Enhancing Accelerator Science and its Impact on Other Sciences: the Role of Universities

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Abstract

The science of particle beams is rich and challenging. Particle beams are many body systems with non-isotropic, non-thermal distribution, exhibiting many collective instabilities and self-organizing phenomena when interacting with electromagnetic fields and plasmas. Studies of these transitions from one non-equilibrium state to another, has progressed rapidly in recent years, but much remains to be done. The impact of particle beam, or accelerator science is extremely broad. Indeed, advances in many branches of science such as the materials sciences, nuclear science, elementary particle science, to name but a few, are paced by advances in accelerator science and technology. Much of the work in these areas has come to reside in the DoE National Laboratories. There is growing realization that universities have a unique and important role to play and that enhancing the university role will result in significant advances in accelerator science and development and in their broad impact on other sciences. The needs and opportunities are discussed herein.

Introduction

Beam Science

The study of particle beams interacting with electromagnetic fields and plasmas is an exciting part of physics. Beam optics, the transport of particles using electromagnetic lenses and bending fields is well developed, and is continuing to evolve to include more complex non–linear dynamical effects, like the long term stability of particle orbits over billions of revolutions

The study of high intensity effects, such as collective instabilities and self organization phenomena, has already achieved important results. As we move toward the study and utilization of beams with higher phase space density, and smaller dimensions of the particle bunches for the next generations of colliders, synchrotron radiation sources, and free-electron lasers, new phenomena continue to appear that will need further studies.

The interaction of laser and plasmas provide a rich new range of possibilities and exciting physics. The interaction of lasers and plasmas with particle beams provides an entirely new paradigm for accelerating and focusing dense relativistic beams at unprecedented high gradients using collective fields. Learning to control these phenomena could lead to table-top, GeV class, accelerators in the near term, and to a much more compact high energy machine at the energy frontier in the future.

Progress in these fields may also make it possible, in the not too distant future, to simulate certain aspects of particle and plasma astrophysics phenomena in the laboratory by studying the behavior of co- and counter-propagating electron and positron beams with or without external magnetic fields. Examples of these are gamma ray bursts, pulsar winds and acceleration mechanisms for cosmic rays. In summary, it is clear that beam physics is a rich area of science, in which we expect exciting breakthroughs for the foreseeable future.

The Broader Impact

Accelerators now find essential uses with amazing breadth of purpose from materials analysis to alteration of materials on an industrial scale, from medical diagnosis to medical treatment, from age determination of ancient artifacts to microanalysis of meteorites and, of course, to the many uses where structure determination is central to many areas of science from the molecules of life to the elementary particles that underlie the material world [1,2,3]. (See Appendix 1 for an approximate enumeration of the number of the various types of accelerators now in use.)

Historically, the application of accelerator science has led to rapid progress in the creation of accelerators as illustrated by the famous Livingston Chart [4]. As the accelerator dependent sciences advance the needed accelerators become more sophisticated and scientifically and technologically challenging. This leads to the need for increasing intellectual input into accelerator science and technology. In many cases, the frontiers of the scientific and technological activities based on accelerator usage are set by the current capabilities of the accelerators being used. The most obvious and well-known cases are the various branches of nuclear and particle physics and those myriad sciences using synchrotron radiation as a basic tool. Because of the breadth of applications and the critical societal impact of advances in accelerators, it is important that a systematic approach be used in accelerator development. This approach must range from the proof of principle and basic accelerator physics studies known as Advanced Accelerator Research and Development to technological developments directly relevant to accelerators and to concepts for new facilities that will serve accelerator based sciences and technologies.

In this White Paper we give specific examples of important scientific frontiers that will be advanced by new accelerator developments, and some specific accelerator physics and technical areas from which these frontier advances will derive. A listing of some of the scientific and technical advances needed to push forward accelerator science and technology will be found in Appendix III.

In working to improve our programs for accelerator development, it will be essential to cultivate appropriate intellectual [5] and infrastructure resources. While it is true that we will always need accelerator physicists and other professionals to design, build and operate these instruments, it will also be important to educate the scientists and technologists who use the accelerators and its auxiliary equipment to better understand their capabilities and limitations. In this way they will be able to understand where accelerators can be better used and improved, and where the always necessary compromises can be made. As much of the strength of the US scientific community lies in our universities, it follows that any scheme for improving the way in which we develop accelerator science and technology needs to involve universities in a fundamental way. Aside from enhancing the numbers of minds focusing on the challenges, there are two other very important aspects of university involvements. Many of the scientific uses of accelerators cross the boundaries of many sciences and technologies, making interdisciplinary efforts mandatory, both in the apprehension of the needs and in the capabilities needed for implementation. Universities have these breadths "in house" if we can learn how to engage with them. Last but far from least, universities offer a natural setting for the training of the next generations of accelerator and beam line scientists while at the same time entraining scientific users in the process of advancing the accelerators that they need for their science. The present shortage of expert manpower is made painfully evident by the many "help wanted" advertisements carried in any journal dealing with the accelerator-based sciences. Below we attempt to suggest some ways for enhancing university involvement in accelerator development.

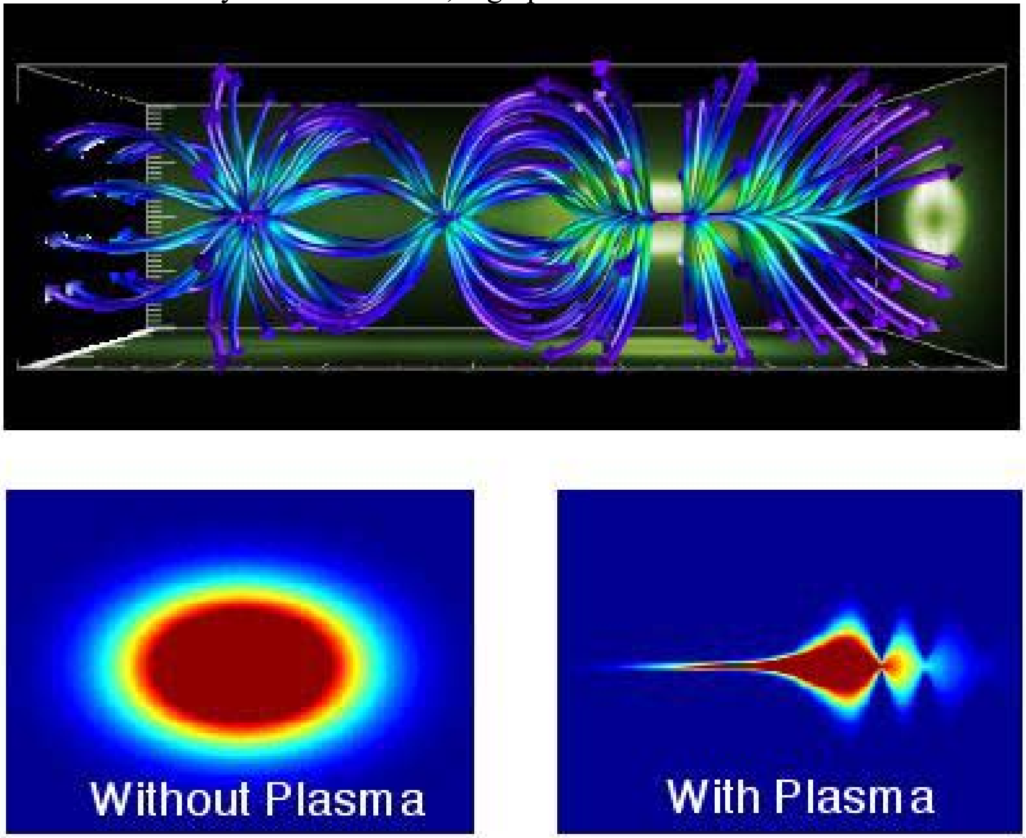
Needed Advances in Accelerator Science, Technology and Related Apparatus

Particle Beam Science

The science of particle beams is rich and challenging. The field of particle beam optics, the study of the transport of particles using electromagnetic lenses and bending fields is well developed. It is now possible to include many effects of non-linear fields, to control and minimize aberrations, and to include some self –field effects like space-charge or wakefields. More work will however be needed in the future when pushing the frontier to beams with extremely high phase-space density or to the case of very high intensity beams where even small losses can be very important.

In the case of storage rings there has been a large effort to study the stability over billions of revolutions, and understand the effects of resonances on the long-term stability of the beam. Advanced instrumentation to measure the response of the beam to external excitations has been developed, and the analysis tools to relate these results to the short and long-term stability have been the subject of intense studies. This area of research has offered and will continue to offer very interesting interdisciplinary opportunities for joint work with other physicists and mathematicians studying dynamical systems, and with astronomers studying the stability of the solar system and its constituents.

Particle beams are many body systems with a non-isotropic, non-thermal distribution, exhibiting many collective instabilities and self-organizing phenomena when interacting with electromagnetic fields and plasmas. Studies of these transitions from one non-equilibrium state to another, have progressed rapidly in recent years, but much remains to be done. Particularly important is the question of the limits produced by collective instabilities on the 6-dimensional phase-space density achievable in a beam in a given configuration, and, alternatively, what are the more favorable configurations to reach a very high phase-space density. These limits are now partially understood in storage rings and linear accelerators, but questions remain when one pushes the limits toward beams with very small emittance, high peak current and short duration bunches.



Top: Computer generated representation of forces induced by a high-energy electron beam as it propagates through a plasma. Bottom (left) The beam contours without the plasma and (right) when propagated through the plasma. The plasma in turn can tightly focus the electron beam by partially or fully neutralizing the space charge of the beam (Courtesy C. Joshi, UCLA)

Also important is the question of understanding self-organization phenomena -due to the interaction of the beam with the long range electromagnetic forces it produces- and of using them to achieve desirable beam configurations not reachable with external control systems. One example is the free-electron laser instability. In this case the initial state is a beam produced by an accelerator in a non-equilibrium state. If the beam phase space density satisfies the conditions for the free-electron laser instability to take place while the electron beam traverses an undulator magnet, a transition occurs. The beam final state has a high degree of order, similar to that of a 1-dimensional crystal, with the electrons contained in slices equally separated by a distance equal to the radiation wavelength. New developments, like the X-ray free-electron lasers now under development in the US and Europe, and to which universities have made essential contributions, are only possible because we can control the instabilities in the linac producing the electron beam, and thus preserve a large beam phase space density, and then create the conditions for the free-electron laser instability to develop.

The interaction of lasers and plasmas with particle beams provides an entirely new opportunity for accelerating and focusing dense relativistic beams at unprecedented high gradients using collective fields. For instance, the possibility exists of synchronous acceleration of particles using wakes, produced in a plasma by a short intense laser pulse or by the beam itself, that have gradients in excess of 100 GeV/m and focusing beams using effective gradients on the order 10^6 T/m. Learning to control these phenomena could lead to table-top, GeV class, accelerators in the near term and to a much more compact high energy machine at the energy frontier in the future.

Aside from acceleration and focusing, these fields can be made to undulate beams resulting in efficient generation of radiation. The beams can also be modulated on a sub-femtosecond scale using lasers and plasmas. These bunchlets can be subsequently made to emit radiation in attosecond range. The measurements of such short bunches, phase-locking them to micro-scale accelerating structures and focusing of beams to nanometer spot-sizes are formidable challenges at the forefront of beam physics.

The understanding of the complex interaction of particle beams, lasers and plasmas, and the control of non-linear and multi-particle effects and collective instabilities in beam transport, such as the electron cloud instability, requires extensive use of large-scale massively parallel computing. These requirements will become even more important in the future as we push the frontier toward beams of ever increasing phase-space density, or more complex interactions of beams and plasmas. The continued development of theoretical tools and large-scale simulations will play an increasingly important role in the development of beam physics in universities and accelerator centers.

Particle Beam Physics and Accelerator Development

Particle accelerators have had a broad impact on many areas of science and technology. Further advances in beam science will lead to significantly improved capabilities that will open new opportunities for advancements in physical and life sciences and in medical therapies.

Looking beyond the R&D for the electron-positron and hadron colliders that are either being built or contemplated at the energy frontier (discussed in the next section), the accelerator community is already pursuing other novel machines such as the neutrino factory and even a muon collider. No accelerator has ever been built using an unstable particle such as the muon. There are a number of beam physics issues that are unique to this concept such as "ionization cooling" of the muon beam where energy loss by ionization in matter is alternated with the re-acceleration of muons in radio-frequency cavities. In fact, testing of novel ideas for beam cooling is a forefront beam physics issue irrespective of the type of future machine that is contemplated.

Other beam physics issues that are of pressing concern are a deeper understanding of: the beam-beam interaction that ultimately sets the luminosity limit in e_+-e_- colliders; the propagation of higher current beams (an order of magnitude) through cavities without instabilities; the intra-beam scattering, and other beam dynamics issues in damping rings; the collective effects in proton machines such as the Transverse Mode-Coupling Instability, Resistive Wall instabilities and space-charge tune shifts.

Other current topics in beam physics are beam dynamics in energy recovery linacs, improved operation of polarized electron and positron sources, efficient production of intense beams of protons, other light ions and extremely highly stripped heavy ions using ultra-intense lasers.

Recent progress in the development of efficient infrared lasers and optics has fueled the possibility of building a proof of concept device for a future $\gamma\gamma$ collider by colliding laser photons with relativistic electrons. More radical ideas that utilize an ion column to wiggle the electron beam to copiously produce γ-rays, albeit with a broader energy spread, have been proposed.

The beam physics developments described above are both exciting and essential to extend the capabilities of accelerators, but looking further ahead new technologies must be invented to make a significant impact, at the energy frontier on the one hand and making "desktop" accelerators available for myriad applications on the other. This presents opportunities to do forefront beam physics. We quote from the 2001 Snowmass Accelerator R&D Report from the section on Fundamental Research in Accelerator Physics and Technology:

"To make significant future impact, new ideas are needed not only to accelerate but also to generate, focus, and manipulate charged particles. Fortunately, there are many possibilities to do just that. Over the last fifteen years a small but vigorous advanced accelerator community has been engaged in finding alternatives to radio frequency acceleration methods. These researchers have proposed and demonstrated new ways of accelerating, bunching, and phasing particles. Some have demonstrated the use of laser radiation instead of microwaves to power plasma structures that can sustain accelerating gradients orders of magnitude greater than those in a RF linear accelerator. Other researchers have shown that electron and positron beams from a conventional accelerator can power plasma structures with promising results for developing new types of lenses for future machines and magnet-less wigglers for next generation light sources. Many small groups are actively pursuing this exciting new work in universities and national laboratories.

The Advanced Accelerator R&D effort is poised to leap to the next stage. The initial rounds of experiments demonstrating a factor of 10-100 more accelerating gradient have been done. A new generation of tightly bunched, high quality beam sources is under active investigation. However, it is clear that this field needs scientists and resources if it is to fulfill its promise. It is time to embark on large-scale collaborations, which can leverage the intellectual contributions of the university groups and the infrastructure of the laboratories.

These larger collaborations can address issues that require a significant investment both in the experimental design and execution. Large laboratories possess the infrastructure to provide high quality, stable beams that are critical for the next round of experiments. This is an outstanding research opportunity, especially for physicists that expect to perform experiments at accelerator facilities in the future.

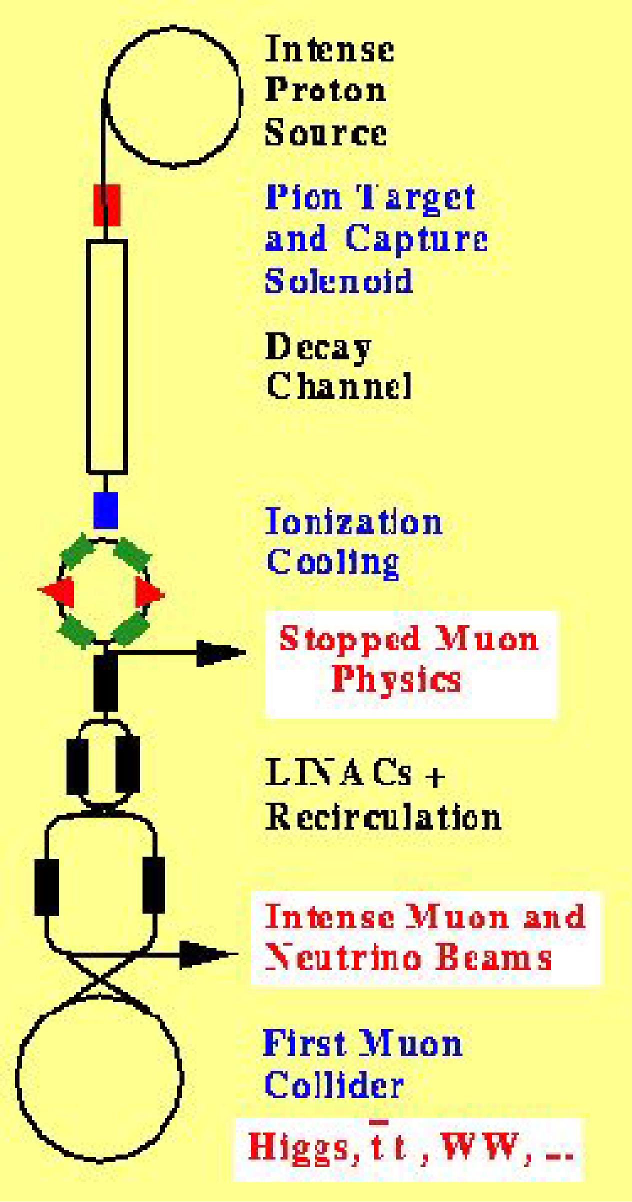
As we push the limits of acceleration to achieve high energy and the limits of beam quality to achieve high luminosity, we must carefully study fundamental limits and processes that are uncovered. The transition from metallic structures to plasma acceleration introduces many new problems and will necessarily involve a deeper understanding of the instabilities that might appear. Higher quality beams might begin to approach fundamental limits that have to be explored. Intense beams interacting with each other push beyond our experience with strong field electrodynamics. However, the key to this progress is to build a substantial experimental foundation, which could form the basis for a new generation of particle accelerators."

The authors of this White Paper concur with this assessment of the opportunities in advanced R&D in Particle Beam Science and accelerators, and what is needed to accomplish them.

Elementary Particle Science

The understanding of the basic features of energy, matter, space and time remain the focus of elementary particle physics. Elucidation of many of the particular questions under these headings will best be done using accelerator experiments under tightly controlled laboratory conditions: what is the origin of mass; what is the mechanism of electro-weak symmetry breaking; is supersymmetry a feature of our universe; what are the dark matter and dark energy that seem to dominate the universe; can the universe be described by four dimensions; is time one of the fundamental dimensions; is there but one fundamental interaction and if so at what energy is it completely unified. Answering some of these questions will require accelerators with energies beyond our current capabilities. Securing the needed capabilities will require intellectual effort at a level significantly beyond current engagements.

Over the history of accelerator based science remarkable increases in accelerator capabilities and cost effectiveness have routinely taken place. In the last 40 years the frontier has moved from a center of mass energy (proton collisions) of about 30 GeV to 14,000 GeV and a cost per center of mass GeV of $8.3M/GeV to $0.3M/GeV. Even so the cost per facility has reached the level of several billion dollars, taxing the economic capacity of the world scientific enterprise severely. Not only is the cost a challenge but the technical requirements become extremely challenging as energies rise. This stems from the fact that the elementary cross-sections that must be measured are inversely proportional to the square of the energy. The practical effect of this is that beam power required for sufficient event rates are very high, demanding unprecedented beam brightness and efficiencies of acceleration to be practical. Input power to accelerators now being planned are of the order of 100 MW. To make practical a further step in accelerator energies beyond that contemplated today will require another order of magnitude unit cost reduction and increase in luminosity. Indeed, even to successfully complete and exploit the proton and electron-positron colliders being discussed today will require accelerator scientific and technical accomplishments and cost reduction measures still under development and needing much further attention. It may well be that the needed advances in the future can only be achieved with radical departures from current approaches. For example, to control radiation effects, it may be necessary in future to utilize muons as the colliding particles, which will present enormous challenges. This same science and technology, if realized, can also provide pure neutrino beams of unprecedented intensity [6]. In the future it may also become feasible to provide large scale electromagnetic acceleration and confinement based on plasma media with internal fields orders of magnitude larger than practical today [7].



Schematic of a muon collider scheme (courtesy Muon Collider Collaboration)

Both hadron and electron machines continue to play important roles in pushing the frontiers of elementary particle science and advances in both areas and more need to be pursued. Some of the scientific and technical advances that will be needed if these difficult goals are to be achieved are brighter and higher current particle sources, higher gradients and improved higher mode damping in normal and superconducting cavities, increased efficiency in transfer of AC power to beam power, faster and higher field beam manipulation devices including normal and superconducting magnets, more inclusive cradle to grave simulations for complete accelerator systems including non-linearities and collective effects, improved manufacturing methods and materials, practical optical wavelength acceleration and manipulation schemes, improved beam cooling methods, beam instrumentation with nanometer and femtosecond spatial and time resolution and improved methods of muon acceleration.

Nuclear Science

In nuclear science both hadron and lepton probes have proven important and complementary in putting together a coherent body of knowledge and will continue to do so, necessitating technical and scientific developments in both of these directions.

Electron Accelerators

Electrons provide precise information about the electromagnetic structure of the nucleus. Increasingly higher energy electrons have been required to probe ever-finer structures of the nucleus. Basic research in Accelerator Physics initially met the increasing Nuclear Science energy requirement by using room temperature copper structures developed in support of High Energy Physics programs. Significant information gains from the Nuclear Science program can be achieved through particle coincidence experiments most efficiently accomplished with cw (continuous wave) beams. This requirement was met by taking benefit of research programs in Superconducting Radio Frequency (SRF) structures. Fundamental understanding of collective beam phenomena has allowed cost-saving strategies such as recirculating-linacs with their lower beam breakup thresholds to be realized through the provision of appropriate damping mechanisms.

Fundamental insights into the nuclear environment have been achieved through the use of polarized electrons from photo-cathode guns most recently achieving after years of basic research very high (>90%) polarization. Today, the premier electron facility for doing nuclear physics with electrons is a recirculating superconducting 6 GeV linear accelerator [ref to an article describing the CEBAF facility] operating in continuous wave mode and having excellent energy resolution and stability. Pressing to double the available beam energy is an important priority for advancing understanding of the strong force and its manifestation in gluonic matter.

Electron-based Nuclear Science has and will continue to benefit from basic Accelerator Physics research which has led to cost-effective tools with cutting-edge performance to advance this field.

Hadron Accelerators

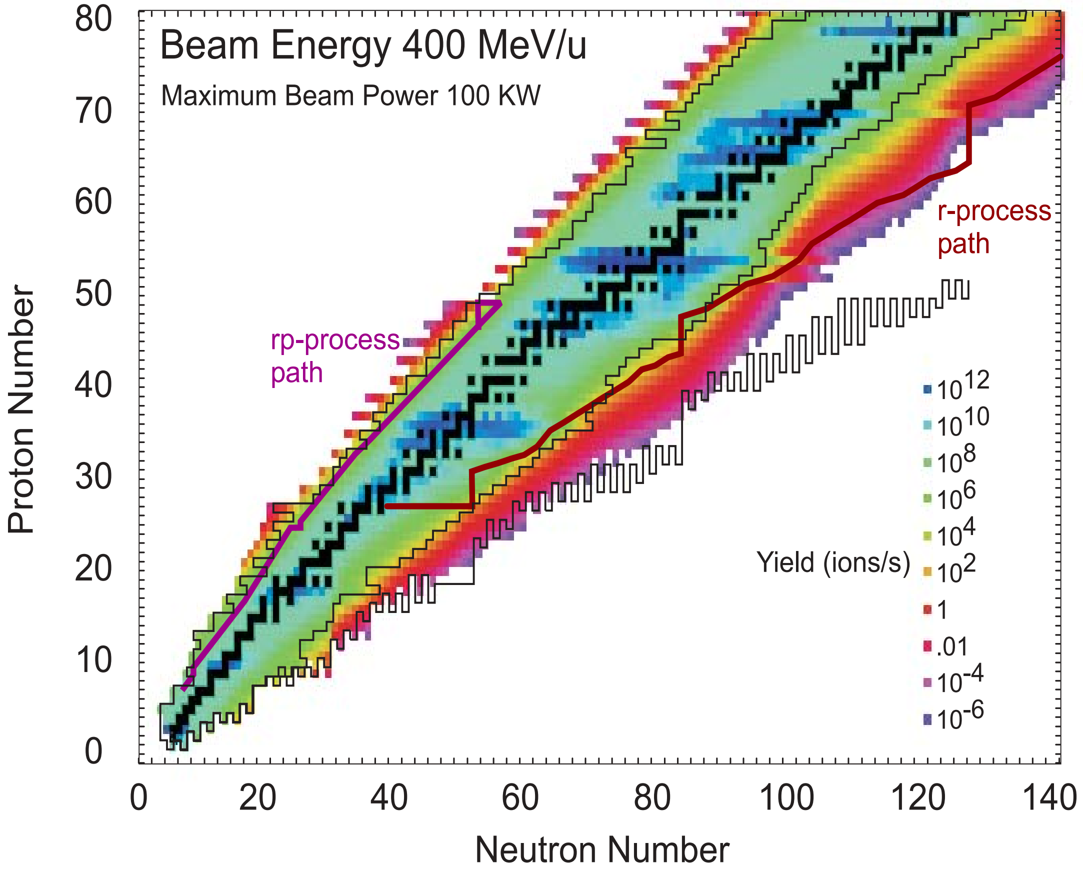
The proton through heavy-ion based Nuclear Science programs owe their research productivity to steady progress in Accelerator Physics disciplines. The forefront accelerator today for Nuclear Science investigations of matter as it existed fractions of a second after the birth of the universe is the Relativistic Heavy Ion Collider. The Accelerator Physics technology base including superconducting magnets, fast cycling cascaded synchrotrons, and colliding beam storage rings developed in support of High

Energy Physics programs allowed the effective realization of the required facility parameters. Future upgrade plans for the RHIC facility call for colliding electron-ion interaction regions effectively requiring both superconducting electron and hadron technologies. Another upgrade plan requires the use of an electron energy recovery linac for electron cooling of the heavy ion beam.

Accelerator physics has brought the invention of the Radio Frequency Quadrupole (RFQ) providing efficient early acceleration for ions of all types and permitting cost-effective and in some cases otherwise unachievable performance parameters. Decades of basic research on Electron Cyclotron Resonance (ECR) ion sources have provided the Nuclear Science program with beams of virtually all stable isotopes at ever increasing intensities. Proton and heavy-ion based accelerators have increasingly taken advantage of SRF technology to provide high performance at modest cost.

The most recent example of Accelerator Physics research and design in support of Nuclear Science is the Rare Isotope Accelerator (RIA). Among other fundamental questions, RIA will provide basic insight into the origin of the elements. RIA received the highest priority for a major new facility in the recent Nuclear Science Advisory Committee Long Range Plan. RIA will accelerate any of the stable isotopes to ~400 MeV/nucleon, and using these stable beams produce beams of radioactive isotopes by any of several methods. Electron Cyclotron Resonance (ECR) ion sources feeding an RFQ will be used as input to a stable beam linac with the ECR performance providing one of the facilities intensity limitations. The SRF-based linac will use superconducting structures suitable for particle velocities ranging from a few percent to about 70% the speed of light. A primary technical challenge will be the achievement of high gradient superconducting structures at high Q. The higher beta (v/c) structures are primarily foreshortened speed-of-light structures and take benefit of the significant advances made from basic research on the superconducting beta =1 designs. The lower beta (<0.5) structures will utilize quite different geometries (l/4 or l/2) where the research maturity is less evident. Understanding the basic physics issues and developing approaches likely following those of the high beta community has the potential of providing breakthrough performance gains. In addition, RIA will require magnetic elements in radiation environments that exceed the dose resistance of normal organic-based insulating systems in an impractically short time. These magnets would benefit from the utilization of superconducting technology. As a consequence the development of radiation resistant superconducting magnet technology would provide a significant cost and performance advantage. (Similar problems have arisen in the muon collider design.) One of the radioactive beam production mechanisms used at RIA utilizes a magnetic chicane to filter the desired radioactive isotopes from the background of other isotopes. Because of the large radioactive beam phase space, the requirements of large bore and relatively high magnetic field designs are most efficiently met by superconducting magnet technology. Advances in superconducting magnets will clearly benefit the performance and reduce the cost of these systems.

The Scientific Reach of RIA



Through understanding the r process, RIA will allow understanding of the origin of the heavy elements and through data on neutron rich weakly bound nuclei promote further understanding of nuclear many body science (courtesy R. York, Michigan State U.)

Key Research Areas

Superconducting radiofrequency structures are needed to provide cw operation. As heavy particles need to be accelerated from low energy to high, structures appropriate to the various velocities are needed. To date, elliptical structures have been used for v/c ~ 0.5 to 1 and are based on decades of R&D which has brought performance to a high level although further improvements can be expected. Non-elliptical structures have received less attention. Using the knowledge base provided by the elliptical structure work, one may expect large advances in the capabilities of non-elliptical structures for low velocity acceleration.

Beam intensity increases can move the Nuclear Science program frontier into uncharted and fruitful arenas by enabling previously unachievable experiments. As a consequence, fundamental research in the areas of intense electron and high intensity heavy ion sources will support advances in Nuclear Science.

Concomitant to increasing beam intensities are increased radiation fields. To achieve appropriate performance often demands the reliable operation of high field magnetic elements a high radiation environment. Basic research into the radiation resistance of materials and magnetic element designs appropriate for their application will support advances in Nuclear Science.

Particle Accelerators for Cancer Therapy

Introduction

In the United States, some 550,000 deaths were caused by cancer in the year 2001, (exceeded only by heart disease as a cause of death). Worldwide, more than 7,500 electron linear accelerators are installed in Radiation Therapy departments and used heavily in the treatment of most forms of life threatening cancer. Most frequently radiation treatments are given in combination with chemotherapy or surgery, the other two major cancer therapy modalities. (The overall effect is that more than 50% of patients with life threatening internal cancers, receive radiation therapy as a part of their treatment protocol.)

Manufacture of radiation therapy linacs is at this time a relatively mature technology but with a large economic impact (roughly estimating: 7,500 linacs @ $2,000,000 with a 10 year useful life implies $1.5 billion/year and approximately half of these devices are manufactured in the USA). In addition to electron linac therapy systems, three other radiation therapy systems are at present in trial use in the world, with the goal of further improving patient survival and/or reducing overall costs. These three systems (referred to as neutron therapy, proton therapy, and heavy-ion therapy) are at the present time heavily developmental in nature and provide many challenging opportunities for major societal benefit from cutting edge accelerator physics research.

Biological Basis for Radiation Therapy

Ionizing radiations injure or kill cells, depending on the ionization density received by a particular cell. (The ionization density is usually expressed as the Linear Energy Transfer or LET of the particular ionizing radiation.) Death of a cell due to low LET radiations depends heavily on the amount of Oxygen in the cell (the “Oxygen effect”), whereas the cell killing capability of high LET radiations is virtually independent of the Oxygen level. The rapid growth of advanced tumors is thought to result in a blood (i.e. Oxygen) deficiency in the tumor since the network of arteries and veins remains the same or is actually constricted by the tumor growth and so the tumor becomes Oxygen deficient, allowing the tumor to “hide” from the radiation injury by a factor of two, relative to the level of radiation required to kill a normal cell. High LET radiations such as heavy-ions or neutrons (recoil nuclei) are then said to have a “biological advantage”.

Charged particle beams such as protons and heavy ions are in contrast said to have a “Physical Advantage” in that they can be aimed to hit the tumor with 5 to 10 mm accuracy. Heavy ions have both the biological advantage and the physical advantage and then would be the clear radiation of choice except for a major cost disadvantage. Thus accelerator physics research at various centers at present focuses on improving one or another of the treatment modalities depending on the experience and facility capabilities at the particular center. With each treatment modality in a reasonably optimum configuration, the nation would have a sound basis for choosing the modality best matched to overall national goals (this decision obviously needing to consider both medical effectiveness and cost containment).

Neutron Therapy Research Issues

Goal – design a facility where physical characteristics match those achieved by electron linacs so that therapeutic comparison between neutrons and electron/photons can be made on even handed basis. (Incentives -- Results for advanced Prostate cancer are better than any other technique, facility costs are comparable to linacs, and advanced prostate is second highest cause of cancer death in males.)

1) Increase cyclotron energy to match attenuation length of modern linacs.
2) Incorporate dynamic collimation.
3) Reduce operator radiation exposure (time in vault and radioactivity in patient alignment area).

Proton Therapy Research Issues

World Status – Operating cyclotron facilities have extraction efficiencies of less than 30% caused by extreme non-linearity of edge field in the region of a tiny (9 mm) magnet gap at edge. Synchrotron facilities are complicated and costly. A German company expects to complete prototype superconducting cyclotron facility in April 2005 – calculations of extraction efficiency involve frontier numerical techniques for shaping main magnet B field, and extraction element fields.

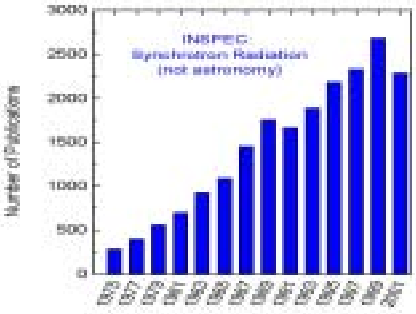
Heavy Ion Facilities

World status – expensive (400 MeV/nucleon needed to achieve 35 cm range)/much higher rigidity than present largest cyclotrons -- synchrotron seems design of choice. The first hospital-based facility (Chiba, Japan) cost 350 million ($US). Second facility designed by GSI has funding approval for installation at major medical center in Heidelberg (costs are said to be much lower than Chiba but accounting differs from US conventions). Beam rigidity makes gantries very costly – superconducting gantry magnets clearly need to be developed.

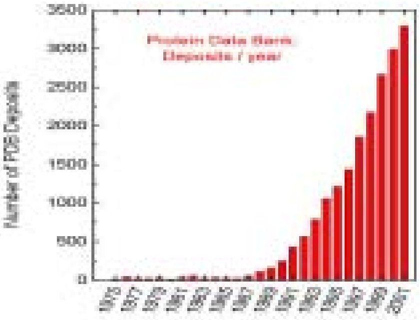
The Materials Sciences Including Biology

Synchrotron Radiation

Accelerators are having an enormous impact on materials and biological science, largely due to their use as radiation sources. World-wide growth in storage-ring based synchrotron radiation (SR) sources has been phenomenal, from just a few machines in the late 1960’s to roughly 70 machines now either built or in advanced stages of development. The capital invested in this activity is in the $10B – 20B range, with yearly operating expenses exceeding $1B and supporting a continuing user base of well over 10,000 scientists and engineers. Synchrotron sources are used throughout the materials and biological sciences for materials and molecular structure determination, elemental analysis, imaging and microtomography, determination of electronic structure, etc. – the list is long and continually growing. An indication of both the rate of growth and present trends in synchrotron radiation usage is given in the figure below. Note that the growth of utilization continues to increase. As opposed to high energy physics experiments, where accelerators serve a small number of very large, long-lived experiments, SR facilities serve a very large number of small, short-lived experiments.



Physics-based publications using SR
(2001 data is incomplete)



Protein structures in Protein Data
Bank (Mostly from SR; 2001 data
is incomplete)

All of this activity is, of course, based on accelerators. Further, the demands of synchrotron radiation have provided an impetus for ever more sophisticated storage rings, actively soaking up available accelerator-skilled research personnel. As the community becomes more and more aware of the possibilities of SR, it increasingly demands enhanced SR source capabilities, specifically, increased photon beam brightness and flux, smaller focused beam sizes, and faster photon pulses. It is now recognized that the limits of storage ring based sources are within sight. In the last decade this has led to a flowering of new ideas for SR sources based on free electron lasers (FELs) and energy recovery linac (ERL) machines.

Fruition of these new developments requires advances in linac, low emittance electron injector, insertion device, and superconducting accelerator technology. It is now generally acknowledged that the rate-limiting step in development of these technologies will be a world-wide shortage of accelerator scientists and engineers.

VUV/Soft X-ray and hard X-ray SR Sources

Broadly speaking, SR sources tend to fall into two categories, depending on the energy of the SR: VUV/soft x-ray machines and hard X-ray sources. At present, storage rings are the predominant sources for both categories. Because low energy radiations may be generated with lower energy particles, VUV/soft X-ray sources are generally smaller than their hard x-ray counterparts. Other distinctions of the radiations (e.g., soft radiation does not readily penetrate windows, necessitating UHV beamlines and experiments) and the applications (e.g., soft radiations are more suitable for many spectroscopic experiments whereas hard X-rays are more suitable for diffraction analysis of molecular structure) distinguish the beamlines of the two categories.

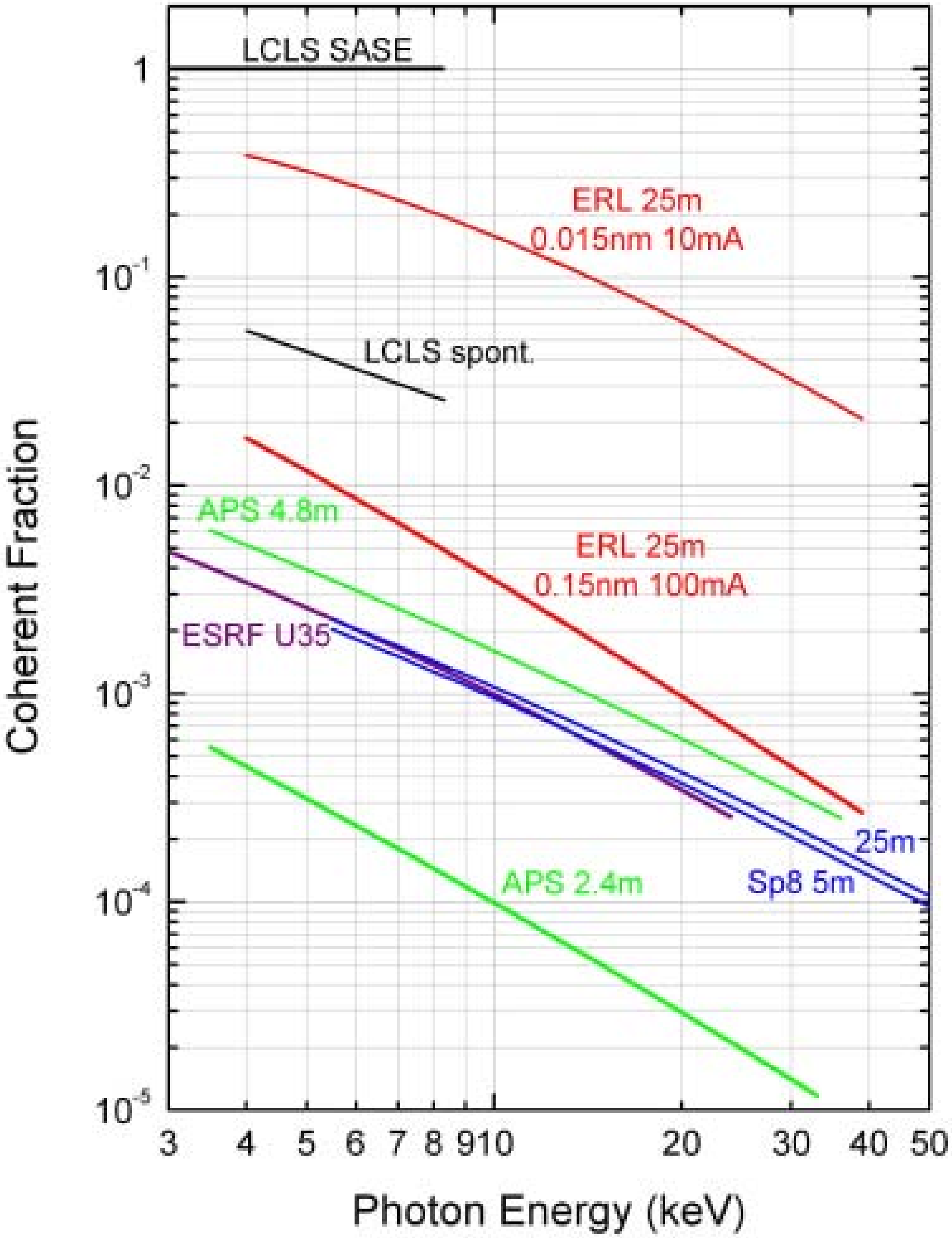
These distinctions carry over into next-generation SR sources, mainly free-electron lasers (FELs) and Energy Recirculating Linacs. The scaling laws for FELs and ERLs are more forgiving at lower photon energies, with the consequence that sources at these energies are in a more advanced stage of development, and the first FEL & ERL user facilities have been constructed. By contrast, hard X-ray FELs and ERLs are more ambitious undertakings.

Two programs for X-ray FELs with the capability of reaching the 1 Å wavelength range have been recently approved, one, LCLS, in the US –a SLAC-ANL-LLNL-BNL-UCLA collaboration- and one in Europe based at DESY. LCLS is now in the design and construction phase and will be completed by 2007. The DESY system will follow a few years later. These two X-ray FELs require electron beams with unprecedented characteristics, in particular a very large 6-dimensional phase space density, and high peak current. The X-ray pulses they will produce will have a pulse duration in the range of 10 to a few hundred femtosecond, and a peak power of tens of GW.

This new generation of light sources, with order-of-magnitude improvements in brightness, flux, spot size and pulse duration, can enable qualitative advances in research capabilities. For example, improvements in brightness will feed new science related to microscopy, either by providing microprobes with tighter focus (zone plates, KB-mirrors) or more intense field illumination in imaging microscopes (PEEM). These sources offer unique advantages due to the penetrating power, spectral features and polarization capabilities of the radiation. Resolution 10 nm and below will be the key to nanoscience and technology. The basic idea is to look at an individual nanotube, quantum dot, etc. as opposed to averaging over an inhomogeneous array. The particular strength of microscopy with synchrotron radiation is chemical specificity. There is a wide range of applications from the chemistry of cells and microbes, geology, and magnetic nanostructures for data storage. The development of spintronic memories will require the nanoscale characterization of electron spin distributions of magnetic clusters.

Discussions about next-generation FEL light sources also revolve around fast timing, coherence, and the large number of photons in a single pulse. In this context, fast means <100 femtoseconds. With this temporal resolution, one can take snapshots of molecules, proteins, cells, and nanostructures during less than a vibrational period and see what happens while the atoms in the molecule are still moving around (Zewail's Nobel-winning work popularized this idea of following a chemical reaction while it is on-going). Coherence opens all kinds of new imaging (and possible microscopy) methods. An essential idea is transforming the diffraction pattern (speckles) of a single molecule/nanocluster/object back into real space without knowing the phase. Iterative methods reconstruct the phase with the help of the knowledge that the object is finite. Coherence properties of various X-ray sources are shown in the figure below.

What enhanced application capabilities might be anticipated for the future? The possibilities would impact, literally, the full span of the materials and biological sciences.



Coherence fraction for various sources of synchrotron radiation (courtesy Q. Shen Cornell U)

These include, to mention a few examples, the ability to determine the structure of non-periodic, complex materials down to nanometer dimensions; extension of analytic capabilities in high-pressure science into new realms of pressure and temperature; structural analysis of non-crystalline proteins, viruses, and macromolecular clusters; wide ranging spectroscopic studies from the microvolt to the eV regime which are key to the properties of new materials and molecules; exploration of non-equilibrium, sub-picosecond electronic excitations; definition of chemical transition states in gases, liquids and enzymes; analysis of the magnetic thin films; coherent phase sensitive imaging of cellular organelles; microtomography of nanoscopic metals and composites; nondestructive 3-dimensional elemental analysis of art works; advanced microfabrication and patterning methods; and submicron imaging of elemental and oxidation states of soils, and biological and environmental materials. The X-ray FEL also opens new capabilities for High Energy Density physics.

Needed Developments

The underlying accelerator research and development necessary to ensure the success of next-generation light sources spans a broad range of physics and engineering. For the storage ring approach, the low energy storage rings that are optimal for producing low energy photons will be limited, much as next-generation B-factories, by the Touschek lifetime. This is especially true as one attempts to store currents of several amperes or short, femtosecond long, bunches. Work to improve nonlinear behavior and coupling in relatively compact, low emittance storage rings will be a high priority in dealing with this effect.

For both FEL and ERL light sources, one of the most crucial areas is the electron-source development. For ERL the issue is achieving storage-ring levels of average current (>100 mA) with normalized emittances of 1 nm-rad or less. For FELs the issue is to reduce the beam emittance while keeping constant or increasing the peak current. Additionally, the understanding of recirculation and energy recovery at these high currents is in its infancy and will require experimental studies to confirm present theoretical models. Issues of halo formation and beam loss are also of importance.

Increased efforts in the development of stabilization schemes and hardware for both the accelerators and their associated photon beam lines are required to take full advantage of the potential offered by the low emittance light sources that will be coming online in the next-decade. This is driven by the smaller beam sizes and by the stringent requirements of experiments using, for example, magnetic dichroism (0.01 % intensity constancy during polarization switching), IR Fourier transform spectroscopy, and monochromators with 10^{-5} resolution. Scanning and modulating insertion device fields have added to the scale of problems that must be addressed, and improvements of an order of magnitude or more have become essential.

Extensive cross-cutting efforts are needed between groups in accelerator physics, diagnostics/instrumentation, optics, signal processing, and researchers to define stability requirements and to solve the fundamental problems presented. Developments in beam-based diagnostics (electrical and optical), component stabilization, active machine feedback, dynamical compensation systems for variable insertion devices, and beam-line feedback on both the photon beam and electron beam will be necessary.

Synchrotron radiation facilities generally want maximum flexibility and range of the radiation provided to users. Advances in shorter-period, variable period, higher field insertion devices would provide this flexibility and enable lower-energy, lower-cost accelerators (both storage ring and ERLs) to provide higher photon energy and increased flux without excessive higher harmonic power. This work would necessitate development of higher remnant field permanent magnets, migration to superconducting devices with exotic coil arrays, or possibly microwave devices.

Neutron Sources

Accelerators are the heart of spallation neutron sources, again with a heavy emphasis on developments in proton linac and superconducting accelerator technologies. There is an emphasis here on improving accelerator technology to provide higher power pulses at low repetition rates with high reliability and constant current to allow long periods of continuous operation. Advanced high power proton accelerators are also a key to very important applications in proton radiography for materials imaging in the stock pile stewardship program.

Other Materials and Biological Accelerator Applications

On a much more modest scale, accelerator technology forms the basis for smaller-scale industries that produce thousands of machines for specific analytical and processing purposes in the materials and biological and medical sciences and for therapeutic applications. These include Rutherford back-scattering instruments, very high-current electron sources, machines for elemental activation and identification, implantation devices, microtron-based UV SR sources for lithography, etc. There is increasing research on developing relatively low-flux, but high brilliance and short-pulse table-top SR devices based on Compton back-scattering of laser light by electron beams. Each of these technologies requires research personnel skilled in accelerator methodologies and a search for higher efficiency in the machines themselves.

Fusion and High Energy Density Sciences

Impact of Accelerator Science on High Energy Density Physics

A fundamental understanding of the influence of nonlinear effects and collective processes on the propagation, acceleration and compression of intense, high-brightness, charged particle beams is essential to the identification of optimal operating regimes in which emittance growth and beam losses are minimized in periodic focusing accelerators and transport systems. This is particularly true at the high beam currents and charge densities envisioned in present and next-generation accelerators for high energy and nuclear physics research, in coherent radiation sources using high-intensity electron beams, in high-current linear ion accelerators, and in the space-charge-dominated beams used in heavy ion fusion.

High-intensity particle beams, like high-intensity lasers, are playing an increasingly important role in the rapidly developing field of high energy density physics, which explores the properties of matter under conditions of extreme energy density (exceeding 10^{11} J/m^3), or equivalently, at very high pressures (exceeding 1 Mbar). Chapters 1, 2 and 4 of the recent National Research Council report entitled *Frontiers in High Energy Density Physics – the X-Games of Contemporary Science* (National Academy Press, 2003 http://www.nationalacademies.org/bpa) provides a summary of particle-beam-related research activities and opportunities in high energy density physics. A few illustrative examples include:

1. The creation of quark-gluon plasmas, simulating conditions in the early universe, using colliding beams of relativistic heavy ions. (See illustration below)
2. The installation of dedicated beam-lines on high energy physics accelerator facilities for the express purpose of carrying out high energy density physics studies, such as the development of ultra-high-gradient accelerator concepts.
3. The use of intense relativistic electron beams to develop unique radiation sources ranging from the infrared to gamma-ray regimes.
4. The development of optimized plasma lens concepts to charge neutralize intense positron beams, thereby focusing the beam to a small spot size in a short distance.
5. Develop a fundamental understanding of nonlinear space-charge effects on the propagation, acceleration and compression of high-current, low-emittance, heavy ion beams, including identification of optimum operating regimes for heavy ion fusion applications.

Gold on Gold Phenix event at RHIC with magnetic field off (courtesy S.Ozaki, BNL)

The machines needed for exploring these important issues span the full gamut of accelerators, so that most of the advances listed in Appendix III will advance high energy density studies: brighter and more intense sources; superconducting magnets; improved simulation; beam cooling; new materials; neutral beam acceleration; traveling wave laser pumping; beam measurement with nanometer spatial resolution and femtosecond time resolution; real time, single shot, beam distribution function measurement instrumentation.

Education and Training Needs

As can be easily seen from the number of advertisements that appear monthly in Physics Today and the CERN Courier, there is a dearth of personnel trained in accelerator physics and related technology. It is widely agreed that the expansion of just synchrotron sources alone, to meet the growing research need, is limited by the availability of expert personnel. If the role of universities in accelerator development is to be enhanced that will put further pressure on the limited pool of accelerator experts. A similar statement can be made about the need for beam line designers and builders for both synchrotron sources and neutron facilities. This points to the need to draw more students into accelerator science and engineering through making the opportunities more widely known and offering easily available training and education in accelerator work either in and of itself or in conjunction with the pursuit of some other scientific area that uses accelerators such as particle and nuclear physics or the many branches of x-ray science. This combined training and education is very valuable, since it is ultimately the science practitioners using accelerators that know best what they need and, if accelerator wise, will see best how to get it.

Currently most NSF education and training in accelerator physics and technology takes place at the university accelerator laboratories supported by the NSF. This takes the form of formal on campus courses, degree granting distance learning courses, distance learning technology courses without formal credit, and apprentice like programs where the students gain most of their experience working on and around the accelerators supplemented by tutoring. In all of these the USPAS (US Particle Accelerator School), supported by joint efforts of the US accelerator labs – NSF and DoE together) plays an important role. It offers twice a year high quality courses and hands on experience to students, provided by outstanding accelerator scientists and technologists from across the country. In total, the number of PhD students in accelerator physics produced by NSF supported accelerator facilities is about 6 – 7 per year along with about 5 MS students per year. Note that the DoE HEP Technology program, and the DOE Basic Energy Sciences program, support significant work in accelerator R&D at universities. (see Appendix 4) For a certain perspective it is to be noted that of the 2850 experimental high-energy physicists in the US, 13% emphasize accelerator research. Three quarters of all high-energy physics experimentalists reside in universities while 2/3 of the accelerator scientists involved in accelerator research reside in the national laboratories.

Current Level of University Involvement in Accelerator R/D

At present there are three major NSF supported accelerator user facilities conducting research in nuclear, particle and synchrotron radiation science. Each of them carries out accelerator R&D largely focused on their own programs but a with a modest portion having a more general character as well. Given the need to boost such activities for the health of the future accelerator based research programs, enhancement of support for R&D at these facilities is a natural step. Some of the subjects of this R&D and NSF accelerator facilities are superconducting radiofrequency accelerating devices both for velocity of light and slow particles, materials and surface science relevant to high power rf devices, medical accelerators, optics and beam theory, full non linear simulations of accelerator operation including beam-beam effects, IR edge radiation, beam lifetime issues, and design of low energy compact storage rings.

Of at least equal importance is the need to engage the accelerator user scientific community in the strengthening of accelerator R&D. Considerable progress has been made in this direction recently. For several years now there has been a grass roots organization known as the Muon Collider and Neutrino Factory Collaboration, or MC, which devotes itself to those subjects. Currently there are 22 universities participating in various accelerator R&D projects associated sponsored by the MC with support from both NSF and DoE. Unfortunately the support level has been modest and in fact has recently been cut. Total annual support is approximately $4 M. The work is a combination of work done at the individual universities, and collaborative work utilizing infrastructure at the traditional accelerator laboratories. Every subsystem of these complex accelerators has enormous technical and economic challenges (see http://www.fnal.gov/projects/muon_collider/prstab/prstab.pdf). For these challenges to be met the support level needs to be raised substantially.

In another positive development there has recently been the formation of two groups of university physicists to engage in R&D for the e+e- linear collider, the LCRD (Linear Collider R&D group), and the UCLC (University Consortium for the Linear Collider). Proposals have been submitted to the DoE and NSF respectively. Forty seven universities are involved, with a total of seventy one individual projects, about equally divided between detector and accelerator R&D projects. Again some of these include collaborations with traditional accelerator laboratories, using existing accelerators and some involve work at collaborating or individual universities (see http://www.lns.cornell.edu/public/LC/UCLC). The combined support level requested for this year is $2.5M, keeping the individual university involvements at a very modest level. The challenges in linear collider accelerator technology and physics reach far beyond this level of support.

Basic research in beam physics is being supported at a small number of universities by DoE. Examples are UCLA, Maryland, and SUNY Stony Brook. These university groups are engaged in the experimental and theoretical study of beam-plasma, beam-laser, and beam-laser-plasma intreractions, high phase-space density electron sources, and collective instabilities. They are also working on the development of advanced numerical codes, including non-linear dynamics and collective effects and the complete simulation of complex experiments. University groups at these institutions offer undergraduate and graduate courses in accelerator physics and technology, and training in in-house laboratories. They produce about five PhDs per year, and some masters degrees.

Enhancing the University Role

As noted in the previous section, there has been a positive trend in the involvement of universities in accelerator work directed at rather specific goals of neutrino factories, muon colliders and electron-positron linear collider. This is all to the good since particle science is being limited while these needed techniques are being developed. However most of the universities involved in this research do not offer a complete undergraduate and graduate training. The number of faculty positions in accelerator physics in universities is also quite limited. For this reason we believe that it will be important to cultivate more university involvement in advanced accelerator R&D so that sufficient work on basic particle beam physics and on developing the next generation of accelerators can extend over a sufficiently long time scale. Improving the effectiveness of university involvements will require both improved organizational arrangements and resource levels.

On the organizational side we note that there are very few remaining university accelerator facilities where student and faculty involvement in accelerator work, training and R&D, comes most naturally. As part of a program directed at enlarging university involvement, we should study how to increase the number of university based accelerator facilities for beam physics research, and to make existing university facilities available to the wider university community by providing opportunities and the needed mentoring. The accelerators at national laboratories tend to be less accessible for training and accelerator R&D owing to their need to be factories for science. There are, of course, notable and important exceptions. These exceptions can serve as models of how to expand the accessibility of our accelerator infrastructure to university participants. Here again work needs to be done to provide the organizational means for this access, including provision of the needed mentoring and service personnel.

On the resource side it will be necessary to make available additional resources for some infrastructure at the universities, as well as for carrying out research work. One needs to create the conditions to have more faculty positions at universities, with the support needed to carry out significant research and attract undergraduate and graduate students. For existing accelerator facilities, university or national lab resources will be needed to provide for the services needed by the new university users. Today, a rough estimate of funds available annually to university scientists for accelerator work is about 20$M so that to make a significant impact on university involvements would require adding a comparable amount.

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APPENDICES

Appendix 1 [1]

Enumeration of Accelerators now in use

Category	**Number**
Ion implanters and surface modifications	7,000
Accelerators in Industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	7,500
Medical isotope production	200
Hadron therapy	20
Synchrotron radiation sources	70
Research in nuclear and particle physics	110

Appendix II

ACCELERATOR FACT SUMMARY

Support body	Sub-unit	Type used	Uses
NSF			
	NP	e,p,I	nuclear physics
	EPP	e,p,	particle physics
	AMO	e(X),?	structures

	DMR	e(X),n,μ	materials, imaging
	CHEM	e,e(X),μ	materials, reaction enhancement
	GEO	e(X),n	mineral phase diagrams, prospecting
	BIO	e(X),n	bio structure determination, imaging
	ENG	I, e(X)	nanostructures, micromachining, lithography
DOE			
	BES	e(X),n,μ	materials research, FEL, em sources devt
	BER	e(X),n	Bio structures
	HENP	e,p,I	nuclear and particle physics
	FUSION	I, e(X)	heavy ion fusion, high energy density physics
	DP	e,e(X),p	explosion physics, FEL, radiography
			waste transmutation, tritium production
DOD			
	NAVY	e,I	FEL, fusion
	QUARTERMASTER CORPS	e(X)	food sterilization
	“GENERAL”	e(X)	inspection
NASA			
		p,I	detector calibration, radiation damage, health
NIH			
	GENERAL MED	e(X),n	bio structures determination
PRIVATE MEDICAL SECTOR		e(X),p,I	therapy, isotope production, radiography
DOC			
	NIST	e(X),e	optical radiometry, materials/biological structures, dosimetry, calibration, radiation effects, imaging
INDUSTRY		e,e(X),n,I	analysis, inspection, implantation, sterilization, polymerization, mass spectroscopy, radiation damage

HOMELAND SECURITY		e(X), n	sterilization, inspection

e – electron
e(X) – UV and x-ray generated by electrons
p – proton
n - neutron
I – ion
μ - muon

Appendix III

Progress Needed in Accelerator Science and Technology and Related Apparatus

Accelerator Basic Science

1. Physics of coherent synchrotron radiation
2. FEL physics
3. Beam and plasma diagnostics with nanometer spatial resolution and femtosecond time resolution
4. Real time, single shot, beam distribution function measurement instrumentation.

Accelerator Applied Science

1. Brighter sources (e,p,I)
2. Higher current sources (e,p,I)
3. High power x-ray optics
4. Micro x-ray beam development
5. Higher gradients in both SC and NC structures
6. Better HOM damping in SC and NC structures
7. AC – beam power efficiency improvements in all accelerator types, laser, conventional
8. Improved devices for beam manipulation (plasma, pulsed and cw electric and magnetic)
9. Superconducting magnets
10. Improved cradle to grave simulation including non-linearities, vibration, wakes, beam-beam etc.
11. More cost effective means for manufacture of major accelerator components
12. New approaches for high flux, high brightness femtosecond x-ray sources
13. Practical optical wavelength acceleration and manipulation schemes
14. Very compact accelerators for medicine and inspection
15. Beam cooling methods (radiation, stochastic, electron, ionization)
16. X-ray imaging
17. Materials (new materials, radiation resistant materials, new magnetic and superconducting materials)
18. Neutral particle acceleration
19. Traveling wave laser pumping with beams
20. Beam measurement instrumentation with nanometer spatial and femtosecond temporal resolution
21. Megawatt capable targets for muon and neutron production

22. Muon accelerators (induction, low frequency linac, FFAG, low frequency superconducting, high gradient, cavities)
23. Energy recovery at high current and brightness
24. Improved insertion devices for FEL and spontaneous synchrotron radiation as well as for use in emittance control in storage rings
25. Real time, single shot, beam distribution function measurement instrumentation.

Appendix IV

DoE University Program

The DoE HEP Technology program also supports university participation in accelerator R&D. Currently the support level is $12.7M annually with 10 to the universities and 2.7 supporting infrastructure at the national labs (mostly BNL) for the benefit of the universities. About 35 universities are in the program. In existence since 1982, the program has averaged 10 PhD degrees annually between then and now.

Details of the DoE university program can be found at http://doe-hep.hep.net/Yearbook%202000/ (DoE/SC – 0032 is the report number)