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Technology Benefits Deriving from the International Linear Collider

1. Introduction

The Funding Agencies for Large Colliders (FALC), a group composed of representatives of national science funding agencies and consortia around the world, was formed in 2003 to inform governments and promote coordination for large new international facilities in high-energy physics (HEP). One of its immediate goals was to support the preparation of a proposal for the International Linear Collider (ILC) in its R&D phase, for later consideration by governments for funding. In early 2007, as a part of its information gathering process, FALC commissioned a study to explore the potential wider benefits of the ILC to industry, the larger scientific community and society at large.

This report responds to that charge. It has been developed through extensive interactions between physicists and industry in Japan, Europe and the United States. Each region conducted its own workshops, interviews, and interactions with industrial representatives to compose lists of potential spin-offs from the ILC. Each region prepared an interim report of its findings [1,2,3]. This report gathers the major threads from the regional reports, and gives a broad survey of possible benefits.

Historically high-energy physics and other fundamental sciences have enjoyed comparatively strong financial support, primarily because of the high value that societies associate with understanding the natural world. This support is also based on the assumption that such research serves as a motor for innovation in general. Governments strive to stimulate new economic opportunities for competing in global markets and for improving the quality of life. The talented people who devise these new technologies migrate into the wider society, bringing their innovative ideas and mastery of new technologies to a wide set of problems. The broader dissemination of both people and new technologies may not be the primary motivation for high energy physics, but are important elements in decisions to undertake new science projects. Although high-energy physics has developed several new technologies of this kind, it is by no means unique in this respect. The element that may make it distinct from other branches of science is the pressure for innovation and its established record of stimulating novel, high-risk and large-scale technologies.

The large uncertainty of predicting the broader economic benefits of cutting-edge R&D must be stressed. Our record of forecasting science and technology research impacts is poor. For example, Thomas J. Watson, CEO of IBM, said in 1943 about the new digital computing machines that were then emerging in laboratory R&D, "*I think there is a world market for maybe five computers*." Thus this report is primarily a compilation of what could, but not of what must, occur. Nevertheless, history shows that widespread benefits have often resulted from inquiry-based research and we should not doubt that the ILC would make its own strong impact on society.

We should also note that although the ILC is developing its own innovative technologies, it is only part of a larger matrix of accelerator developments in various countries, and it shares the role as a driver of new technology with these other projects. The single largest step of the ILC in technology development is the large number of industry-produced superconducting radiofrequency (RF) cavities for efficient acceleration of electron beams to high-energy. This technology has emerged over several decades as accelerators around the world have incorporated increasingly more powerful superconducting acceleration cavities. The next step will be taken by the X-ray Free Electron Laser (XFEL) project in Germany, at approximately 10% the scale of the ILC. It will be the task of ILC-specific developments to improve this technology to even higher accelerating gradients and to improve the yield, reliability and cost per unit energy gain. The ILC will provide other new technologies for the creation and control of particle beams that will have broader impact.

Section 2 of this report summarizes some of the transformative effects of past high-energy physics R&D. In section 3 we list the ILC technologies that seem most relevant for broader applications. Sections 4 and 5 discuss examples of ILC technologies and methods, or accelerator systems proper, that may enter the industrial mainstream and provide societal benefits. Section 6 outlines the impacts of ILC technology on other scientific research fields. Section 7 briefly adds some more general benefits.

2. Benefits from past high-energy physics R&D

We briefly list three areas in which past R&D in high-energy physics have resulted in major and general impacts upon society.

a) Accelerators: Particle accelerators were invented in the 1920s for particle physics research but have since found a multitude of uses, many quite far from particle physics (see Table 1).

CATEGORY OF ACCELERATOR	NUMBER IN USE
High Energy acc. (E > 1 GeV)	~ 120
Synchrotron radiation sources	~ 50
Medical radioisotope production	~ 200
Radiotherapy accelerators	> 7,500
Research acc. including biomedical research	~ 1,000
Acc. for industrial processing and research	> 1,500
Ion implanters, surface modification	> 7,000
TOTAL	**~ 17,370**

Table 1. Number of accelerators in use in 2002 in different technical applications, taken from W. Maciszewski and W. Scharf, Int. J. of Radiation Oncology (2004).

Many concepts and developments from particle physics find applications in health care. High-quality detectors and accelerators, essential for particle physicists to meet their research goals, were later applied as improved medical diagnostic tools and for providing custom radiation treatment of disease. For example, pioneering studies carried out at several high-energy physics labs worldwide in the 1960s showed that treatment of deep-seated tumors using high energy beams of protons or atomic nuclei was superior to gamma rays, owing to the more concentrated deposition of dose at the tumor site. The first proton linac for hospital clinical treatments was built by Fermilab in the US in 1990. Nowadays many centers in Europe, Asia and the Americas are using proton and carbon-ion therapy. So far some 45,000 patients have been treated with protons and many new centers are under construction. Promising biological investigations for future medical applications with antiprotons have been carried out and proposed for new facilities such as the Facility for Antiproton Ion Research (FAIR) in Germany.

Short-lived nuclear isotopes are now routinely used for medical diagnostics and treatment. The techniques for separating individual isotope species were developed by nuclear physicists, and most isotopes are still produced in nuclear reactors. However, production of some key isotopes is only possible in higher energy particle accelerators, which bring the additional benefit of reducing radioactive waste.

Particle physicists routinely use high-energy collisions between electrons and their antiparticles, positrons, to investigate matter and the fundamental forces. At low energies, electron–positron annihilations can be put to different uses in positron emission tomography (PET) machines. This scanning technique for medical diagnostics allows previously unattainable views of the chemical processes within functioning organs. Thanks to the improvements of many associated technologies, PET represents a significant step forward in the way clinicians visualize and monitor treatment on-line (e.g. the spatial distribution of radiotherapy treatment). In association with computer tomography (CT) scanners, PET has become an essential medical diagnostic tool. A first image from a PET camera was made in 1977 at CERN, the European particle physics laboratory. Twenty years later, a combined PET/CT scanner has been advocated as the path to true functional and morphological image fusion.

High-energy physics detectors also have found medical applications. A single-photon-counting pixel detector readout chip, driven by the requirements to study complex high energy collisions, eliminates the background noise associated with more traditional X-ray-imaging approaches and provides energy information that was previously lost. The system has been transferred to industry for X-ray materials-analysis equipment, and several teams are extending its use to the medical-imaging field.

b) Computer science:

Information technology has undergone a rapid development in the past decades due to advances in electronics and network technologies. Physics research, and high-energy physics in particular, has spurred this information revolution. Through the introduction of the World Wide Web (WWW), and more recently of the Grid, particle physics has changed the use of computers in society and stimulated new computing paradigms.

The WWW has become an integral part of every-day modern communications. It represents one of the most striking individual examples of technology transfer in the past two decades. It has profoundly altered information exchange generally and the behavior of individuals specifically. Revenues from the WWW have been rising exponentially and passed the one trillion dollar mark in 2001. This represents a truly giant leap from its invention in 1990 at CERN where it was developed to support the need for efficient communication of the large internationally-dispersed group of physicists working collaboratively on large particle physics experiments.

The Grid provides the next step in this direction. It ties the globally distributed computing resources into a single coordinated computing service. As the Web was a response to a new need for scientific collaboration, the Grid is the response to the need for increased data analysis power that can be made available by accessing remote computer installations in widely dispersed institutes. Typically, at least half of the activities within a big high-energy physics experiment deal with computing and the data transfer needs are huge. The data transfer rate from the experiments at the Large Hadron Collider (LHC) is comparable to that of worldwide public telecommunication. The latest computer and communications technologies and the advanced data flow management software are essential to cope with the demands. The latest features of computer networking (including tele-cooperation, tele-operation of supervisory tasks) and data management have been applied. In terms of the scope of international data communication, high-energy physics labs rival medium-sized countries.

The Grid computing experience in high-energy physics is presently being expanded into new areas, with a number of successful collaborations with industry on common software and early equipment tests. A rapid and natural consequence of the Grid is the application to medicine. The MammoGrid project for a Europe-wide mammograms database distributes information among participating doctors and hospitals. A repository with 30,000 mammograms is now accessible, owing to the prototype developed at CERN. That system provides remote reference for diagnosis and follow-up of difficult cases.

Particle physics institutes devote about half of their large computing capacities to Monte Carlo calculations that simulate the extremely complex phenomena behind the experimental data. This technique finds broader use. For example, codes for simulating energy deposition by electron and photon showers in dense media were developed in a collaboration led by SLAC in the US. This code has since been distributed to more than 1000 external users for simulating treatments of cancers using electron accelerators.

c) Impact on high-tech industry:

High-energy physics collaborates extensively with high-tech industry to develop the technologies needed for its accelerators and detectors. The R&D initiated by various laboratories has led to patents, licenses, and new companies that help make the new technology available to society at large.

A study conducted in 2000 estimated that about 2 billion euros were spent in Europe on technology-oriented products by inter-governmental science research projects. Several studies worldwide, based upon information from industrial companies, estimate that the resulting income for the participating industrial companies is about three times the project expenditures. Surveys in the late 1990's of high-tech companies working with CERN, DESY and other large accelerator-based institutions indicate that more than half of the projects showed a gain of technological know-how, and over a third developed new products as a result of the collaboration.

3. ILC technology sectors

As noted in section 2, the development of particle accelerators has had pervasive and profound impact on society in general through innovative applications and transfer of technology to the medical, industrial, energy, homeland defense and military sectors.

Much frontier scientific research now depends on the use of energetic beams of electrons, photons, protons, neutrons and atomic nuclei. This trend is expected to increase in the future. While the direct impact of ILC technology on new accelerator facilities is reasonably well understood the implied scientific understanding deriving from those advances will depend upon the ingenuity of future researchers. The highly collaborative nature of the ILC R&D and industrialization efforts does ensure that the new technologies will be disseminated rapidly among all the participating nations.

In this section, we briefly review the key ILC technologies that are most likely to lead to new applications.

Superconducting radiofrequency (SCRF) acceleration: Acceleration of charged particles to high energies is typically accomplished through application of radiofrequency waves within evacuated cavities surrounding the particle beam. The electric field of the RF wave, arranged to be in synchronization with the particle motion, provides the acceleration. The figure of merit for accelerating cavities is the gradient, measured in megavolts per meter: the higher the gradient, the shorter the accelerator for a fixed final energy. The resolving power of the particle beam is inversely proportional to the particle energy, so typical scientific applications require energies in the billion electron volt (GeV) range. To achieve its scientific goals, the ILC in its initial phase will have two opposing linear accelerators, each with beams accelerated to 250 GeV.

Traditionally, accelerators used copper RF cavities. Such cavities are readily fabricated but suffer large power losses due to induced surface currents. More recently, superconducting cavities made from ultra-pure niobium have been developed, in which the energy losses are reduced to nearly zero. Early applications of SCRF achieved gradients of around 5 megavolts per meter. The coordinated effort of the TESLA collaboration, combining the world-wide expertise in this field, led to a more than 5-fold increase in gradient, while reducing the cost by a similar factor. The 15,000 cavities for the ILC are specified to achieve 35 megavolts per meter in an attempt to reduce the overall length of the collider.

The primary challenge for high gradient SCRF is the preparation of ultra-smooth niobium surfaces, capable of retaining superconductivity in the presence of the large RF magnetic fields, and of avoiding electrical discharges induced by the high RF electric fields. To date the ILC operational goal has been achieved for some cavities in the laboratory, but the industrialization program is still ongoing through collaboration of accelerator physicists, materials scientists, and high tech industry. Achieving the high gradient capability will yield similar improvements to any future research accelerator.

<u>RF power sources</u>: The high power RF needed for acceleration is provided by high-voltage pulse generators and special klystrons that convert the pulses into radiofrequency waves. Typically these devices consume a large fraction of the electrical power for the accelerator, and are prone to failure. The ILC need for over 600 pulse generators and klystrons (with perhaps 10 – 20 failing each year) drives the development of more efficient power devices with high component reliability.

<u>Damping rings</u>: Typical accelerator applications require a very small beam size for high brightness and large interaction rates. The ILC calls for unprecedented small beam sizes, typically on the micrometer scale but decreasing to a few nanometers in height at the collision point. The small sizes are achieved in very high-current circular accelerators called damping rings. Complex collective effects in the damping rings, such as the interaction of the beam with electrons emitted from the beam vacuum chamber, tend to limit the sustainable currents. Solving these issues will require new techniques for vacuum chamber design, surface preparation or application of special electric and magnetic fields to limit the electron density on the beam line. These technologies will directly benefit any new circular accelerator facility that seeks high brightness, and may have broader application.

The ILC damping rings need to extract an individual beam bunch from its neighbors only a few nanoseconds apart using very fast kicker magnets. Development of fast kickers will considerably extend current beam manipulation capabilities.

<u>Beam instrumentation, control and alignment</u>: The ILC must control the beam position to the micrometer level over the length of the accelerator to assure head-on collisions at the experimental detector. This control must be maintained in the presence of thermal and ground motions and environmentally produced vibrations. New devices for measuring the beam position at the micrometer level, and the feedback of the measurements for orbit control are being developed for the ILC.

The ILC needs very accurate metrology data over kilometer scale distances to provide the reference context for establishing the locations of magnetic and accelerating components and correction loops for minute ground motions.

<u>Electron and positron sources</u>: The ILC requires high-current, low-emittance, fast-cycling beams of both electrons and positrons. These sources must be capable of delivering beams with particle spins highly aligned (polarized) either parallel or anti-parallel to the particle direction. For the electron source, this can be achieved by irradiating special crystals with high-power polarized laser beams, a technique that was demonstrated at SLAC in the nineties. Positron production is more complex. A 150 GeV electron beam traverses a helical undulator, generating circularly polarized photons of several million electron volt (MeV) energy, which in turn create polarized positrons in a conversion target. The positrons are captured and rapidly pre-accelerated before being injected into a

damping ring. A more futuristic alternate design generates the photons from circularly-polarized high-power laser beams back-scattered from a few GeV electron beam. This scheme is still under development but could form the basis for a number of important applications discussed below.

Accelerator simulations: Computer codes to simulate the ILC beams from start to end are necessary to recognize and mitigate effects that increase the beam size. The simulations for the ILC damping rings will also further our understanding of very high intensity short-bunch beams in circular machines. These codes will be applicable to a wide range of other accelerator applications.

Particle detectors: While some detector requirements are unique to the high-energy collisions at the ILC, the technologies for very finely subdivided two-dimensional pixel detectors for micrometer-level position measurements and very large inexpensive arrays of millimeter-scale detectors will find use in other scientific applications.

Computing applications: The ILC will engage a large community interacting with large data sets from many sites around the world. Handling this data access in a transparent and efficient manner will stimulate further advances in computing grids.

Global remote facility operation: The ILC will be operated through multi-national consortia, often with remote access for controlling key components of the accelerator and detector complex. Development of remote control methodologies will find applications in other large international projects.

4. ILC technology benefits to industry and the broader society

Benefits from accelerator research to industry and society can be categorized in two classes. The first class comprises the spin-offs of new technologies or methods that can be applied in areas far from their original purpose in HEP. Past examples are the development of high performance steel for use in powerful accelerator magnets, now adopted by the electrical machinery industry, or the development of superconducting magnets subsequently adopted in medical therapy and diagnostics, power generation or transportation. The second class is the application of accelerators themselves, or their major subsystems, for wider applications. An example is the use of linear accelerators in medical and non-destructive materials inspection industries.

Examples of the first class of technology and methods advances which have good potential for opening new opportunities include:

1. The number of superconducting cavities and cryomodules in the main ILC linacs require that a vigorous R&D and value engineering effort succeed in developing a reliable and cost effective industrial production capability. The ILC cost drives the design of the cavities to higher accelerating gradients than was achieved in previous facilities. The gains in yield and high gradient cavity performance will benefit a wide

variety of industries, such as lower cost, lower power consumption electron or X-ray sources or better performance non-destructive materials inspection devices.

2. ILC R&D on advanced superconducting materials such as ultra-pure small grain niobium, single crystal or large grain niobium, or niobium-cladded copper could advance superconducting applications generally. New fabrication and surface treatment methods will promote a whole suite of applications. Examples include hydroforming of cavities to minimize the introduction of materials defects and to reduce the large cost associated with electron beam welding, the preparation of ultra-smooth and ultra-clean surfaces through electro-polishing and high pressure water rinsing (which could benefit the metallurgical and electronics industries generally), and mechanical polishing through tumbling abrasive balls in a rotating cavity (largely eliminating the use of toxic chemicals).

3. Large-scale high-power RF systems will have impact on electron beam applications such as remote micro-chemical analysis used for environmental protection, non-destructive testing, intelligent platforms for agile radar systems or new secure communications systems.

4. Short intense bunches of electrons developed for the ILC source will open new applications for study of very short time-duration phenomena in materials, and should extend electron beam lithography by improving the ratio of depth of carving to the feature width.

5. Beam position monitoring and control systems to maintain micrometer beam accuracy should impact new electron microscopy tools and very highly integrated electronic circuit fabrication methods. The ILC will challenge state-of-the-art standards for keeping the downtime for electronics systems at the one part per million level, a development that provides benefits for any application that is highly dependent on uninterrupted operation.

6. Techniques for measuring small displacements due to ground motion and environmental noise, and development of mechanical systems that correct for such motions, could be applied to improved systems engineering for nano-manufacturing facilities, or early warning of seismic activity.

7. Simulation tools for understanding the ILC beams, and the non-linear effects caused by interactions among the particles in a bunch and with the metallic beam enclosure structures will be important for improving instruments such as scanning electron beam microscopes and beams for medical irradiation therapy facilities. The simulation tools developed for predicting complex electromagnetic field patterns in ILC cavities and power insertion devices will find application in improved electrical power machinery design and electromagnetic interference analyses.

8. Large area particle detection systems developed for ILC experiments could provide an effective technology for cargo container inspections either through X-ray excitation or using naturally occurring cosmic radiation.

9. ILC detectors will push the imaging resolution by silicon pixel devices to new levels. Development of radiation-hard silicon sensors and readout electronics will find spin-offs in space and medical applications. Large-scale integration of new silicon photomultipliers in ILC experiments will find wide usage elsewhere.

10. Architectures of electronic chips developed for massively parallel signals from gigabit/second detector sources will find applications in other high data rate environments.

11. ILC and other high-energy physics experiments require grid architectures of distributed computing capability and advanced software systems for monitoring and securing large data set transmissions that will find applications broadly within information technology.

5. Potential applications of superconducting accelerators and subsystems.

In the past, accelerators have found wide applications in such sectors as medical diagnostics, clinical treatment, food sterilization and electronics fabrication. The new superconducting RF accelerating technologies and associated advances in high current polarized sources for electrons and photons may have considerable impacts in these and other sectors in future. There are considerable uncertainties, including the success in developing reliable and cost effective technologies, the competitive position relative to other more established technologies, and the ease with which complex infrastructures such as cryogenic systems can be provided. In some cases, the new applications may fail to materialize due to competition with existing technologies; an example is cancer therapy using GeV scale proton/heavy ion beams which is based on the already commercialized cyclotron technology.

The examples below give some of the potential new uses for linear accelerator systems or the intense sources being developed for the ILC:

1. Short-pulse, low-emittance electron beams derived from laser irradiation of crystalline ILC-like targets can provide very high quality micro-beams for applications such as intensity modulated radiation therapy in which cancer cells are selectively targeted with minimal damage to surrounding normal tissue. The short pulses allow the possibility for irradiation delivered in synchronization with patient breathing cycles, thus avoiding the smearing effect as the patient moves.

2. Very intense X-ray beams can be produced by backscattering high-power pulses of laser light from intense electron beams of a few GeV (themselves possibly produced in superconducting RF energy recovery linacs). ILC R&D is exploring this technique as a way to create circularly polarized X-rays for producing polarized positrons. The general technique however is of wider interest for creating intense monochromatic X-rays of tunable wavelength and short bunch duration. Such gamma or X-ray sources would open many new important opportunities:

- Monochromatic X-ray sources could sharpen the clarity of images well beyond that achievable with current sources. Radiation doses in medical treatment using highly directed backscattered X-rays for treatment could be substantially reduced over current techniques.
- Pharmaceutical research on protein structure would benefit from compact monochromatic sources. The availability of cost-effective stand-alone units would free pharmaceutical firms from the need to use open-disclosure government-funded light sources.
- High intensity monochromatic X-rays in the 10 nanometer wavelength region would open new possibilities for ultra-highly integrated semiconductor circuit lithography, allowing perhaps a hundred-fold increase in circuit density.
- Monochromatic soft X-rays in the 1 – 2 nanometer range are not absorbed in water, but are highly attenuated by biologically active proteins and nucleic acids. Use of X-ray sources in this range would permit new studies of in-vitro biological processes. Contrast would be enhanced by varying the X-ray energy, and the short bunch length would mitigate image blurring due to radiation and thermal effects.
- Backscattered circularly polarized lasers will create polarized X-rays, sensitive to details of the magnetic structure of data storage devices not accessible with existing sources, opening the way for new, higher information-density magnetic disks.
- Non-destructive testing units for examination of corrosion in materials or testing thick concrete structures would be feasible with the backscattered X-ray sources.
- Irradiating nuclear waste materials with gamma rays with a programmed sequence of energies would reveal its nuclear isotope makeup, enabling a segregation of different species for more efficient disposal.
- Unstable nuclear species in waste material may be transformed by irradiation with carefully chosen wavelengths of intense gamma rays into harmless stable nuclei.

3. The polarized electron sources developed for the ILC will allow new probes for performance evaluation and dynamic observation of the formation processes in magnetic materials. New devices involving two electrodes separated by a thin insulation layer use the magnetization state in a nanometer sized array on one electrode to form a memory bit. Probing these arrays is presently accomplished with scanning tunneling microscopes with magnetic probes; the performance of current STMs is limited by the influence of the magnetic probe with the specimen under study and by the poor control of beam direction. Characterization of these devices using spin-polarized electron beams would bring major improvements. The beam can be made as small as the structures under study, adjusted to any angle of incidence, and the measurement does not influence the magnetic state of the array under study. There is good potential for transforming the high-density magnetic disk industry, currently estimated at ~$100 billion/year, if better control of intensity and position stability can be demonstrated.

A related benefit could result from the use of polarized electron beams as the source for a low energy electron microscope to image the formation and evolution of nano-magnetic devices, and to dynamically inspect the surface structure of magnetic domains in new materials for devices. For this application, the high-intensity polarized electron beams developed for the ILC are the key enabling technical step.

4. Free electron lasers with tunable wavelengths can be used to selectively excite or break chemical bonds, thus opening new technologies for chemical and pharmaceutical industry.

5. High power electron beams have potential for rapid, effective scanning of cargo container contents, improved semi-conductor lithography facilities, and non-destructive testing of civil and mechanical structures.

6. Production of new species of radio-isotopes for medical diagnostics and therapy could be facilitated by high-energy (50-100 MeV) proton linacs.

7. Very high power GeV scale proton beams from superconducting linacs can be directed upon subcritical (thus immune from runaway modes) thorium reactors to induce fission and create more energy than used in the acceleration process by a factor of ten or so. Thorium is a relatively abundant material. The radioactive isotopes produced in a thorium reactor are relatively short-lived (~30 years half life), reducing the nuclear waste problems. The proton beams themselves may be used for transmutations of nuclear waste. The advent of new high-power superconducting proton linacs is the enabling aspect of this old idea.

6. Impact of ILC technology in other sciences

The development of the new particle accelerators used across many scientific disciplines has historically been driven by high-energy physics research. The ILC R&D and subsequent development of new industrial capabilities can be expected to have further large impacts on research facilities that explore broader sectors of science. Among these, we note:

<u>Light Sources and Energy Recovery Linacs</u>: Light sources have brought broad advances within many sciences over the past few decades. Traditionally these have been based on circular electron machines from which beams of synchrotron radiation photons ranging from infrared light to X-rays can be generated. A brief sampling of recent accomplishments serves to demonstrate the breadth of these programs:

- Researchers at the Advanced Light Source in the US solved the structure of the avian flu virus and analyzed its specificity to human receptors.
- Synchrotron light from the European Synchrotron Radiation Facility in France produced a movie visualizing catalyst operation in chemical oxidation reactions.
- Studies at the Spring-8 facility in Japan elucidated the role of the ‘heavy’ electrons implicated in generating superconductivity.
- Studies at the Stanford Synchrotron Radiation Facility in the US demonstrated how water-borne mercury contaminations enter the food chain.
- X-ray studies at the Synchrotron Radiation Source in the UK understood the structure of metal-organic frameworks for use in hydrogen storage cells.

- Experiments at the Pohang Accelerator Laboratory in Korea developed non-invasive techniques for visualizing moving blood cells in living animals.
- Work at the Advanced Photon Source in the US mapped the atoms in 450 million-year old proteins and helped explain evolutionary biological processes.
- Scientists at ELETTRA in Italy unraveled the processes at work in growing reproducibly high-purity nanocrystals.
- The Photon Factory in Japan has pioneered X-ray lithography at the 0.2 micrometer level for industrial fabrication of computer memories.
- Studies at HASYLAB in Germany showed iron-containing structures in the beaks of pigeons which may serve as a magnetometer to the Earth's magnetic field.

SCRF has already enhanced the brightness of advanced circular light sources. Fourth generation light sources now planned around the world are designed with SCRF cavities. However the synchrotron radiation beams derived from such machines are becoming limited by the electron beam quality due to inherent quantum fluctuations in photon production, and the next generation of light sources are being developed using linear accelerator technology. In the Energy Recovery Linac (ERL) design, a pair of linacs separated by short arcs first accelerate the beams to the energy required for the synchrotron light generation, then decelerate them, recovering the large amount of stored energy for re-use in the next acceleration cycle. Re-acceleration of new beams in each cycle removes the beam quality limitations of circular machines. The ILC development of high gradient SCRF will permit substantial savings in size and cost for ERLs. The ILC beam source technology will provide the high currents needed for advances in brightness. The ERLs will extend the brightness of the beams by a factor of a thousand over circular light sources and will significantly expand the capabilities for studies in nuclear science, materials science, chemistry, structural biology and the environment.

<u>Free electron lasers</u>: The first Free Electron Lasers (FELs) now being built in the US, Japan and Germany are based directly upon linear collider R&D. These machines provide X-rays in the sub-nanometer wavelength range, with pulse durations down to a hundred-thousandth of a nanosecond and brightness up to a million times greater than the ERLs. The German XFEL incorporates most of the elements developed for the ILC and the physical layout is similar.

The scientific potential of the XFELs derives from the combination of small wavelength, very high brightness and ultra-short bunch size and spacing. The small wavelength is essential for resolving atomic-level detail. The high brightness means that a single bunch of X-rays is sufficient to provide enough contrast and detail without the need for averaging over long times. This single bunch intensity and the short duration of the bunch makes it possible to take snapshots of biological and molecular systems with a trillionth of a second shutter speed, thus freezing the molecular motions in an image before the high beam power has a chance to disrupt the system. The short bunch interval makes it possible to take repeated stroboscopic snapshots and assemble them into movies that reveal the time evolution of complex systems. Examples of the new territory that will be opened up by XFELs are: revealing the mechanisms at work in protein folding and biological processes in real time; creating and exploring the warm dense plasmas that are thought to occur in planetary interiors or cool dense stars; and catching chemical reactions as they proceed, giving a detailed picture that could lead to the ability to sculpt the reactions needed for new materials and pharmaceuticals.

The new XFELs are directly enabled by years of ILC-related R&D. The ongoing projects will help develop the ILC technology. In turn, future X-ray machines will benefit directly from the advances made by the ILC in SCRF, high current polarized electron sources, fast kicker extraction magnets, beam instrumentation and feedback over large distances, and in spent-beam handling.

<u>Proton and heavy ion linacs, and high power neutron sources</u>: The SCRF accelerating structures that are being designed for the electron and positron beams in the ILC can be applied to the acceleration of protons and nuclei, with some modification to account for the lower speeds of the heavier particles. Very intense proton and heavy ion beams are the key to opening new research capabilities for nuclear physics, astrophysics and materials science. SCRF linacs offer the best avenue for extending such sources to the multi-megawatt levels, and the upgrade to the LHC complex for higher luminosity is predicated on this technology. The advances being made in high-yield, high-gradient SCRF, RF power generation and beam handling for the ILC will translate directly into new capabilities for these proton and ion facilities.

Multi-GeV heavy ion linacs will be used to create highly unstable and rare nuclei and study their interactions. Studying new neutron-rich nuclei will help refine our understanding of nuclear structure. Some rare nuclei are involved in the reactions that occur during the collapse of stars and supernova explosions. Their interaction rates are not known, and the heavy ion accelerators will provide the data needed to understand these spectacular astrophysical events.

High power proton linacs constructed with ILC technology can provide very intense neutrino beams that can be directed to giant underground detectors capable of acquiring large data samples of neutrino interactions. These experiments will inform us about the mysteriously small mass of neutrinos, and the way in which they transform from one type to another. The payoff of this program should come with a determination of the asymmetry between neutrinos and antineutrinos, which could hold the key to understanding why our universe is built of matter and not anti-matter. The same high-power proton linacs could also serve as the source for very high-energy muons that could provide the basis for a next generation collider at the energy frontier beyond the LHC and the ILC.

Proton linacs for intense spallation neutron sources provide the probes enabling a wide range of studies of materials and biological properties. The current generation of high power neutron sources in Europe, Asia and the Americas are being built on the SCRF technology developed for particle physics accelerators. Future facilities will use the ILC technology advances as a springboard.

The spallation neutron sources are an excellent example of the application of fundamental tools from basic science to a wide range of socially important problems. Such applications include:

- Chemical studies of molecular structure using neutron scattering will facilitate new designer drugs, plastics and healthier foods.
- Study of complex fluids will enable better lubricants, detergents, paints, and time-release drugs.
- Detailed understanding of crystalline materials such as ceramics, semiconductors and metals should lead to new computer chips, batteries, high-temperature processing vessels and superconducting materials.
- Study of disordered materials will provide understanding of melting transitions and multi-component systems, giving improved techniques for extraction of oil from rock, hazardous waste handling or new materials for medical implants.
- High power neutron sources provide a tool that allows engineers to probe metal fatigue for structural safety tests, and to control corrosion.
- Deeper understanding of the complex mechanism of magnetism will lead to new permanent magnets for micromotor applications, and will help develop high temperature superconductors for practical use.
- New information on polymer structure and processing will give lighter materials for cars and airplanes, help devise better processes for environmentally risky fluorocarbon production, and aid in polymer blending and disposal technology.
- Neutron scattering from crystallized proteins complements the studies using XFELs by focusing on specific atomic species in biological molecules. These studies will help decipher the protein folding mechanisms and enzyme activity, aiding in the development of engineered pharmaceuticals.

Detector applications: The large physical scale of ILC experiments and the demand for very high spatial and energy resolution provide the impetus for new high precision detector technologies that allow scaling to larger areas of coverage, and cost reductions. The new detector technologies themselves derive from industrial advances, but their adaptation for high-energy physics use has traditionally driven detector innovations in other fields. We should expect that ILC development of small silicon pixel detectors of unprecedented resolution and low material density will find wide application. The very large area detectors needed to track particles in the outer reaches of large ILC detectors will also find application in other large detector arrays for nuclear physics, heavy ion research, and large area cosmic ray detectors.

Virtual control room: Remote operation of the ILC accelerator and detectors should allow dispersed experts to interact with the systems in real-time through a virtual control room. The Global Accelerator Network project has demonstrated prototypes for such operation, and this development should benefit all large-scale international technical projects.

7. Other benefits

Over the past four decades, high-energy physics experiments have become increasingly international. Collaborating scientists at current large experiments at particle colliders in the US are more than half from non-US institutes. The Large Hadron Collider experiments now starting in CERN are even more international in character. This growth of international collaboration has enabled nations whose wealth is insufficient to host major accelerator facilities to participate meaningfully, and to train the new generation of scientists that they need for domestic programs. A key benefit from these collaborations is the development of close cooperative working relationships and mutual trust, which later on may influence the relationships among nations when the scientists return to important government positions in their home countries. Within the large consortia, important regional partnerships are developed that link and help develop relations between scientists from countries such as India and Pakistan, Iran and Israel, Turkey and Greece, or China and Japan.

A very real benefit of accelerator research is the diffusion of highly qualified and innovative scientists and engineers into the industrial and commercial sectors of society, bringing new ideas and talent to a broad range of problems. This 'technology transfer of people' has tremendous impact on society generally.

High-energy physics has historically played an important role in capturing the interest of young people and encouraging them to seek careers in science and technology. It is not that high-energy physics is more important or ultimately more rewarding as a career path than other science and technology sectors, but that the questions asked are more immediately recognizable as simple, profound and understandable. Young people often relate more naturally to questions such as whether the forces of nature are unified into a single whole, how the universe came into being following the big bang, or what are the most basic building blocks of matter, than they do to the more detailed and complex questions of other areas of research. The ILC, in addressing these questions, will play an important role as a magnet to attract the new generation of scientists and engineers that society needs.

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