of the ongoing need for both directed and more generic accelerator R&D to provide the tools needed to ensure the continued health of the field. This recognition and acceptance has led to the commitment of significant resources by each of the HEP laboratories plus the proposal-driven, peer-reviewed program administered by the DOE HEP office that supports long-term accelerator R&D at the universities and HEP laboratories. That program also provides funds for accelerator schools, which have become a major training ground for accelerator scientists and engineers. This training, plus many of the advances in accelerator science and technology supported by the HEP programs, have formed the basis for the development of forefront facilities in the other OER programs.

Fermi National Accelerator Laboratory (Fermilab), Stanford Linear Accelerator Center (SLAC), and Cornell are all currently engaged in significant upgrades to their facilities. The Main Injector project at Fermilab is designed to support a factor of five increase in the luminosity in the Tevatron Collider. At SLAC, the Positron-Electron Project (PEP-II) B-factory is currently under construction and is targeted at observation of CP violation in the B-system. A luminosity upgrade at the Cornell facility is also aimed at enhancing research capabilities in the B-system. Significant R&D programs have been associated with these projects, which are all scheduled to come on-line in the 1998-99 period.

More forward looking mission-directed research is also being conducted at the DOE HEP accelerator facilities. Fermilab is developing plans for enhancements to their antiproton production facility and is in the process of reconstituting a superconducting magnet development program. The medium-term goal is to achieve a luminosity of $\sim 10^{33} \text{ cm}^{-2}\text{sec}^{-1}$ in the Tevatron. A key component of the superconducting

magnet effort is the development of superconducting components for the Large Hadron Collider (LHC) program in Europe in collaboration with Brookhaven National Laboratory (BNL) and Lawrence Berkeley National Laboratory (LBNL). This work is being targeted toward areas that are of potential long-term use to the U.S. program.

A significant effort, centered and coordinated at SLAC, is aimed at developing the technology required for a next generation linear (e^+e^-) collider. The short-term goals are to validate requisite technologies and to produce a conceptual design for a facility operating at 500 GeV (center-of-mass), upgradable to 1500 GeV. Other national laboratories and universities are contributing significantly to this program. A novel idea that has resurfaced recently, the muon collider, is receiving serious attention at Fermilab and BNL. Both Fermilab and BNL are also investing some modest effort towards the understanding of issues related to a very large (multi-tens of TeV) hadron collider that could be a candidate for construction following completion of the LHC.

A variety of more exploratory accelerator research investigations are taking place, supported by DOE, at a variety of laboratories and universities around the country, including research into new accelerator and acceleration concepts, superconducting magnet and materials development, high-power rf sources, high-brightness sources, polarized beams, plasma lenses, and space-charge dominated beams. Both experimental and theoretical investigations are supported.

R&D Needed to Support Future Requirements

A number of "enabling technologies" are intimately related to the performance of HEP facilities, and continuing advances in these technologies are required to ensure the continued health of the field. Superconducting magnets are the enabling technology for proton-proton (and proton-antiproton) colliders. Ever increasing energies will be dependent on the development of higher performance magnets. Given the immense size of high energy hadron colliders, the R&D challenge is not only to

develop magnets capable of operating at fields approaching 10 Tesla, but also magnets designed to be fabricated and operated at a significantly reduced unit cost relative to current practice.

High-power rf sources and efficient high-gradient rf structures are the enabling technology for electron linear colliders. An intermediate goal is the development of effective accelerating gradients in the vicinity of 100 MV/m. Reduction of fabrication costs and associated operating costs is an important development goal.

A number of next-level technologies remain critical to further advances in hadron and electron colliders. Advances in antiproton production, beam cooling, targeting, beam stabilization, and understanding non-linear effects are all required for both short and long-term advances in hadron colliders. Non-linear optics, beam control, instrumentation, and feedback, are all areas in which advances are required to fuel continued advances in e^+e^- colliders.

More forward-looking R&D is also essential to the continuing health of the field. Investigations, both experimental and theoretical, into new novel collider types, such as muon or gamma-gamma colliders, and new acceleration techniques are examples. While by their nature there is no guaranteed pay-off from any of the areas being investigated on an individual basis, history teaches that it is likely that fundamental developments significantly impacting the future of HEP are likely to emerge.

This was reinforced by the 1980 HEPAP Subpanel chaired by M. Tigner which reviewed accelerator R&D and looked at the future of accelerators and colliders. The Tigner Panel recommended that about 4% of the DOE high energy physics operating budget be dedicated to long-term R&D, beyond the immediate needs of the laboratories. Although this funding level has not been fully reached, the goal led to the establishment of a separate effort within the DOE high energy physics program for

long-term R&D. This program funds research groups at the national laboratories, at universities and in industry, and provides the main support for training graduate students in accelerator physics. Some of the significant contributions resulting from this program include:

- Research at the University of Wisconsin led to a basic understanding of the flux-pinning mechanism in NbTi superconductors, which produced a 50% increase in the short-sample limit. This improvement in performance is critical for high energy hadron colliders. In addition, these improved superconductors have found wide use in high-field magnets in many fields such as Magnetic Resonance Imaging (MRI) scanners and insertion devices for synchrotron radiation.
- Nonlinear dynamics and classical physics research at the University of Maryland led to widely used applications of Lie algebra in computing nonlinear lattices. There have also been important theoretical contributions to electromagnetic field computations, impedance calculations, beam-breakup physics, beam halo formation, and design of permanent magnet optics.
- Research on alternate methods of acceleration with very high peak power lasers has generated accelerating gradients in excess of 1 GeV/m over small distances. These gradients are well beyond the capability of existing technology and could lead the way to very high energy accelerators in the future.
- The U.S. Particle Accelerator School, founded as a result of the Tigner Panel, has trained accelerator scientists who have gone on to contribute to accelerator-based projects within all five OER programs, as well as to the projects of other agencies.

Nuclear Physics

Nuclear physics research is conducted to understand, at a fundamental level, the structure and dynamics of strongly interacting matter, its properties under a wide variety of conditions in the laboratory and the cosmos, and the forces that govern its behavior.

Pursuit of this goal entails development of new technologies and advanced facilities, and education of young scientists.

The centerpiece facilities of the nation's nuclear physics program are the Continuous Electron Beam Accelerator Facility (CEBAF), which is just coming into operation, and the Relativistic Heavy Ion Collider (RHIC) which is scheduled to begin operations in 1999. Other accelerator facilities include electron, proton, and ion accelerators at a variety of DOE laboratories and those at universities supported by both DOE and NSF for use by nuclear scientists supported by both agencies. Each of these facilities has developed in close association with R&D in accelerator science and technology, particularly short-term R&D. In this section examples are given of the medium-term accelerator R&D that will enable these facilities to remain at the scientific forefront during the remainder of their productive lives as well as the long-term accelerator R&D that will lead to new technologies and new science in nuclear physics with significant spin-off into other areas of science.

Superconducting rf cavities, successfully developed over the past two decades for high-velocity electrons (primarily at Stanford (HEPL), Cornell, and Wuppertal, Germany) and for low-velocity heavy ions (primarily at Argonne National Laboratory [ANL] and State University of New York [SUNY] at Stony Brook) are pushed even further. Based on the former, the accelerator R&D at CEBAF led to the development of reliable high-gradient, high-Q cavities with higher order mode suppression that exceeded design specifications and will permit upgrading the CEBAF energy at small

cost. Long-term R&D in this area will likely lead to a further factor of two or so in gradient and will likely open this technology to other applications such as the use of superconducting rf cavities as accelerator drivers for high-power interaction regions (IR) and ultraviolet (UV) free electron lasers (FELs) and, possibly, in high energy linear colliders. On the other end, superconducting heavy-ion cavities are extended down in velocity for important applications with very heavy beams and low-charge state radioactive ion beams.

Beam dynamics studies of high-current, low-emittance beams are essential for understanding wakefields, instabilities, beam breakup, bunch lengthening and emittance growth in order to obtain the most effective beam characteristics for facility performance. In nuclear physics, such studies are needed for the development of polarized electron sources, heavy ion sources, radioactive beams and electron cooling.

The development of high-charge state electron cyclotron resonance (ECR) ion sources is revolutionizing the acceleration of heavy-ion beams both at cyclotrons and heavy-ion linacs. A program of heavy ion source development based on the EBIS technology is underway at BNL for possible use at RHIC. The R&D goals are increasing the intensity and extending the ion species.

The development of polarized gas targets at Wisconsin and of polarized ion sources and _____ polarized target at TUNL has important applications to the research programs at large accelerators and exemplifies the symbiotic relationship between small university accelerators and large national and international facilities.

The use of electron cooling of ion beams has been greatly advanced by recent R&D. In fact, the low emittance of the cooled beam has proved to be an excellent tool to observe non-linear, single-particle beam dynamics effects. The medium-energy electron cooling R&D initiated at the University of Indiana has been carried over to

Fermilab where it is being further developed in support of the design of a new antiproton accumulator ring.

The RHIC accelerator R&D program is focused on superconducting magnet technology, bunched beam stochastic cooling, and implementing polarized beam operation. Among the advances in magnet technology are techniques to measure the magnetic fields and then to correct for deviations from the design values. These will have impact in other accelerator projects worldwide. A viable bunched-beam stochastic cooling system has the potential for ameliorating the effects of intrabeam scattering in heavy ion beams and thus providing a significant performance improvement. A recent decision has been made by the RIKEN Research Institute in Japan to fund both the detector and accelerator modifications needed to implement polarized proton operation at RHIC. This has led to an R&D program to develop so-called Siberian snakes and spin rotators based on a superconducting helical dipole magnet design. In addition, there is an accelerator physics program to develop the tools and techniques needed to analyze spin dynamics.

The National Superconducting Cyclotron Laboratory (NSCL) facility at Michigan State University and the Indiana University Cyclotron Facility (IUCF) are both supported by the NSF. The recent Nuclear Science Advisory Committee (NSAC) long-range plan recommends an upgrade of the radioactive-beam capabilities at Michigan State and support for a Light Ion Spin Synchrotron based on the Indiana infrastructure. The upgrades proposed at both the NSCL and IUCF are based on technologies developed through R&D at those facilities during the past two decades, and funded as part of their on-going NSF nuclear physics research programs.

The NSAC long-range plan also recommends a design study for a next generation ISOL-type (Isotope Separation On-Line) radioactive beam facility based on the two accelerator (driver/post accelerator) concept and its construction once construction of RHIC is substantially complete. The advanced ISOL facility will bring

together the fruits of many accelerator developments of RFQ's, conventional linacs, superconducting linacs, and target/ion source systems carried out in recent years at a variety of nuclear physics facilities such as LBNL, Los Alamos National Laboratory (LANL), ANL, and Oak Ridge National Laboratory (ORNL).

Basic Energy Sciences

The Office of Basic Energy Sciences (BES) conducts research in materials and chemical sciences, geosciences and other fields directly related to the DOE energy mission. As part of its program, BES supports the design, construction, and operation of synchrotron light and neutron sources at a number of DOE laboratories. These major user facilities are used by researchers from DOE laboratories, industry, and universities.

Synchrotron Light Sources

Areas of accelerator science and technology that have led to significant improvements in synchrotron radiation source performance are the development of low-emittance lattices, the development of insertion devices, and improvements in orbit and beam control. Low-emittance lattices are accelerator magnet configurations that lead to high brightness beams without deleterious effects. Insertion devices are special magnets that can be designed to give higher energy X-rays than bending magnets, to concentrate the photon beam intensity into narrow energy bands, or to control other photon beam properties such as polarization. The accelerator beam must be stable to unprecedented levels to take advantage of the high brightness beams, and this has led to the development of new instrumentation and feedback techniques.

Developments that could lead to synchrotron light sources with improved capabilities is the subject of accelerator R&D supported by BES. One approach is higher brightness storage rings based on extensions of the storage ring designs used for

the Advanced Light Source (ALS) and the Advanced Photon Source (APS). This will require increased understanding and improvement of low-emittance lattices, insertion devices, and beam stability and will be based in large part on the experience gained with the ALS, APS, and other similar synchrotron radiation sources.

The other approach to light sources with advanced capabilities is the Free Electron Laser (FEL). FELs can be based on high brightness storage rings or linear accelerators. Linear accelerator FELs could cover energies from the infrared to X-ray. Infrared FELs have the potential of being of moderate size appropriate to a university or industrial setting; here the accelerator R&D is aimed at lowering the cost of critical elements. FELs for higher energies would be larger and would be multiple user facilities located at a national laboratory. The accelerator science and technology of these larger FELs has considerable overlap with that required for the development of linear colliders for high energy physics: high brightness electron sources must be developed and beams must be accelerated without suffering loss of brightness. In addition, there are R&D issues unique to FELs: the study of self-amplified spontaneous emission and construction of long, precisely aligned undulators.

Neutron Sources

High-current, medium-energy proton accelerators are used to produce spallation neutrons for condensed matter research. The two spallation neutron sources operating in the United States, LANSCE and IPNS, have beam power of 64 kW and 7 kW, respectively.

The development of designs and technologies for spallation neutron sources with beam power in the 1-5 MW range is being considered by BES. The R&D needed for such sources includes producing beams with high current and short pulses, controlling beam halos that can heat up and activate accelerator components, handling

high-power deposition in the targets, and developing time-of-flight instrumentation. The first two topics are accelerator-related R&D.

Fusion Energy

The mission of the DOE fusion energy program is to demonstrate the scientific and technological basis for fusion energy. There are two approaches to fusion energy, magnetic (MFE) and inertial (IFE).

Magnetic Fusion Energy

MFE uses strong magnetic fields to confine the energy of high temperature (~ 10 keV), low density ($\sim 10^{20}$ particles m^{-3}) plasmas for long times (\sim several seconds) thereby achieving a net energy production. Accelerators impact the MFE program through their extensive use in neutral beam heating systems and in the future as the source for neutrons in an International Fusion Materials Irradiation Facility (IFMIF). High-power neutral beams based on positive ions accelerated to about 100 keV were developed in the late 1970's, primarily for the Tokamak Fusion Test Reactor (TFTR), and are used extensively in the world fusion program to heat Tokamak plasmas. Development of this technology was terminated in the United States. R&D is being carried out primarily in Japan and Europe and is focused on the production of beams of negative ions accelerated to about 1 MeV.

The IFMIF will use a high-intensity (125-mA), modest-energy (35-MeV) deuteron accelerator to bombard a flowing lithium target to make a high-intensity neutron source with a spectrum and fluence simulating that from a fusion reactor. Candidate materials for an MFE reactor first wall and blanket will be exposed to the neutron flux up to fluences expected over the operating life of the fusion reactor. Currently an international design team from Europe, Japan, Russia and the United States is carrying out a conceptual design study of IFMIT. R&D is planned to be part

of the IFMIF project with key R&D efforts focusing on developments needed to produce high-current continuous-duty beams with very low beam loss and high (>90%) reliability and availability.

Inertial Fusion Energy

IFE uses a repetitive short-pulse (~ 10 -ns) intense ($\sim 10^{14}$ -watts/cm²) ion or laser beams to compress a fusion fuel pellet that would then produce more fusion energy than was needed to produce the beam. OER is supporting the development of heavy ion induction accelerators as drivers for this application.

Heavy ion fusion requires a 10-GeV high-current (~ 10 kA) ion beam resulting in about 5 MJ/pulse delivered to a fusion target. The primary development path for accelerator-based inertial fusion drivers in the United States involves advanced induction linac accelerators. Complementary development is being carried out in Europe on an approach using an rf accelerator and multiple accumulator rings.

The principle R&D issues for heavy ion fusion drivers are related to maintaining high beam quality during beam manipulation and in the presence of space-charge effects.

There is important synergism between basic plasma science and the advanced accelerator science needed for fusion energy applications of accelerators. For example, the quantitative assessment of collective effects in high-intensity accelerators has its foundation in plasma theory and in computer models developed by the fusion energy program.

Although theoretical modeling related to these issues is well advanced, experimental confirmation has been limited. Major accelerator topics that need to be experimentally confirmed at the appropriate scale are: beam merging with low

degradation of emittance, transition from electrostatic to magnetic focusing, low-cost fabrication of induction modules, and beam neutralization in the drift space between the accelerator and the fusion target.

Health and Environmental Research

DOE's Office of Health and Environmental Research (OHER) has as its overarching scientific goal the understanding and technological solution of major problems in biology, medicine, and the environmental sciences as related to energy use and development. Although many OHER programs use accelerators to some degree to address these problems, the most substantial use is in the structural biology and nuclear medicine programs.

Structural Biology

For structural biology, the use of X-ray crystallography to obtain structural information about complex biological molecules drives OHER's interest in beamlines and infrastructure at the nation's synchrotron light sources. There is also OHER interest in X-ray microscopy and spectroscopy, as well as angiography, at synchrotron sources. Neutron scattering is also of interest to structural biology, especially for determining the location of H atoms.

R&D supported by the structural biology program is not directed at accelerator issues; it is primarily directed towards detectors and other instrumentation for X-ray (synchrotron sources) and neutron (reactor and spallation sources) applications, but also includes some development of software systems for data acquisition and beam line management.

Nuclear Medicine

OHER's nuclear medicine program currently supports a modest program of accelerator-related R&D. An upgrade of the Brookhaven Linac Isotope Facility includes a modest amount of accelerator R&D. A project is also underway at the Biomedical Research Foundation at Louisiana State University to develop a prototype $^3\text{He}^{++}$ RFQ-based system for production of PET isotopes.

In nuclear medicine development of new target designs for the efficient production of radioisotopes at accelerators is a priority. In most cases, emphasis is on modeling of heat transfer properties; however, for the RFQ-based facility the major issues relate to understanding how $^3\text{He}^{++}$ targeting can effect chemistry changes at high rates.

There is also growing interest in Boron Neutron Capture Therapy (BNCT) now undergoing clinical trials at BNL and MIT. If BNCT is demonstrated to surpass the efficacy of conventional cancer therapy, accelerator-produced neutron beams may be an alternative to reactor-based treatments. This technique is likely to be based on RFQ or electrostatic tandem technology and requires ~1 mA of protons at 3-5 MeV.

Advances in proton therapy will require appropriate access to a 100-250 MeV proton beam line for dosimetry studies, bench marking 3-D simulation codes, developing national calibration standards, and developing new beam scanning techniques. Synchrotron radiation-based coronary angiography will require the development of simpler light sources, with low capital and operating costs.

Opportunities for Cross-cutting Accelerator R&D

Accelerator R&D is currently carried out in support of the mission needs of the OER at national laboratories, universities, and in industry by researchers with interests directed towards a variety of potential applications. While the specific implementations and applications of accelerator technology may vary across the ER programs, in many instances the underlying accelerator physics concepts are shared. Examples which are relevant to the needs of a number of ER programs include:

- production and acceleration of high current ion beams
- production and acceleration of high brightness electron beams
- superconducting rf structures
- non-linear dynamics and optics
- beam stability and feedback
- storage ring quality magnets
- new superconducting materials
- novel lattices and beam optics
- high efficiency rf sources and accelerating structures
- beam polarization
- beam cooling
- targeting
- beam instrumentation and diagnostics
- beam control
- particle sources
- computer codes

This high degree of common interests provides important opportunities for both positive synergy and for the coordination of accelerator R&D activities within OER.

APPENDIX G

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Professor Stanley Wojcicki, Chair
High Energy Physics Advisory Panel
Stanford Linear Accelerator Center
Mail Stop 63
P. O. Box 4349
Stanford, CA 94305

Re: HEPAP Subpanel on Accelerator Physics

Dear Professor Wojcicki,

I have received your letter of February 3, 1996 inviting a formal Basic Energy Sciences Advisory Committee (BESAC) response to your subpanel report prior to HEPAP consideration of the draft on February 27. While BESAC does not normally meet so regularly, I am pleased to report that there was a regularly scheduled meeting of the BESAC on February 5-6, 1996. We were able to add a discussion of your draft report to our agenda. After discussing the report at length, I have been instructed to transmit to you the following unanimous sentiment of BESAC.

The Basic Energy Sciences Advisory Committee (BESAC) at its February 5-6, 1996 meeting reviewed the Draft Report of the Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology. We compliment the Subpanel on documenting an excellent case for the significant contributions and wide ranging impacts that Accelerator Science and Technology have had on many areas of research, particularly those sponsored by the Office of Energy Research. The research programs sponsored by the Office of Basic Energy Sciences have benefited not only from storage rings for the production of synchrotron radiation and spallation neutron sources, but also from electron microscopes and accelerators for surface modification. In fact, the Office of Basic Energy Sciences presently supports a vigorous program of short, medium and long term research activities related to accelerator science. This program is proposal driven and peer-reviewed, as are all OBES programs. We recognize the importance of this field, as one of the many areas critical to the fulfillment of the OBES mission.

Over the years both BESAC and OBES management have struggled with the maintenance of an appropriate balance between support for facilities (planning, R&D, construction and operation) and research in the Basic Energy Sciences. The BESAC has taken an active role in advising DOE of our concerns and our analyses of this balance, but we have left to OBES management the detailed implementation of our advice.

Given this background, BESAC is deeply concerned with some aspects of an otherwise thoughtful report. One focus of our concern is Recommendation C, "The Director of OER should charge the ... advisory committees with recommending the appropriate level of ... funding for each program." Of even greater concern is the subtle elaboration of this recommendation in the "Funding" section on pages 46 and 47 of the draft report. This section gives a "suggested" OBES 1% protected accelerator related funding level for long term research. Such a recommendation made in the absence of a study of the entire program has the potential to be very counterproductive. We respectfully but strongly urge that HEPAP consider the consequences of Recommendation C before adopting the draft report of the HEPAP Subpanel on Accelerator Physics.

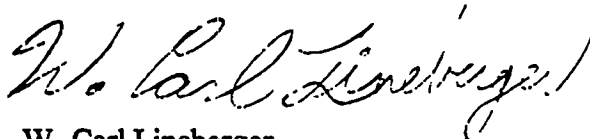
It is the very strongly held view of BESAC that it sets a dangerous precedent to identify any level of earmarked funding for a given area of research, unless that recommendation is taken in view of the totality of the program. A research program as diverse as that required by the mission of the Office of Basic Energy Sciences would rapidly become balkanized by such piecemeal earmarking. Our opposition to such a "set aside" is completely unrelated either to our view of the merit of accelerator research or to the need for such research in OBES. Thus, we would also be opposed (for example) to an earmarked level for the Office of High Energy Physics to support long range developments in materials science.

After considerable discussion, BESAC has concluded that it strongly disagrees with Recommendation C of the Subpanel Report. Because this recommendation is the primary substantive recommendation of the report, BESAC unanimously opposes the Subpanel Report in its current form.

We do appreciate this opportunity to express our opinion on the draft report. While the rather short notice of the HEPAP meeting precludes BESAC participation in that discussion, I believe it very unlikely that our position on this matter would have been modified by BESAC participation in the final discussion of the draft report.

If I can provide more detailed information concerning the BESAC position, please contact me.

With best wishes,



W. Carl Lineberger
Chair,
Basic Energy Sciences Advisory Committee

cc: Dr. Patricia M. Dehmer
BESAC Members



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May 3, 1996

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Professor Stanley Wojcicki, Chair
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In regard to: DRAFT Report of the Composite Subpanel for the Assessment of the
Status of Accelerator Physics and Technology

Dear Professor Wojcicki:

As we discussed last month, the HERAC meeting on April 11, 1996 included time for formal consideration of the draft subpanel report provided to us in February. The draft report was distributed ahead of the meeting to all members of HERAC. As an introduction to the discussion, I highlighted aspects of the report and indicated the wording changes that had been approved by the full subpanel (this was done during the meeting as I obtained notice of the formal approval from Jay Marx, subpanel chair, on April 9, 1996). The report was discussed at length and the outline of this HERAC response was unanimously adopted during the meeting. I am transmitting to you the following statement which has been written subsequent to the meeting and has been circulated to all HERAC members, their input incorporated, and consensus achieved.

HERAC recognizes the seminal role that DOE ER (and its predecessor agencies) has played in the worldwide development of accelerator science and technology and believes that the composite subpanel has done an outstanding job of documenting and describing the achievements, scientific and societal benefits of these endeavors. As is discussed in the report, OHER does not support the R&D on, or central operations of, accelerators in any significant way and in contrast to other offices such is not a part of its mission. OHER-funded programs do, however, make extensive use of synchrotron sources for structural molecular biology (SMB) research, and a variety of accelerators for medical applications. In the synchrotron arena, OHER depends upon the excellent BES-funded programs which provide for operations of and R&D on the synchrotron storage rings. OHER funds peer-reviewed, nationally competitive programs to enable use of these storage rings for SMB research.

HERAC has a sustained interest in R&D as it relates to the core programs of OHER and periodically reviews all areas involving its instrumentation programs. Our most recent subpanel report (HERAC subpanel on Instrumentation Programs in the Medical Applications and Biophysical Research Division, November, 1995) considered among other areas the future needs for accelerator based technologies in structural molecular biology and in medical applications. Relevant to the discussion of the accelerator subpanel report was the recommendation that highest priorities should be given to full time, reliable running of existing and planned synchrotrons and providing adequate staff to support SMB users. The need for advanced R&D on instrumentation and for specialized infrastructure to facilitate use for SMB research was also identified as a high priority. The previous subcommittee report on Structural Biology (October, 1992) made substantially the same recommendations with specific proposals for implementation. Neither report identified serious shortcomings in the accelerators themselves requiring long term R&D in accelerator physics.

Page 2

Professor Stanley Wojcicki, Chair, HEPAP

May 3, 1996

It is within this context of OHER's mission and programs that the HERAC discussion was set.

In the synchrotron area, HERAC believes that virtually all of the OHER-funded activities for SMB are serving "customers" for which the existing and soon to be operational BES facilities are extremely well matched to the current and projected needs. It was felt that the level of R&D investment by BES through its excellent stewardship of the synchrotron radiation facilities was more than adequate and at an appropriate ongoing level to meet anticipated needs of OHER programs even over the longer term. This investment has, and will very likely continue to meet the vast majority of the needs for SMB research well into the next decade.

HERAC felt strongly that the most productive utilization of diminishing OHER funds in the coming years is for targeted R&D in specialized infrastructure and instrumentation to enable OHER's most effective use of these facilities. This will certainly yield the most productive science programs and was felt to be the most effective way to leverage the substantial investment by the DOE that has been made in its National user facilities.

The Committee felt that it was appropriate for HEP to continue to be the driver for blue sky R&D on accelerators; that is, it holds the trust within DOE for this endeavor (with is appropriately focused on HEP related needs). HERAC would welcome the opportunity in the future to consider specific developments identified by HEPAP/HEP or other means that may have relevance to enabling significant new science in a specific area like SMB so that it (HERAC) can make recommendations for R&D funding which are considered within the totality of the BER portfolio.

HERAC is **strongly opposed** to any kind of "set aside" or earmarked funding that allocates some fraction of the base to a specific endeavor. Such actions will rapidly lead to fragmentation of the OHER program and ultimately reduce flexibility and ability to meet the program's strategic goals. It was strongly felt that it was not within the scope or mission of OHER to participate in such a program (recommendation B. of the report as implemented by recommendation C.). Hence, HERAC **does not** support these two recommendations.

We apologize for the delay in providing definitive input on our position but the subcommittee timetable for submission of the report to HEPAP would have required a response without any opportunity for discussion of the issues by the full HERAC. If we can provide further details concerning HERAC's position, please feel free to contact me and I will respond as quickly as possible.

Sincerely yours,



Keith O. Hodgson, Chair
Health and Environmental Sciences Advisory Committee

cc: Dr. A. Patrinos
HERAC Members

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May 6, 1996

Professor Stanley Wojcicki,
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Stanford, CA 94305.

Dear Professor Wojcicki,

Research into and development of new accelerator techniques has always played a fundamental role in nuclear physics, from the first Cockcroft-Walton and Van de Graaff structures to superconducting cyclotrons and linear accelerators. There is no question that this research will always be vital to the future progress of nuclear physics as a discipline.

For this reason, NSAC was very pleased that the Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology was formed recently (under the aegis of HEPAP) to document the important contributions of this field and to assess means to assure its vitality in the future. We feel the Subpanel's formation provides, in itself, essential and overdue recognition of the key contributions of this area of research to many areas of science, technology, and human welfare.

NSAC has considered the Subpanel's recommendations and is in agreement with them. Specifically, in the case of Recommendation B, *"Each OER program should have proposal-driven, peer-reviewed long-range accelerator R&D as part of its research portfolio,"* and the supplementary language amplifying it, NSAC views accelerator R&D as a proper subject for basic research within nuclear science, and one that should be judged by peer review and in the context of the long-range goals of the discipline. We anticipate that the level of activity in this field will fluctuate as new ideas are identified. NSAC will, of course, respond to a charge by the

Director of OER as described in Recommendation C, taking account of the constraints imposed by the quality of proposed programs and the long-range plans for nuclear science.

We would like to convey our thanks to the Subpanel for their hard work and for the highly constructive report that resulted.

Yours Sincerely,

A handwritten signature in dark ink, appearing to read "R.G. Hamish Robertson", with a long, sweeping horizontal stroke at the end.

R.G. Hamish Robertson,
Chair, Nuclear Science Advisory Committee.

RGHR

Cc: Dr. David L. Hendrie,
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