

The Potential Impact of ILC Technologies

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I Foreword

The mission of the International Linear Collider (ILC) is to explore the fundamental principle of nature, i.e. the material and energy constituting the universe, by observing reactions among fundamental particles at the extremely high energy attainable in the superconducting linear collider. For the ILC project to bring this challenging research program to fruition, it needs to develop substantially innovative breakthroughs in various systems/subsystems and common technologies indispensable for the designing, engineering and constructing of its research facility, and for the carrying out of its research activities.

Respective component technologies and systems/subsystems developed for advanced scientific research programs have always spilled over, as has typically been the case in high energy physics and nuclear fusion research facilities, to related industrial sectors, resulting in a coming into being of innovation in not only industrial but also consumer products. In other words, advanced scientific studies have given birth to numerous substantially new industrial sectors.

There are two types of such spin-offs. The first is a diversion of innovative technology originally developed for scientific research. A remarkable case in particle accelerators research, for example, is the spilling over of high performance electromagnetic steel specifically having been improved and fabricated as the iron core for accelerator magnets. Ever since, the electric machinery industry has combined the high performance electromagnetic steel with substantive progress in electromagnetic field analysis software to manufacture a variety of electric machinery with lower and lower power loss rates.

The second is a spilling over of newly developed systems/subsystems themselves and/or common technology thereof to related industry sectors. A conspicuous illustration of this case is seen in the expanding applications of the electron linac, which was initially developed solely for nuclear and high energy physics research, to the medical and non-destructive inspection industries. Another well-known example is the growing application of superconducting magnets, having been greatly improved as an outcome of its successive adoption in particle accelerators, not only to industrial sectors such as medical therapy, material research, and power generation/transmission, but also to a magnetic levitation, ultra-high speed public transportation system.

II Distinctive Features of The Superconducting Linear Collider Technology

In short, the ILC is comprised of the five subsystem/component technologies illustrated below.

- Generation of low emittance large current electron/positron beams,
- Electron/positron acceleration by high power RF systems,
- Electron/positron acceleration in an acceleration cavity requiring an interior highly polished by an ultra-clean surface treatment technique,
- Accomplishment of an instantaneous feed-back control of electromagnetic fields to rectify any distortion thereof, and
- Precise recording of the tracks of particles in a set of detectors produced by an ultra-precise assembly technique.

In addition, the ILC needs to be equipped with the systems/subsystems as listed below.

- Electron and positron generation,
- Damping rings,
- Acceleration cavities,
- Cryogenic modules,
- Klystrons,
- Modulator power supplies,
- Couplers,
- Beam positioning and beam shape monitoring devices,
- Computer systems, and
- Detector systems integrated with data-processing systems.

Each of the above-mentioned component technologies and systems/subsystems must be breakthrough innovations of currently applicable accelerator/collider technology.

Currently, national high energy physics research laboratories and universities throughout the world are enthusiastically exerting a great deal of effort in developing such component technologies and systems/subsystems. It is not necessary to mention that a wide variety of basic research is being carried out in support of these development efforts. The High Energy Accelerator Research Organization: KEK studies potential future ILC technology spin-offs by carefully considering the implications of this basic research.

III Superconducting Linear Collider Technology Spin-offs

In Chapter III, the KEK looks into anticipated future ILC technology spin-offs: (1) systems/subsystems, and (2) common technologies.

III.1 Overview of the Spin-offs: (1) Systems/Subsystems

The KEK hereinafter presents its overview on anticipated spin-offs of the systems/subsystems being compiled in compliance with the designation by FALC[1].

(1) Linear Accelerator System

A superconducting linear accelerator system is composed of a superconducting cavity, high power RF system, and a cryomodule. The conventional technology required for the design and construction of lower energy level and smaller-scale superconducting linear accelerators has yet to be essentially improved, and research institutes and relevant industries are jointly exerting extensive efforts to accomplish the necessary innovations. The important targets of such R&D include technologies needed for the industrial scale mass production of machinery and equipment at minimum production cost, and for the securing of the overall reliability of the entire system.

As soon as industries establish the technology required for the manufacture of a sufficiently compact, stable and reliable (Note: Presently, stable enough acceleration can be attained only under an electric field gradient less than, say, 20MV/m.) superconducting linear accelerator system that enables the construction and operation of a system at a reasonable cost, the large-scale spin-off of superconducting linear accelerator technology to a wide variety of industries such as, for example, electron or X-ray sources with lower power consumption rates applicable to medical therapy and non-destructive inspection equipment will start.

(2) High Gradient Superconducting RF (SCRF) System

In addition to the improvements mentioned above (1), higher gradient particle acceleration (exceeding 30MV/m) in a superconducting cavity will make the size of accelerators smaller and the rate of power consumption lower. This will make possible the industrial application of superconducting linear acceleration technology to superconducting X-ray free electron laser (XFEL) units and the energy recovery linac (ERL), both of which generate narrow wavelength light near the range of X-ray wavelength usable in wider fields such as experimental physics, bio-technology, new material development, high accuracy analytical instruments, environmental protection facilities, and so on.

As the technology is capable of accelerating protons and other particles as well, the above-mentioned improvements will open the door to the application of the technology to such physics research as neutrino detection units, transmutation facilities, and so on.

(3) RF Superconductivity Material Technology

(See III.2. (2) Material Technology)

(4) High Power RF System

High energy physics research institutes and industry have jointly established near-satisfactory levels of performance of klystron technology and modulator power supply technology, which generate L-band high frequency power for the ILC, lacking only confirmation of the sufficiently long durability of klystron.

Large-scale high power RF generation technology will certainly be applicable not only to the ILC but also to superconducting XFEL and ERL, and possibly further to remote micro-chemical analysis technology that is very valuable for environmental protection activities.

(5) Damping Ring System

Damping ring technology initially developed for the ILC is composed of such technologies as beam injection and extraction with a very high speed pulsed field, beam compression/control and super-high vacuum generation. These technologies will be applicable not only to the ILC but also to superconducting XFEL and ERL and no doubt will further spin-off to synchrotron radiation facilities, by which spatial resolution and time resolution of the facilities are to be remarkably improved.

(6) Precise Beam Control

The development of beam position and profile control technologies such as the cavity type monitor and the laser beam wire technique of nanosecond time resolution and nanometer spatial resolution are going to be finished rather soon for the ILC. The control technologies will be adopted as an essentially important basic technology not only in the next-generation accelerator but also as a spin-off to other industry sectors such as the electron microscope and super-highly-integrated semi-conductor manufacturing.

(7) Ultra Precision Large-scale Equipment Set-up System

For the generation of an electron beam with nanometer-level precision, it is vital to have a comprehensive set of techniques that enable the ultra-precise installation of heavy and gigantic machinery and equipment (an accelerator system, an acceleration cavity and other system/subsystem units) along a track more than 35 kilometers in length. In addition, an ultra-precision finishing technique is of critical importance in the construction, installation and alignment of a set of particle detectors. Further, vibration-resistant buildings are required for certain research facilities.

Technologies now under development that are aimed at assuring the above-mentioned conditions will certainly spin-off to the civil engineering and construction industries in general and to the integrated semi-conductor manufacturing industry in particular.

(8) Electron and Positron Sourcing System

While conventional thermionic electron guns generate a continuous electron beam, the ILC requires an ultra short pulse electron beam as its major objectives are to execute research experiments using polarized electron beams. For this reason, conventional electron guns do not satisfy the needs of the ILC. In response to this, the development of a polarized electron gun that generates polarized electron beams by irradiating a circularly-polarized laser light to a certain type of semi-conductor cathode for the purpose of the ILC has been proposed. More specifically, Titan-sapphire laser irradiation of a GaAs super-lattice semi-conductor cathode under electromagnetic field generated by direct electric current has been proposed.

Another candidate is an electron gun equipped with a GaAs photo-cathode installed inside the RF cavity. Currently, however, researchers are not yet fully able to obtain sufficiently stable polarized electrons from the RF electron gun.

Meanwhile, the ILC is planning to generate a positron beam by selectively extracting positrons under electromagnetic field from a mixture of electrons and positrons generated by the pair creation of the mixture by irradiating high energy γ -rays to target matter. As long as the injected high energy γ -ray is circularly-polarized, either the electrons or positrons so obtained are polarized. It is practical to generate high energy γ -rays either by passing high energy electron beams through a periodically fluctuating magnetic field produced in wiggler-type or undulator-type equipment or by Compton scattering between a high energy electron beam and a laser light.

These new electron/positron generation technologies will bring about as yet unknown scientific and industrial knowledge that will lead to innovative applications

in a variety of industries. Already, applications of the ultra-short pulse electron beam are expanding. For instance, the pulse radiolysis method, that makes it possible for the first time to look into extremely short-duration phenomena taking place between the ultra-short pulse electron beam and material, and Lithographie Galvanoformung Abformung (LIGA), that is capable of attaining high aspect-ratio material processing using extremely small electron beams, are already employed in industry.

Whereas until now conventional type semi-conductor electronic devices have been employed to execute the transportation and storage of information signals by utilizing a free electric charge over carrier, R&D on polarized electron guns is about to throw open the doors to a revolutionary new concept, spintronics, which will allow the exploration of remarkably new semi-conductor functions by utilizing the degree of freedom of the spin of electrons of carrier material.

(9) Accelerator Simulation

(See III.2. (4) Software Technology)

(10) Particle Detector System

Particles generated by the collision of a pair of primary particles (electron/positron, for example) are detected by a comprehensive set of many types of conventional detectors: Silicon detectors, solenoid electromagnetic detectors, wire chambers, scintillation counters, and different types of calorimeters. These detectors, however, have to be endorsed of capability that overwhelms conventional detectors in high detection speed, microscopic accuracy, high sensitivity, data-processing capacity and/or detection precision. The continuing joint endeavor to achieve improvements by physicists and the semi-conductor industry strongly suggests that an extensive counter-current spin-off of technological knowledge among the development partners over time will remain robust. As an outcome of counter-current spin-offs, an image analysis technique based on high-density pixels is set to provide valuable benefits to the development of an individual identification/authentication system.

Every particle reaction that takes place inside an acceleration cavity is detected by a group of detectors that outputs particle track information in an analogue signal via transmittal wire. This analogue signal is transformed to a digital signal and sent to a computer. The size of the track data is estimated to reach one gigabyte per second. High-speed processing of such massive data can be accomplished only through the appropriate coordination of the most advanced high-speed electronics circuit and data processing technology.

Semi-conductor devices to be installed in the various types of detectors ought to be resistant to all forms of radiation. The radiation-resistant semi-conductor devices, now in the developmental stage, will very likely spin-off to space science and industries that develop the instruments, materials and systems to be installed in space stations and space ships.

(11) Integrated Super Computer System

It is a well-known fact that the Internet world-wide-web (WWW) has been expanding as a tool of information exchange, particularly among particle physicists working on particle accelerators.

The ILC will invite particle physicists from around the world to watch the progress of the ILC research program, evaluate the detected track data of generated particles, and participate in the preparation of the ILC research program by means of counter-current information exchange through the Internet.

To pick out yet unknown fundamental particles from the track data of the different kinds of particles generated in numerous collision-events demands a terrifyingly massive quantity of computer data processing. To execute such data analyses, it is necessary to mobilize a considerable number of super-computers located throughout the world by connecting them with ILC facilities via the Internet. To make this concept a practical reality, the ILC needs to have an innovative computer system equipped with terabyte storage and gigabytes-per-second transmission capacities. Such a conceptual computer grid has already been put onto the planning board, and the development work involved is already under way. The volume of data to be ultimately collected in the system is predicted to be on a magnitude of petabytes.

Another important aspect of the data processing computer system is the need to build up a tight security system to protect the computer grid from external intervention. The intended computer grid system and the security system will certainly spill off to every industry throughout the world.

III.2 An Overview of Spin-offs: (2) Common Technologies

The KEK hereinafter presents its overview of anticipated common technology spin-offs.

(1) Material Technologies

Whereas existing accelerator research laboratories have adopted superconductivity technology mainly in the electromagnet component of their accelerators, the distinguishing feature of the ILC is the adoption of a superconducting cavity made of

niobium (Nb) alloy as the key component for particle acceleration. Several types of niobium alloy have already been tested and evaluated with fair success for worthy improvement in cavity performance. The improvement looks to be having a technical and economical impact on a wide variety of industries.

The niobium alloy continues to have several points that need to be addressed. One of these points is that a superconducting cavity made of Niobium alloy tends to become unstable in a region higher than 30MV/m, where the level of electric power input into the cavity and electric field gradient (acceleration electric field intensity) inside the cavity start local fluctuation. It is assumed that a field emission of electrons due to microscopic unevenness in the uniformity of the cavity surface and local concentration of the high-frequency electromagnetic field are responsible for the phenomena. To solve the problem more completely, more extensive surface treatment techniques such as chemical polishing, electro-polishing, high-pressure ultra-high-purity water rinsing and vacuum baking are being developed. Once the physical mechanisms of the problem are elucidated during the course of countermeasure development, an innovative jump in metal surface total cleaning technique will become possible.

The use of large grain niobium or single crystal niobium may be another effective countermeasure for the local fluctuation of electric field intensity in the acceleration cavity. In the course of carrying out chemical polishing, the intensity of the RF magnetic field exceeds that of the critical magnetic field strength time and again because of a microscopic surface effect consequential to the polishing process. This experience strongly suggests that the considerable advantage of adopting the large grain niobium or single crystal niobium technique.

Though it is still premature to attempt to forecast to which industries the niobium technology could spillover, heat- and corrosion-resistant metals, electronic devices equipped with controlled magnetic flux quantum, magnetism sensors, or superconducting computer elements may be prospective candidates.

(2) Measuring Technique

The demanded accuracy for set-up of the particle acceleration system of the ILC is $\pm 100 \mu\text{m}$, which is essentially identical to that demanded for conventional accelerators. The problem is, however, that the ILC requires the installation of a more than 35 kilometer long acceleration cavity, and the final alignment of the cavity is going to be done by beam-based alignment. In addition, new particle beam diagnosis techniques have been proposed, one for beam position monitoring by a cavity-shaped instrument with nanometer spatial analysis and nanosecond time analysis capabilities, and another for

beam profile monitoring by a laser wire monitor capable of non-destructive beam measurement. The combination of technology for generating highly accurate electron beams with the above-mentioned nanometer spatial analysis technique will no doubt yield great contributions to super-integrated semi-conductor manufacturing.

(3) Mechanical Assembling and Installation Technique

The currently available method for assembling the more than 35 kilometer long acceleration cavity of the ILC is to connect large numbers of unit cavity pieces made of niobium alloy to each other by electron beam welding. The technique has, however, several problems that need to be addressed. Electron beam welding requires a great deal of time and, as a consequence, consumes a lot of money for assembly. Moreover, the circular welding bead along the welding line on the inner surface of the cavity should be completely eliminated in one way or another to secure the uniformity of the acceleration electric field along the total length of the cavity.

These problems call for an effort to develop technology that will enable the fabrication of a seamless cavity. The saving of extremely precious niobium metal is another target of the continuing development activity. The direction of the development is to fabricate niobium/copper-clad pipe in the first step, followed by a drawing and hydroforming process for the pipe to get longer pieces of clad pipe. This sort of technical development is under way in industrial sectors, and the extensive countercurrent technical stimulation among industries is highly appreciated.

(4) Software Technology

Various electromagnetic field analysis codes have been developed for the purpose of accelerator beam track analysis, and the development of even more highly advanced simulation codes is currently under way for the establishment of ILC technology. The software will be applicable with great benefit for the tuning-up and evaluation of a variety of electron-beam-based industrial equipment such as mask-pattern formation simulation for semi-conductor manufacturing processes, critical-dimension scanning electron microscopes (CD-SEM) and scanning electron microscopes (SEM). In the field of medical therapy, the software has already been applied to the evaluation of a radiation dose at an irradiated part in boron neutron capture therapy (BNCT), and to proton and heavy ion irradiation therapy for different types of cancer.

General-purpose electromagnetic field analysis software is used to design the shape of the superconducting acceleration cavity and find the cavity design most suitable for extensive electric field acceleration. The software has been applied for the

purpose of minimizing the rate of eddy current loss in different kinds of electric power machinery and equipment, and for eddy current testing (ECT) purposes. Quite recently, the software has been applied for the purpose of simulation/evaluation of electromagnetic compatibility (EMC) essential for any piece of electric machinery, the design of electric machinery that clears the upper limit of electromagnetic interference (EMI) to the human body and also securing sufficient electromagnetic susceptibility (EMS) to protect the function of a piece of electric machinery from interference by electromagnetic waves generated by other electric equipment located close by.

III.3 Summary of Spin-offs of the Superconducting Linear Collider

The summary of the aforementioned spin-offs of the superconducting linear collider (systems/subsystems in III.1 and common technologies in III.2 above) is illustrated in Table 3.1 attached hereto.

IV Details of Expected Spin-offs

IV.1 Scope of Detailed Study

Spin-offs of ILC technologies are summarized in Table 3.1. Spin-offs shown in the table are those that are relatively near to actualization. In this chapter we focus on a more detailed study through potential spin-offs from the table. We decided the scope of the study based on the following criteria:

- (1) We limited the scope of study to the spin-offs of new ILC technologies, excluding those of conventional accelerator technologies in general.
- (2) The ILC technologies, whether electron acceleration or ion acceleration, have an impact on the development of next-generation accelerators. For our study, we make no mention of the impact on the accelerators themselves.
- (3) We do not consider spin-offs already clearly expected for other scientific technology fields, industrial sectors or those already in use; namely, actualized spin-offs.
- (4) Further, we don't consider spin-offs of linear collider technologies adopting X-band RF acceleration, though they belong to linear accelerator technologies.
- (5) In conclusion, we put forth herein potential spin-offs of ILC technologies to other scientific technology fields or to industrial sectors that have not yet been actualized.

Table 3.1 Spin-offs of ILC Technology

	ILC components/subsystems	Technologies to be developed for construction of the ILC	Component technology/subsystems to be developed	Product/market image for spin-offs (excluding those directly related to accelerators)
1	Linear electron accelerator system	Superconducting acceleration tube High-power RF system Cryogenic module	Superconducting electron accelerator Compton scattering γ -ray and X-ray sources	Cancer therapy by radiation (X-ray) Nondestructive testing systems such as X-ray, CT, etc. Medical diagnostics transmutation of long half-life nuclear waste High-reliability space equipment Spallation neutron source
2	High gradient superconducting RF acceleration system	High gradient cavity Electron beam welding 2k Helium cooling and thermal insulation	High-capacity superfluid cryogenic system	Physical and chemical apparatuses (analysis, structural analysis of proteins) Environmental protection facilities Material analysis system Irradiation units for food Sterilization by electron/X-ray Energy Recovery Linac Exhaust Gas Desulfurizer Electron beam welder Ultrahigh vacuum generation unit
3	Superconducting RF material technology	Metal surface cleaning Discharge suppression Hydraulic molding	High-purity metal materials Bimetallic bonding New niobium materials	Semiconductor manufacturing system High power equipment New heat-resistant materials Tantalum Cryogenic equipment Functional materials
4	High-power RF system	Klystron Coupler Modulators power supply Wave guide	Ultra-short-pulse power supply	Sterilization by electron beam Short-pulse klystron Magnetron
5	High-brightness accumulation ring system	Beam control Ultrahigh vacuum	High-brightness light source Aluminum vacuum chamber	Microanalytical system Ultrahigh vacuum generation unit Semiconductor lithography High-brightness radiation light facilities
6	Precise beam control system	Charged particle control Suppression of ion/electron clouds Beam position monitor (BPM)	Decentralized autonomous control	Cancer therapy by proton beam radiation Cancer therapy by heavy particle beam radiation Electron microscope Semiconductor manufacturing
7	Large scale ultrahigh precision installation system	High precision relocation of heavy load Special design to suppress vibration	Buildings with suppression of microvibration	Precision transfer system Semiconductor manufacturing system
8	System for electron/positron source	Femtosecond photocathode GaAs superlattice cathode	Polarized electron / positron source Wiggler Undulator	Equipment applying electron beams Spintronics
9	Accelerator simulation	Electromagnetic field analysis Beam simulation	Software for high precision electromagnetic field analysis	Electromagnetic equipment (transformers, current transformers) Electromagnetic shielding Designing with electromagnetic compatibility Designing of equipment with electromagnetic interference Evaluation of electromagnetic sensitivity Electron microscope
10	Particle detector system	Semiconductor detector ultra-fine machining Gas Electron Multiplier	Large scale underground cavity	Medical image diagnostics High-speed nuclear medicine PET (Positron Emission Tomography) Authentication system
11	Large-scale computer system	GRID network system	Supercomputer	Information security system Authentication system Network computing

In most cases, the more high-tech and advanced the developed technologies are, and the earlier the stage of development is, the more difficult it is to foresee what new field the developed technologies might spin off to or how the technologies might spin off to other existing areas. However, to select key technologies for which spin-offs are not yet actualized and carefully examine the potential impact is a very effective way to minimize the time necessary for realization of the technology spin-offs.

From such a viewpoint, this chapter takes up (1) Photo-cathode RF electron guns (2) Laser Compton scattering beam sources and (3) Polarized electron beams. In our examination, we carry out a hearing from academic and industrial societies to obtain a more up-to-date picture of the field beyond the information already published in the literature.

IV.2 Spin-offs of ILC Technologies

(1) Photo-cathode Electron Guns

As high luminosity is required at the collision point in the case of the ILC, it is necessary to generate large current, ultra-short pulse, low emittance electron beams at the stage of beam generation. Meanwhile, there are kinds of electron guns, such as thermionic cathode guns, photo-cathode guns, and so on. Thermionic cathode guns collect thermal electrons with speed in random directions, causing a large emittance already at the time of collection, which makes it impossible for this type to satisfy the low emittance condition required for the ILC. On the other hand, photo-cathode guns offer small thermal emittance, though the emittance due to the space charge effect is relatively large due to the fact that electrons have almost no speed at the time of generation, which can, however, be suppressed by applying an accelerating electric field immediately after generation. Further, the short pulses inherent to irradiated laser beams result in the short pulses of electron beams. Therefore, photo-cathode electron guns are suitable as the high-quality electron beam source mentioned above. Furthermore, we can give versatile characteristics to the generated electron beams by devising appropriate ways to process irradiated laser beams. In this way, photo-cathode guns have become necessary as a source of electron beams in various fields, including XFEL and ERL, requiring high-quality electron beams that have resulted from the development of cathode materials with high-quantum efficiency as well as the improvement of laser technologies, and their application is being carefully studied.

As the examples of electron beam application are too numerous to mention we show an example of a method of therapy under development in the medical field [2, 3].

Intensity Modulated Radiation Therapy (IMRT) is a modern radiotherapy method

[4]. In the case of normal radiotherapy, as the normal tissues are irradiated together with the cancer cells at the time of irradiation, the radiation dose is limited by the amount of radiation normal tissues can endure. The result is that the irradiation to the cancer cells tends to be insufficient. On the other hand, in the case of IMRT, radiation is provided from various directions at various intensities based on optimum radiation conditions derived from computer simulation. In doing so, a sufficient radiation dose is provided for cancer cells only, without causing damage to normal tissue. As a new method of such IMRT, it is proposed to generate radiation with optimum intensity and shape by creating electron beams with modulated intensity and shape to bombard targets. For the creation of such electron beams, photo-cathode RF electron guns are used; namely, electron beams with the appropriate profiles are to be created by irradiating optically processed laser beams on cathodes.

More effective aspects of this method as compared with conventional IMRT are shown as follows:

1. Quicker beam shaping

In this method, beam shape and intensity are modulated directly by processing laser beams, and both intensity modulation and the shaping of beams are performed at the same time. In the conventional method, however, the scope of irradiation and intensity are adjusted by manipulating more than 100 lead sheets mounted on the irradiation nozzles under computer control. Therefore, we think that beam shaping can be made quicker with this method as compared with conventional methods.

2. Easier synchronization with respiration by irradiation of pulse beams

By pulsing electron beams, X-ray beams to be applied to patients can also be pulsed and irradiation synchronized with respiration becomes easier, resulting in potentially safer therapy.

The outline of the unit is shown in Figure 4.1. Electron beams with modulated intensity and shape are generated by irradiating the properly processed laser beams on cathodes. Such electron beams are converted into X-ray beams by collision with targets after acceleration and are irradiated to cancer cells. This method can be applied on account of the following characteristics of photo-cathode electron guns:

1. Generated electron beams can be controlled by processing and controlling incident laser beams.

2. Generated electron beams have low emittance; namely, they do not diffuse much.

The shape and intensity of electron beams generated by processing incident laser beams by means of photo-masks are shown in Figure 4.2. The left figure shows integrated cross type electron beams and the right figure shows multi-spot type electron beams. Cross type beams show thin branches clearly. As to multi-spot type beams, the total size is 3.2mm, with one spot size of about 1mm and a gap of 0.3mm, and the borders between the positions where beams are and are not show a clear contrast with no blurring, which makes the generated X-ray beams suitable for attacking cancer cells only. Meanwhile, if beam shapes are generated with the accuracy shown in Figure 4.2, the spatial resolution required for medical purposes can be achieved. Though development has progressed for stage electron beam generation only, we expect that almost the same shape of X-ray beams can be generated by the collision of electron beams with targets that are very thin. In order to get X-ray beams with more accurate shapes, we think it necessary to process the incident laser beams further based on feedback information.

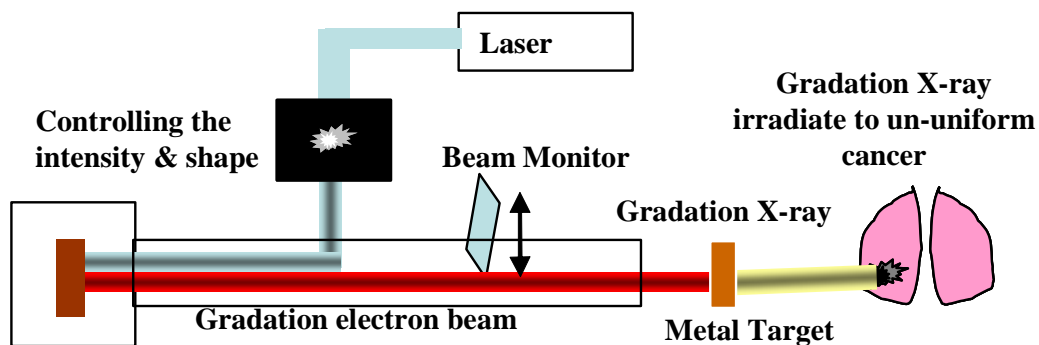


Figure 4.1 New IMRT apparatus using a photo-cathode RF electron gun [2, 3]

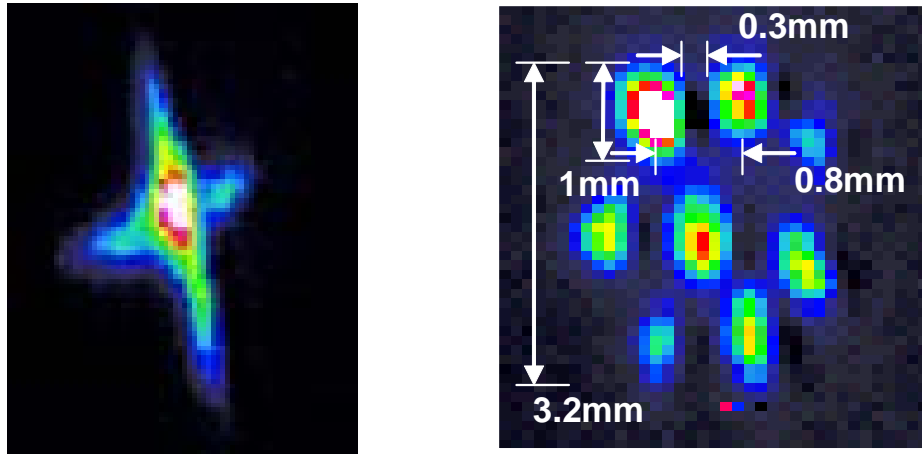


Figure 4.2 Processed electron beam shape
(Left) Cross type, (Right) Multi-spot type [2, 3]

(2) Application of Laser Compton Scattering Beam Source

There are two methods used to generate polarized positron beams proposed for the ILC. In any case, circularly-polarized γ -ray beams are to be generated, and then polarized positron beams are to be generated through pair production. The one is a method to generate circularly-polarized γ -ray beams by getting electron beams (150GeV) before collision through a helical undulator, and the other is a method to generate circularly-polarized γ -ray beams by means of inverse Compton scattering by bombarding circularly-polarized laser beams on electron beams (several GeV). The latter method is attracting special attention because of the advantage that electron beams used for collision with laser beams can be low energy (several GeV), which can be created separately from electron beams to be used for collision with positron beams, enabling execution of testing and maintenance of the positron side independent from those of the electron side.

Such γ -ray and X-ray sources applying laser Compton scattering have become possible as a result of the recent development of high-power laser technologies and high-level laser accumulation technologies (Super-cavity).

Laser Compton γ -ray and X-ray beams have high mono-chromaticity, variability of energy and short-pulse characteristics. As for intensity, they have attained a certain level though they are still under development. Furthermore, they offer the advantage of possible downsizing as X-ray sources. Based on such advantages, it is expected that the laser Compton γ -ray and X-ray sources will find various industrial applications. Application examples are shown below.

a) Application of laser Compton γ -ray sources

The following applications are proposed:

1. Segregated disposal of nuclear wastes
2. Transmutation of nuclear wastes

Details on each item are shown as follows:

- Application to segregated disposal of nuclear wastes

It is estimated that the treatment and disposal of nuclear wastes within Japan will reach a cost of about 3,000 billion Yen [5] in 2020, and safe as well as low-cost disposal methods are being sought.

As for the disposal of nuclear wastes, if proper segregation can be achieved based on the identification of nuclides and their respective concentration by means of non-destructive testing, the cost of disposal can be minimized and cost saving can be realized. For this purpose, the application of photonuclear resonance scattering of laser Compton γ -rays and radioactive nuclei to segregation of nuclear wastes [6, 7] has been proposed. That is to say, nuclides and their respective concentrations are identified based on the peak positions of the photonuclear resonance scattering spectrum of the radioactive wastes through the utilization of the high monochromatic characteristics and energy-variability of laser Compton γ -rays.

Other than laser Compton γ -rays, several methods to probe nuclear wastes are also proposed. One is to detect the neutrons generated as a result of the fission reaction of thermal neutrons created in waste by irradiated fast neutron beams and radioactive nuclei contained in the waste. Another method is detecting neutrons generated as a result of fission reactions of radioactive nuclei contained in the waste caused by broad energy γ -ray irradiation. However, in such methods it is not possible to identify ratio of nuclide. Only when the ratio is given, such methods can measure concentration of radioactive nuclei.

On the other hand, the laser Compton γ -ray can identify almost all nuclides including stable isotopes, enabling an appropriate segregation of wastes.

A high-intensity γ -ray source using ERL and laser Compton scattering as shown in Figure 4.3 is proposed. On the electron side, electron beams are created by photo-cathode electron guns and accelerated by ERL. On the laser

side, fiber lasers that can be made compact and stable are used and the beams are strengthened by means of super-cavities. The strengthened laser beams are to be bombarded on the accelerated electron beams to generate high-intensity γ -ray beams by inverse Compton scattering. The parameters of the designed device are shown in Fig.4.4. According to the design, γ -ray fluxes $10^8 \sim 10^9$ times larger than those of conventional γ -ray sources can be obtained. By recovering and reusing electron energy, ERL can accelerate large-current electron beams continuously and create high-intensity γ -ray beams meeting the requirement of the intended use.

Supporting the ERL technologies are the superconductivity technologies developed over the past few years, making operation at viable cost possible for industrial application. That is to say, as a result of the growth of ERL technologies including super-conducting cavities, γ -ray sources practical for industrial use can now be realized.

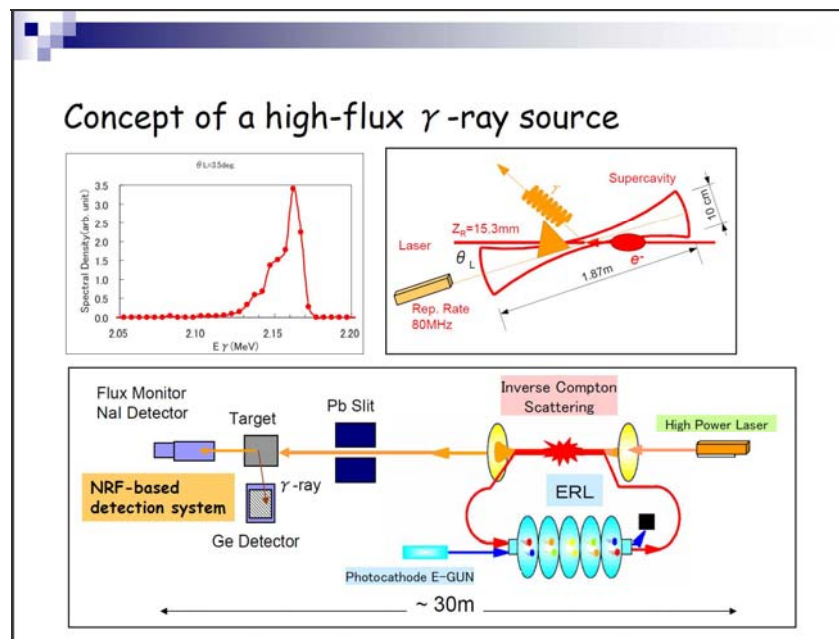


Figure 4.3 Laser Compton γ -ray source applying ERL[6]

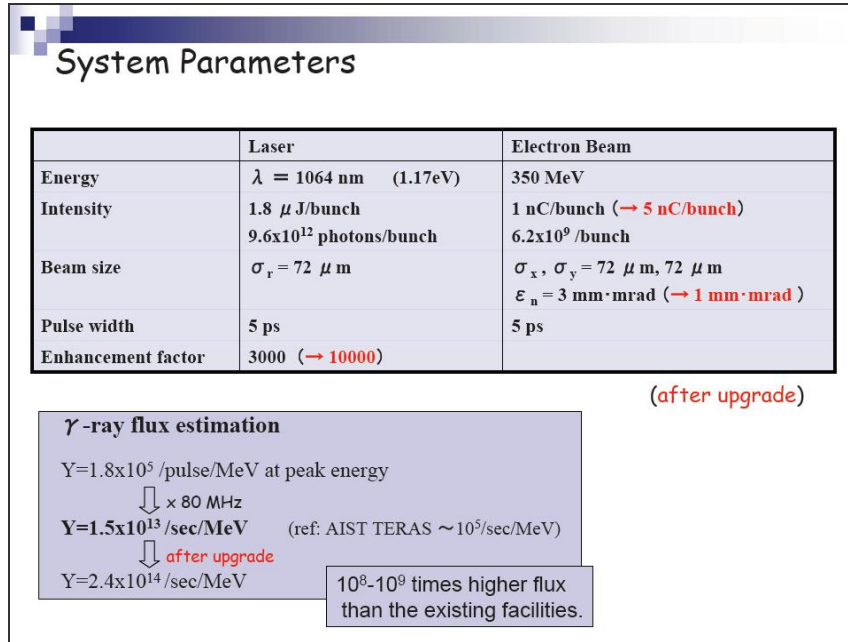


Figure 4.4 System parameters for laser Compton γ -ray source applying ERL [6]

- Application to Transmutation Nuclear Wastes

As an example of the transmutation of nuclear wastes[8], a method has been proposed to transmute contained nuclei into stable nuclei by means of giant nuclear resonance caused by bombarding high-intensity γ -ray beams on nuclear transmutation targets. Energy dependence of the cross section of a typical giant nuclear resonance and the outline of a typical nuclear transmutation treatment facility are shown in Figure 4.5. γ -ray with the energy and spectrum width necessary for resonance is created owing to the high monochromaticity of the laser Compton γ -ray mentioned. Experiments are under way for this purpose using large-scale accelerator facilities.

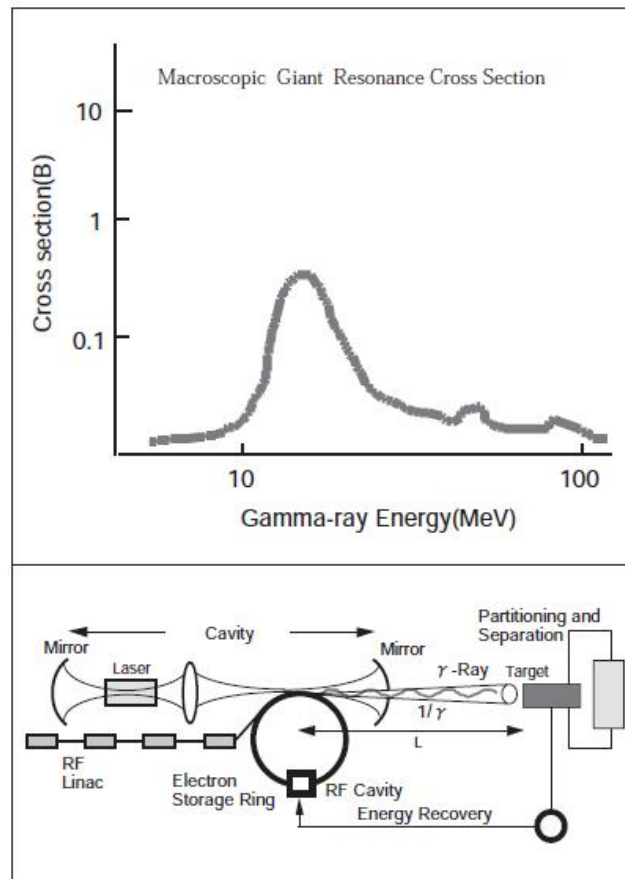


Figure 4.5 (Upper) Cross section of Giant Nuclear Resonance
(Lower) Laser Compton γ -ray generation unit for nuclei extinction treatment[8]

b) Application of laser Compton X-ray sources

Many applications of laser Compton X-ray sources have been devised in the medical, semiconductor and various other fields, and units for the structural analysis of proteins have been realized. [9].

- Application to the semiconductor field

In the semi-conductor field, application of X-ray sources (wave length: around ~ 10 nm) for lithographies necessary for creating ultra-highly integrated circuits is under study. A high output of 10W to 100W is required for X-ray beams for lithography. If lithography with 10nm wave-length is commercialized, the integration level of semiconductors can be increased to 100 times the current level. Generation of ultra-high strength X-ray beams by means of the inverse Compton method combining super-conducting linacs capable of large current

acceleration and super-cavities has been devised. [10]

- Application to X-ray microscope for vital observation

An application for a new generation X-ray microscope has been devised. It generates soft X-ray beams in the range of 250eV~500eV (the so-called "Water Window") which are not absorbed in water, while being absorbed greatly in proteins and nucleic acids by means of laser Compton scattering [11]. The application of X-ray beams of "Water Window" range does not require the drying of proteins and enables vital observation. Furthermore, such microscopes offer the following advantages based on laser Compton X-ray beam characteristics:

1. Due to short-pulse characteristics, image blurring as a result of damage and thermal diffusion caused by X-ray beams is reduced.
2. It is possible to observe the contrast changing X-ray wave-length owing to an energy variability feature.
3. Microscope unit downsizing is possible.

Development is under way to commercialize these as biomicroscopes.

- Application to compact performance evaluation units for magnetic materials

We consider it possible to apply these technologies to circularly-polarized X-ray sources using circularly-polarized lasers. For example, we expect that R&D for new magnetic materials thus far executed only in the beam lines having helical undulators in large-scale synchrotron radiation facilities can be produced in company laboratories owing to the downsizing of the units. As a result of R&D for magnetic materials, drastic density growth in magnetic data storage units (hard discs) is expected.

- Application to on-site non-destructive inspection units

As apparatuses for laser Compton X-ray sources can be made compact, application to on-site non-destructive testing units for examination of corrosion and erosion within large plants seems to be promising.

Furthermore, these apparatuses have potential for use in the non-destructive testing of thick concrete, and application to earthquake resistance diagnostics in old buildings is under study. As the remaining life of many old concrete buildings in Japan is regarded as an issue, a very large demand for portable

generation units for hard X-ray beams with high penetration force is expected.

- Application to medical fields

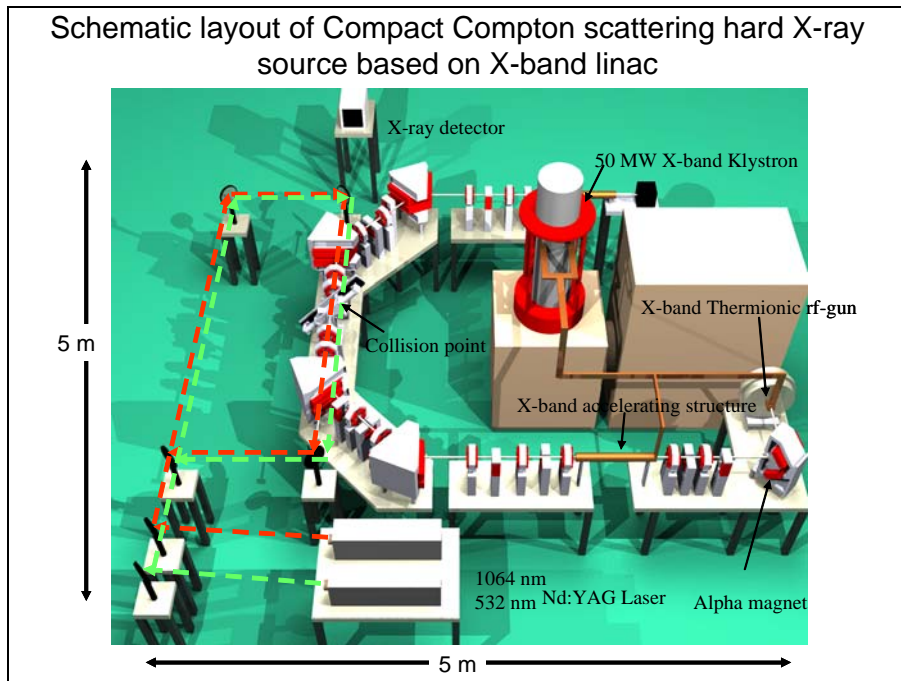
In medical fields, application to medical X-ray sources is under study. The majority of current medical-use X-ray sources generate X-ray beams by bombarding electron beams (generated by electron linacs) on targets. Such X-ray beams have broad energy width and, therefore, a large volume of contrast dye must be administered to obtain X-ray images of sufficient quality for diagnostic use. For example, the diagnosis of angina and cardiac infarction requires the deep insertion of catheters toward the vicinity of the heart and to the injection of a large volume of contrast dye. This places a great physical strain on patients and can cause a potential threat to life. Furthermore, as a large radiation dose is needed, X-ray exposure becomes another issue.

On the other hand, the application of laser Compton X-ray sources yields clear X-ray images with the administration of a small quantity of contrast dye through intravenous injection, imposing a smaller physical burden made possible by monochromatic X-ray beams with good directivity and the appropriate intensity of these sources. In addition, the X-ray exposure issue is resolved because of the smaller doses required. Dynamic X-ray imaging without the need for catheters has been carried out experimentally at large scale synchrotron radiation facilities with fair results; however, it has not been applied in actual clinical settings due to the necessity of using large-scale synchrotron radiation facilities. As the application of laser Compton X-ray sources makes the apparatuses compact, application at local medical centers becomes possible. Currently, medical X-ray sources at many of local medical centers are aging and becoming obsolete, and new high-performance X-ray sources are being sought. If compact and low-priced medical-use laser Compton X-ray sources are developed and placed on the market, they can be expected to see wide use in the medical field.

In the pharmaceutical field, thus far, the structural analysis of proteins, for example, has been undertaken at large-scale synchrotron radiation facilities such as SPring8 and, depending on the licensing conditions, some licensees have been obliged to disclose the contents of their developments partly to the licensors. If compact and low-priced laser Compton X-ray sources for structural analysis of proteins become widely used, R&D within the closed environment of the companies becomes possible.

An example of the apparatus under development as a medical-use laser Compton X-ray source and its parameters are shown in Figure 4.6[12,13]. In this apparatus, electron beams (35MeV) are created by a thermionic electron gun, and X-band linac and laser beams are accumulated and multiplied by 4 pairs of mirrors, generating X-ray beams by Compton scattering. As shown in Figure 4.7, the apparatus is designed to use two kinds of lasers, 532nm and 1064nm, to obtain an energy-variable X-ray source ($\leq 42.9\text{keV}$).

(a)

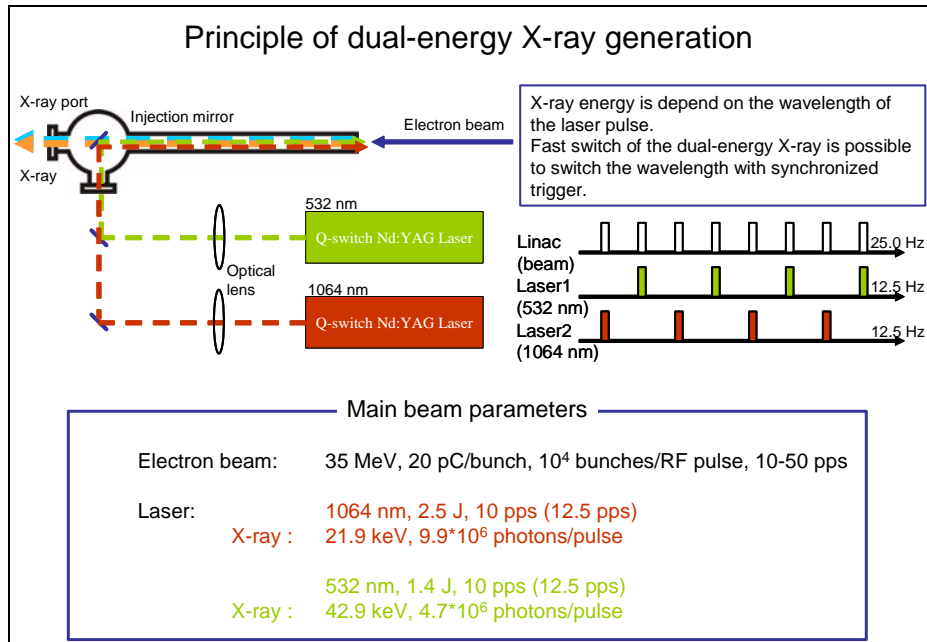


(b)

Performance of compact hard X-ray source	
Electron beam	Frequency : 11.424 GHz (X-band) Electron gun : 3.5-cell thermionic RF-gun Energy : 35 MeV Charge : 20 pC/bunch Micropulse duration : ~ psec Multi-bunch : 10^4 bunches/RF pulse RF pulse length : 1 usec
Laser	Q-switch Nd:YAG laser: 1064 nm, 2J/10ns, 10 pps 532 nm, 1.4 J/10 ns, 10 pps
X-ray	Energy : 21.9 keV (1064 nm), 42.9 keV(532 nm) Intensity : 10^7 photons/sec

Figure 4.6 An example of a medical-use laser Compton X-ray source
(a) System layout (b) System parameters [13]

(a)



(b)

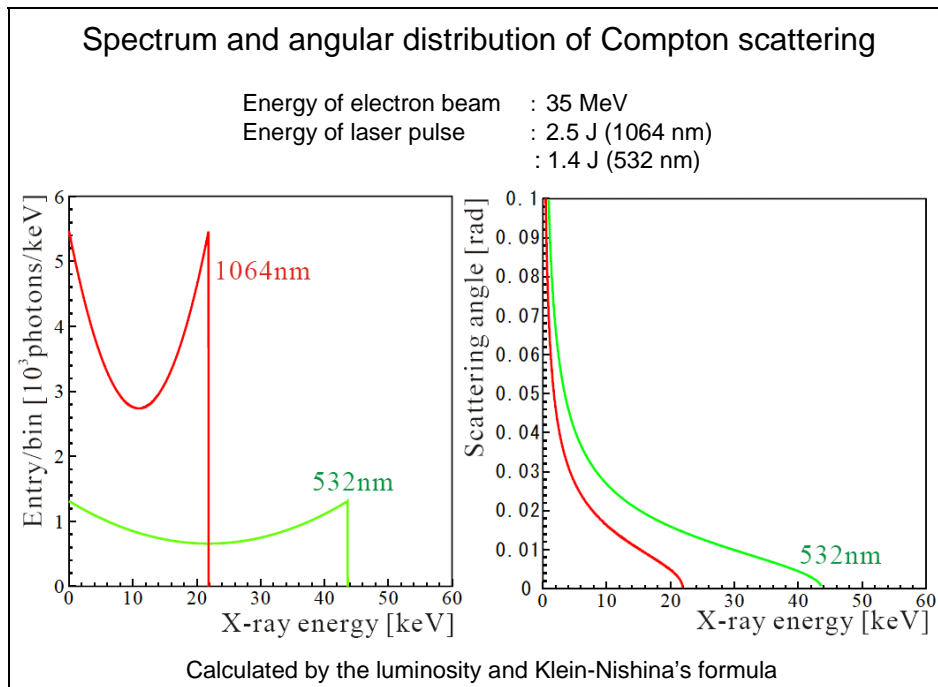


Figure 4.7 (a) Principle of X-ray generation and (b) characteristics of generated X-ray beams of the system shown in Figure 4.6 [13]

(3) Application of Polarized Electron Beam

The physics research programs to be carried out in the ILC require a polarized electron beam with high spin-polarization. In order to generate the beam, a super-lattice photo-cathode was developed (see [14], [15], [16]). A highly polarized electron beam can be obtained by irradiating a circularly polarized laser on a super-lattice photo-cathode. The ILC plans to use electron guns that employ GaAs-GaAsP super-lattice photo-cathodes (DC electron gun).

Industries plan to make use of a polarized electron beam for the purpose of performance evaluation and dynamic observation of the formation process of magnetic material (particularly, high performance nanometer-sized magnetic devices such as those made possible through spintronics). Industries eagerly await good news concerning the completion of a polarized electron beam device with a sufficiently satisfactory level of performance and reliability for use in industrial practice for the development and evaluation of improved HDD and memory devices, the current global market size for which being estimated at some ¥10 trillion (US\$100 billion) per annum. More detailed descriptions of instrumentation equipment based on the polarized electron beam are given below.

- Spin-polarized scanning tunnel microscope (Spin-polarized STM)

The TMR element (see [17], [18]) is an elemental component of newly developed memory devices such as the MRAM and next generation magnetic heads. The element is composed of two layers of electrodes with a thin insulation layer in between. The one electrode is magnetized to a fixed direction while the other is able to change its magnetic direction by which the electrode generates “0” or “1” signals. TMR elements have become increasingly small and extensively integrated. Therefore, for the purpose of making an assessment of the element’s characteristics and performance, it is necessary to make an observation of the internal structure of an element having a thickness of only 20nm. Currently, such assessment is carried out using a spin-polarized STM, the probe of which is at present composed of magnetic material made of an iron alloy. The problems with the iron-made probe are, firstly, that it is possible to send a spin-polarized tunnel electric current only to the one direction dictated by the direction of magnet of a probe and, secondly, the magnetism of the probe influences specimens.

Generating a polarized electron beam with high spin-polarization by

irradiating a circularly polarized laser on a super-lattice GaAs-GaAsP photo-cathode has innovative advantages in comparison with using an iron-made probe as 1) the angle of spin-polarized electron beam can be changed freely to any direction, and 2) specimens are not influenced by the magnetism of a probe as the probe has no magnetism at all. It may be worthwhile to note that the above-mentioned technique has something in common with another technique from ILC technology, the way a spin-polarized electron beam is generated from a photo-cathode DC electron gun.

The GaAs super-lattice photo-cathode probe as it is currently deteriorates rather quickly and, therefore, industrial application of the technique it is at present premature. In addition, it is pointed out that the method to generate a spin-polarized electron beam by irradiating a circularly polarized laser has the following problems: 1) the position and intensity of the beam tends to deviate from an intended value when the angle of irradiation of the laser is altered; and that 2) the laser irradiating a specimen causes an additional spin-polarization depending on the circularly polarization angle of the specimen. To resolve these remaining issues, further improvements in the technique are necessary.

- Electron Microscopes

A typical example of the application of electron microscopes to magnetic material is the spin-polarized scanning electron microscope (spin-polarized SEM) (see [19], [20]). This application is made by means of observing the spin polarization of the secondary electron generated by irradiating a non-polarized electron beam to a magnetic material.

On the other hand, there is the recent development of another type of electron microscope that uses a spin-polarized electron beam itself as its probe.

It is possible to build a spin-polarized low energy electron microscope (SPLEEM) that irradiates a spin-polarized electron beam by adopting a super-lattice photo-cathode as the cathode of the microscope. Once this becomes a reality in the near future, it may become possible to watch the process of the formulation of high performance nano-magnetic devices in a dynamic manner. The LEEM (see [21]) is a device used to observe via a CCD camera an image of an interference phenomenon of the elastic scattering of

electrons in the 180-degree backside of a specimen caused by the irradiating of low (a few eV) energy electrons (see Figure 4.8 below for an illustrative overview of the LEEM). In Figure 4.8, an electron beam irradiated from the left-lower side of the illustration is slowed down to a low energy state by means of electric field before hitting a specimen perpendicularly. Then the electron beam elastically scattered toward 180-degree backside of the specimen is accelerated by the electric field and detected at the right-lower side of the illustration.

If a spin-polarized electron beam (see [22]) is used instead of an electron beam, it would become possible to dynamically observe the surface structure of the magnetic domains of the specimen, provided, however, that the luminosity of the spin-polarized electron beam would be sufficiently high to make the dynamic observation, which has, until recently, not been the case. As a result of the very recent improvement of the method of irradiating of a laser to a super-lattice photo-cathode it has become possible to obtain a spin-polarized electron beam possessing a sufficiently high luminosity, and this technique has finally reach the stage of practical industrial application. It may worth mentioning that industries began to study the use of a spin-polarized electron beam not only in the LEEM but also in transmission electron microscopes.

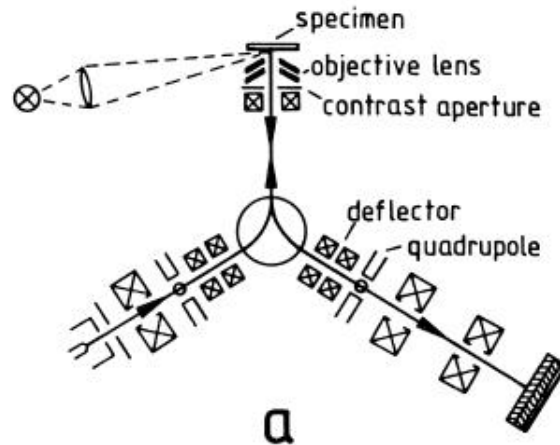


Figure 4.8 The Principle of a Low Energy Electron Microscope (LEEM)
(See [18])

- *Spectroscopy*

Spectroscopy which makes use of a spin-polarized electron beam is spin-polarized inverse electron spectroscopy (see [23]).

In spin polarized inverse electron spectroscopy, a spin-polarized monochromatic electron beam irradiates a specimen and a spectroscopic instrument detects the light emitted by the electron as a result of a dipolar transition of the electron into a lower energy level in a non-possessed state so as to obtain information on the state of the spinning of the electron in the non-possessed state. The information to be acquired is extremely valuable and important for the development of a new type of magnetic material and for the attainment of an improvement in the performance of magnetic devices because the non-possessed state of an electron is largely determined by the excited state of the material. This is one example in which the source of spin-polarized electrons contributes to industries either directly or indirectly. As the performance of these instruments improves (see [24], [25]), analytical observation of magnetic material is carried out (see [26]) by a wide variety of industries expecting increasing applications of this instrument in coming years.

V Concluding Remarks and Acknowledgements

The mission of the ILC is to observe reactions among fundamental particles at an extremely high energy level attainable only at its superconducting linear accelerator/collider research facility. For the research project to bring this challenging research program to fruition, the physicists and R&D personnel working for industries concerned need to develop substantially innovative breakthroughs in various component technologies and systems/subsystems indispensable for the designing, engineering and constructing of the research facilities, and the carrying out of research activities. R&D efforts are going to consume massive human, material, financial, and time resources on a global scale. It is anticipated, therefore, that the fruits of the R&D will spill off to a wide expanse of industries and will be used as starting points for the innovation of industries and, consequentially, to secure the total welfare of the human societies of the world.

In view of the above, the KEK looked into the impact of potential spin-offs of ILC technology to various industries, and also studied the beneficial information and expected extent of the potentiality of the spin-offs of several of the important technologies. The staff of the KEK and its consultants took time to conduct interviews with a number of physicists and R&D personnel working in industry so as to acquire not only up-to-date information on the actual current status of R&D based on the spin-offs, but also overviews of future possibilities and the anticipation of those scientists and engineers.

The KEK believes that this report is going to help to considerably shorten the period of time needed for spin-offs of the technologies and systems/subsystems to industries of the world by providing the industries with valuable knowledge on current and future possibilities.

The KEK would hereby like to express its profound thanks to the physicists in high energy research, the staff of consultants to the KEK, and the R&D staff of industries for their provision of extensive and valuable cooperation in the preparation of this report.

References

- [1] FALC Study of ILC technology benefits
- [2] T. Kondoh, J. Yang, Y. Yoshida and S. Tagawa: “Electron Beam Pulse Processing Toward the Intensity Modified Radiation Therapy (IMRT)”, Proc. of EPAC2006, Edinburgh, Scotland 2334-2336 (2006)
- [3] T. Kondoh, H. Kashima, J. Yang, T. Yamamoto, Y. Yoshida, and S. Tagawa: “Electron Beam Modulation by a Photocathode RF Gun toward the High Performance Intensity Modulated Radiation Therapy (IMRT)”, A 24, 2007 Annual Meeting of the Atomic Energy Society of Japan
- [4] http://www.kuhp.kyoto-u.ac.jp/~rad_onc/Public/state_of_art/IMRT.htm
- [5] <http://www.numo.or.jp/faq/qa07.html>
- [6] http://beam.spring8.or.jp/beamphysics/proceedings/Proceedings_2006/17_kikusawa.pdf
- [7] R. Hajima, N. Kikusawa, T. Hayakawa, and E. Minehara: “Proposal of an ERL-based High-flux Gamma-ray Source for Radioactive Waste Management (I) Conceptual design of the system” A 11, 2007 Annual Meeting of the Atomic Energy Society of Japan
- [8] <http://www.ilt.or.jp/cross/no145.pdf>
- [9] <http://www.lynceantech.com/>
- [10] http://adweb.desy.de/mpy/FLS2006/proceedings/TALKS/PLT05_TALK.PDF
- [11] R. Moriyama, K. Hidume, T. Saito, K. Sakaue, Y. Hama, A. Oshima, and M. Washio: “Development of High Brightness Soft X-ray Source Based on Inverse Compton Scattering” Proc. of EPAC2006, Edinburgh, Scotland 166-168 (2006)
- [12] <http://www.nuclear.jp/~kiki/uesaka/pdf/X-band.pdf>

- [13] M. Uesaka, F. Sakamoto, A. Fukasawa, H. Ogino, T. Yamamoto, and D. Meng: "Multi-Beam Compton Scattering Monochromatic Tunable Hard X-ray Source", *International Journal of Modern Physics B*, Vol. 21, Nos. 3&4 pp.559-571(2007)
- [14] T. Omori, Y. Kurihara, T. Nakanishi, H. Aoyagi, T. Baba, T. Furuya, K. Itoga, M. Mizuta, S. Nakamura, Y. Takeuchi, M. Tsubata, and M. Yoshioka: "Large Enhancement of Polarization Observed by Extracted Electrons from the AlGaAs-GaAs Superlattice", *Physical Review Letters* Vol.67 (1991), pp.3294-3297
- [15] T. Omori, Y. Kurihara, Y. Takeuchi, M. Yoshioka, T. Nakanishi, S. Okumi, M. Tsubata, M. Tawada, K. Togawa, Y. Tanimoto, C. Takahashi, T. Baba, and M. Mizuta: "Highly Polarized Electron Source by Using InGaAs-GaAs Strained-Layer Superlattice", *Jpn. J. Appl. Phys.* Vol.33 (1994) pp.5676-5680
- [16] T. Nakanishi, K. Togawa, T. Baba, F. Furuta, H. Horinaka, T. Kato, Y. Kurihara, H. Matsumoto, T. Matsuyama, T. Nishitani, S. Okumi, T. Omori, T. Saka, C. Suzuki, Y. Takeuchi, K. Wada, K. Wada, M. Yamamoto, M. Yoshioka: "Polarized Electron Source for a Linear Collider in Japan", *Nucl. Instrum. Meth.*, A455, pp.109-112 (2000)
- [17] T. Miyazaki and N. Tezuka: "Giant Magnetic Tunneling Effect in Fe/Al₂O₃/Fe Junction", *Journal of Magnetism and Magnetic Materials*, Vol.139, pp L231-L234 (1995)
- [18] J. S. Moodera, Lisa R. Kinder, Terrilyn M. Wong, and R. Meservey: "Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions", *Physical Review Letters*, Vol.74, pp3273-3276(1995)
- [19] Kazuyuki Koike and Kazunobu Hayakawa: "Scanning Electron Microscope Observation of Magnetic Domains Using Spin-Polarized Secondary Electrons", *Japanese Journal of Applied Physics* Vol. 23, pp L187-L188 (1984)
- [20] M. Konoto, T. Kohashi, K. Koike, T. Arima, Y. Kaneko, T. Kimura and Y. Tokura: "Direct Imaging of Temperature-Dependent Layered Antiferromagnetism of a Magnetic Oxide", *Physical Review Letters*, Vol.93, pp. 107201(2004)

- [21] <http://www-surface.phys.s.u-tokyo.ac.jp/sss/Vol23/23-05/5g262-270.pdf>
Takanori Koshikawa: "Image Formation Processes of LEEM and PLEEM and Its Future Trend", Journal of Surface Science Society of Japan, Vol.23, No.5, pp262-270, 2002
- [22] K. L. Man, R. Zdyb, S. F. Huang, T. C. Leung, C. T. Chan, E. Bauer, and M. S. Altman: "Growth morphology, structure, and magnetism of ultrathin Co films on W(111)", Physical Review B 67, 184402 ~2003!
- [23] F. Ciccacci, E. Vescovo, G. Chiaia, S. De Rossi, and M. Tosca: "Spin-polarized Electron Gun for Electron Spectroscopies", Review of Scientific Instruments, Vol.63, pp. 3333-3338 (1992)
- [24] F. Schedin, R. Warburton and G. Thornton: "Bolt-on Source of Spin-polarized Electrons for Inverse Photoemission", Review of Scientific Instruments, Vol.69, pp. 2297-2304 (1998)
- [25] M. Cantoni and R. Bertacco: "High Efficiency Apparatus for Spin Polarized Inverse Photoemission", Review of Scientific Instruments, Vol.75, pp. 2387-2392 (2004)
- [26] M. Cantoni, M. Riva, R. Bertacco, and F. Ciccacci: "Uniaxial Magnetic Anisotropies in Fe Films on Single Crystal and Virtual Ge(001) Substrates Studied with Spin Polarized Inverse Photoemission and MOKES", Physical Review B 74, pp. 134415 (2006)