The Final Report of the Subcommittee on Future Projects of High Energy Physics in Japan

19 May 1997

Subcommittee members:

K. Hagiwara (KEK), K. Inoue (Kyushu Univ.), K. Kawagoe (Kobe Univ.),
S. Kim (Univ. of Tsukuba), S. Komamiya (Univ. of Tokyo, Subcommittee Chair),
Y. Kuno (KEK), H. Kurashige (Kyoto Univ.), T. Matsui (KEK),
A. Suzuki (Tohoku Univ.), S. Suzuki (Nagoya Univ.),
N. Toge (KEK), K. Tokushuku (KEK), T. Yanagida (Univ. of Tokyo),
T. Yamanaka (Osaka Univ.), M. Yamauchi (KEK), Y. Yamazaki (KEK),
M. Yoshioka (KEK, Subcommittee Secretary)

Preface

Development of High Energy Physics in Japan has reached a new stage following the construction of TRISTAN. Through landing at once at the energy frontier, our accelerator technology has been advanced drastically and established a quality abreast with the leading technology of the world. We believe that the era of pilgrimage for foreign frontier research bases is over, and it is globally recognized that scientists in Japan have gained ability sufficient to carry out top-quality researches, even domestically. Although TRISTAN was not blessed with the discovery of new particles, their testing of the gluon self-coupling, their contribution to the understanding of the photon structure function, and their first verification of the short-range increase of the electro-magnetic interaction, are amongst the many results respected internationally.

Here, by High Energy Physics we mean the experimental study of elementary particle physics by means of high energy accelerators. From the post-war era of recovery, until very recently, we cannot deny that our research in fundamental science, which includes the field of high energy physics, has relied to a considerable extent on the research done in the West. However, we have now technology, industrial basis and economic power sufficient to contribute internationally even in the field of fundamental science. In order to achieve an international contribution based on a long-term perspective, it is essential not only to fortify the collaborative links overseas, but to develop world-class research facilities in Japan, to explore the frontier technology, and to substantiate the new creations in the culture of mankind.

Currently in high energy physics we are witnessing the completion of a paradigm so-called the ‘Standard Model’. However, the fundamental questions such as that concerning the origin of mass are still unsolved. We firmly believe that the experimental discoveries of the near future will give answers to these questions, and open up a new horizon of science. Given this situation, the scientists of the European nations have decided on the construction of the next generation hadron collider LHC. On the other hand, we believe that experiments at an e^+e^- Linear Collider will be crucial in order to determine with confidence the directions of Physics beyond the Standard Model. Thus a consensus has been attained amongst the community of particle physicists in Japan that our next principal project in high energy physics should be the construction of this e^+e^- Linear Collider as its host country, and that it is an international contribution which also profits our country.

Following major developments in the field such as the starting of the KEKB project in Japan and the termination of the SSC project in the United States, the High Energy Physics Committee of Japan set up the second Subcommittee on Future Projects of High Energy Physics in Japan in 1994. The mission of the subcommittee is to study the perspectives of the international academia, and to examine the future directions of Japanese high energy physics over the next ten years. The Subcommittee began its activity in the August of 1994, and has examined the future projects, concentrating in particular on the physics and the technology of the e^+e^- Linear Collider. In the meanwhile, there have been further academic developments such as the precision measurements at LEP and SLC which indicate the presence of Physics beyond the Standard Model, and the discovery of the top quark at TEVATRON, which has strengthened the physics case for the e^+e^- Linear Collider. The Subcommittee, after one year of intensive studies, therefore submitted an Interim Report in July 1995 to the High Energy Committee of Japan, which recommended an early construction of the e^+e^- Linear Collider. Since then, we have continued assessing and debating on the Linear Collider and other future projects in high energy physics, leading to the submission of this report.

Contents

Preface ii

Principal Recommendations 1

Executive Summary 2

1 The Value of Fundamental Science 7

2 The Status of Particle Physics and the Challenges at the Energy Frontier 9
- 2.1 The Status of Particle Physics and Perspectives 9
- 2.2 The Challenges in the Energy Frontier 11
- 2.3 The Necessity of an Early Construction of an e^+e^- Linear Collider 12
- 2.4 The First Phase and the Second Phase of the Linear Collider Project 15

3 Directions of High Energy Physics in the World and Future Projects in Japan 17
- 3.1 The History of High Energy Physics in Europe and the United States 17
- 3.2 An Analysis of the Current Status of High Energy Physics in Overseas 18
- 3.3 The History of High Energy Physics in Japan 19

4 The Principal Project 23
- 4.1 The Linear Collider Accelerator 23
  - 4.1.1 The Principles of a Linear Collider 23
  - 4.1.2 The First Challenge: High Power RF Technology 24
  - 4.1.3 The Second Challenge: Collisions 24
  - 4.1.4 The Third Challenge: The Optimization of Parameters 24
  - 4.1.5 The Fourth Challenge: Reliability and Cost 25
  - 4.1.6 Approaching the Problems 25
- 4.2 The Basic Construction and Development of the Linear Collider 26
  - 4.2.1 The Electron and Positron Sources 27
  - 4.2.2 The Damping Ring, the ATF 27
  - 4.2.3 The Bunch Compressor 27
  - 4.2.4 The Main Linear Accelerator 28

4.2.5 The Final Focus Unit 29
4.2.6 Other Factors 29
4.3 Organization for the Linear Collider Development and Construction 29

5 Other Projects **33**
5.1 An Overview 33
5.2 Projects in Japan 34
5.2.1 The KEKB Project 35
5.2.2 The Long-Baseline Neutrino-Oscillation Experiments 37
5.2.3 The Japan Hadron Facility (JHF) 37
5.2.4 Non-Accelerator Particle Physics Programs 39
5.3 Projects in Overseas 40
5.3.1 The LHC Project 40
5.3.2 The SLC/SLD Experiments 40
5.3.3 LEP 41
5.3.4 Fermilab TEVATRON 41
5.3.5 DESY HERA 42
5.3.6 Fixed-Target Experiments 42
5.3.7 The Tau-Charm Factory 43

6 Human Resources Development and Organization **44**
6.1 An Overview 44
6.2 The Roles of KEK and the Universities 45
6.3 Diversity of the Human Resources for the Principal Project 46
6.4 The Structuring of a Suitable Environment for an International Laboratory . . . 47

7 Interdisciplinary Aspects **48**
7.1 An Overview 48
7.2 High Energy Physics as a Branch of Science and its Relationship to Other Fields 49
7.3 Other Fields of Accelerator Science 50
7.4 The Relationship between Accelerator Science and Other Fields 53

Principal Recommendations

Concerning the future projects of high energy physics in Japan, we make the following recommendations.

1. The e^+e^- Linear Collider project is the next principal project for research in high energy physics in Japan.
    - The center-of-mass energy of the collision in its first phase will be 250~500 GeV. Aiming at its concurrent operation with LHC, every effort has to be taken to start its construction in the beginning of the 2000s. After the completion of the first phase, the second phase upgrade to the center-of-mass energy $\gtrsim$1 TeV will be made.
    - The e^+e^- Linear Collider project should be open to the international research community, and Japan should play the leading role as its host country.
    - An organization to execute the project should be formed and its globalization should be actively pursued.
2. It is essential to carry out the KEKB project, which is under construction, as planned. The other domestic and international projects in accelerator and non-accelerator experiments should also be promoted, in order to develop a broad academic basis.
3. The cultivation of human resources should be pursued in order to push forward the principal and the other projects.

Executive Summary

There is enough evidence for us to expect that the experiments in the near future will enable us to discover new directions in high energy physics and thereby lead to its major development. The 'Standard Model' of the modern particle physics is based on a principle called the gauge symmetry. Under this symmetry, it is natural for the fundamental particles to be massless. The most important untested sector of the 'Standard Model' is the 'mechanism for giving masses to the fundamental particles', or the mechanism that breaks the gauge symmetry. This is the sector whose experimental resolution will bring out the direction for a new paradigm beyond the Standard Model.

This will be made possible by the discovery of the particle involved in the mechanism of mass generation, the Higgs particle, and by analyzing its properties. The 'Supersymmetric Grand Unified Theory', which is currently the most promising candidate for a theory beyond the 'Standard Model', predicts the presence of at least one Higgs particle with a mass below 150 GeV. The determination of the existence or absence of this light Higgs particle and the analysis of its properties is the most important and urgent project of the current high energy physics.

The e^+e^- Linear Collider is a unique facility capable of unambiguously determining whether the light Higgs particle exists and, once the particle is found, its properties can be studied in great detail. For this reason the research and development (R&D) of the e^+e^- Linear Collider has been actively conducted throughout the world over the past ten years. Also in Japan, the R&D of the Linear Collider project has been actively pursued and the major achievements have been made in collaborations and competitions with physicists in other countries, by utilizing the accelerator technology which is now abreast with the frontier in the world. And, at last, its realistic design is about to be made.

In general, proton–proton colliders such as the LHC can produce new particles of very large masses. However, the background level compared to the signals of the new particles is generally high, and hence only those produced in large numbers and with distinctive signatures are detectable. In comparison, at an e^+e^- Linear Collider, the signals of new particles are generally at the same level as the background, and also the production processes are often simple enough to facilitate accurate predictions of signals and backgrounds. Thus if the new particles are within the energy range of the e^+e^- collider, they will be readily detected and their properties can be analyzed in detail.

The e^+e^- Linear Collider will have the greatest impact on the progress of particle physics if it begins operation concurrently with the European proton–proton collider LHC, and at the center-of-mass energy of 250$\sim$500 GeV. This is because the model-independent determination of the presence or absence of the light Higgs particle at the Linear Collider is expected to help improving significantly the discovery capability of the LHC experiments. This Subcommittee proposed the early construction of this e^+e^- Linear Collider (LC1) in the Interim Report in 1995. Reflecting upon the substantial recent progress in the development of accelerator technologies, the proposal was considered realistic by the community. Furthermore, as the second phase Linear Collider project (LC2), we proposed that an upgrade to a center-of-mass energy of about 1 TeV or higher should be made after the completion of LC1. At LC2, extending upon the achievements of LC1, the search for the colorless supersymmetric particles and measurements their properties, as well as the search for the heavy Higgs bosons, will be made. Also, even if the light Higgs particle does not exist, the precision experiments on the pair productions of W^+W^- and $t\bar{t}$, which will be done simultaneously with the LHC studies of WW scattering, will provide clues for the determination of the origin of mass. Regarding this e^+e^- Linear Collider project as the next principal project of Japanese high energy physics, we have clearly stated in the Interim Report that it is the consensus amongst us the high energy physicists of Japan to announce our intention to host the project in order to make possible its early realization.

Construction of the Linear Collider must be based on technical design standards that meet the international critical assessment. To this end it is essential to create an organizational and developmental structure that is open to the international community. In order to realize this principal project, the e^+e^- Linear Collider project, it is essential for the entire high energy physics community of Japan to contribute. In order to reflect maximally the opinions of the community onto the realization of the project, a committee made up of the leaders of the Linear Collider project in the universities and KEK should be formed, where the global strategies should be determined based upon a research into the various possibilities of its realization. KEK should host the 'LC project promotion office' in order to execute the project with due responsibility. The office should operate as the executive center for the research and development and the construction of the collider and the preparations for experiments, in such a manner to respect strategic recommendations given by the above committee.

If the European LHC and the Asian–Pacific e^+e^- Linear Collider should harness research activities in mutual influence and cooperation, the global pursuit of particle physics research will be accelerated. The construction of the e^+e^- Linear Collider, while being hosted and principally executed by Japan, should be done in collaboration with the whole world, in particular with the Asian and Pacific countries that have been making marked economic developments. Thus the Linear Collider project should be regarded as a part of Japan's international contribution in the field of fundamental science, and it is a project in accord with the spirit of the Basic Law of Science and Technology which was passed in multi-partisan approval in the 1995 national congress. For our country to continue having an active economy and lively culture into the future in a society with more elderly people and higher cost for social services, such a project capable of motivating the participants of the next generation is necessary. In this context, the investment into scientific technology, in particular the fundamental science, should be made, now.

The era of catching-up in technology and basic science with the western developed nations is over, and the international expectation for our contribution is high. It is the duty of our country towards the 21st century to tackle the unexplored areas of fundamental science and, within the international cooperation and the sharing of responsibilities, to take a part in the birth of the new human intellectual asset. For this reason also, projects capable of creating common human academic and cultural asset should be actively pursued. The merits of the e^+e^- Linear Collider project should be envisaged with such broad perspective.

High energy physics to this date has developed along with the accelerator experiments at the energy frontier. Our principal project, the e^+e^- Linear Collider, is also along this main course. However, history provides ample evidence that a major academic development can have unanticipated starting points. Thus, with an emphasis still on the Linear Collider project, the formation of a broad academic basis requires promotion of a variety of complementary experimental projects. In particular, the low-energy high-luminosity e^+e^- collider KEKB is expected to continue producing valuable data for more than ten years after its commissioning. Its on-schedule execution is essential in order to gain a handle onto the problem of CP-violation, which is one of the central problems of particle physics.

Among other national projects, the Super-Kamiokande experiment has been brought into operation by the leading contribution from Japanese physicists. Together with various other non-accelerator experiments, it is expected to bring many new results on the nucleon decay, the neutrino oscillation, and the search for the dark matter, which will lead to breakthroughs both in particle physics and astronomy.

Furthermore, at the 'Japan Hadron Facility (JHF)', which is basically a nuclear physics project, various particle physics experiments are anticipated, such as the measurements of rare hadron decays and neutrino oscillations utilizing the high-intensity K, π, neutron and other secondary particle beams, which may bring insight into physics beyond the Standard Model.

It should be also pointed out that we have taken part in international collaborative experiments abroad and have achieved a number of remarkable results. In collider experiments we contributed to the discovery of the top quark at the Fermilab TEVATRON experiments. Also in the US, at SLAC SLC we have been taking part in experiments using polarized electron beams. In Europe, we have been participating in the CERN LEP collaborations, making the precision tests of the 'Standard Model' by studying the Z and W boson properties. At DESY HERA we are taking part in the study of the proton structure using electron–proton collisions.

Besides the collider experiments, we have been conducting the CERN neutrino oscillation experiments. Also at Fermilab and BNL, we are contributing to experiments on CP violation and rare processes by utilizing K mesons. Our participation in these international collaborative experiments has not only helped achieve first class research results but has contributed to the training of many physicists with global orientation capable of conducting fruitful collaborations in the international environment, and to developing our experience and personal relationships necessary for the large-scale international collaborations in the future.

The CERN LHC project, which has the utmost academic importance rivalling our principal project, the e^+e^- Linear Collider, has also seen our major contributions. The LHC project is to start operation in 2005, and it has introduced a new scheme in which the European member states of CERN lead the project jointly, while asking for monetary contributions from other non-member nations participating in the project. In the case of DESY HERA, Germany is its host country and part of its funding is made up by contributions from other countries. These various forms of international collaborations will be respectable reference when we begin the construction of the e^+e^- Linear Collider as its host country. It is crucial to develop an environment that promote active participation by overseas researchers in our country and in this respect too, there are many points to learn from these projects.

However great may be the scope of the project, the prime driving force in research is the creativity and enthusiasm of the individual scientists and engineers. A research organization capable of drawing on their creativity is necessary, and the project must be executed by an organization receiving just scientific reputation internationally. In order to execute major enterprises such as our principal project, the e^+e^- Linear Collider, the nurturing of the scientists of the younger generation is necessary. In this respect, the effective collaborative relationship between the universities and the central laboratory (KEK) needs to be reinforced. We hope for discussions on this matter with broad perspectives and support the activity of the Subcommittee for enhancing the activities of university high-energy-physics groups. In particular, although the centralization of funding and personnel to the central laboratory may seem efficient, it may not be the most effective approach in the light of the long-term collaboration between the central laboratory and the universities. Improvements are needed in the funding to university groups and their management in order to help the development of core facilities of universities which will strengthen the baseline of the academia as a whole.

History has shown repeatedly that many of the fruits of fundamental science, although not of direct applicability to the economy and living of the era, can lead to technological revolutions at later times. In addition, the spin-off technology from fundamental science can often lead to immediate developments in industrial technology. Concerning the influence of high energy physics, there are numerous applications of the accelerator technology. The analysis of the structure of material using synchrotron radiation, the structural analysis of organic polymer by neutron scattering, the medical applications of particle beams *et cetera* are innumerable instances of these. The Linear Collider with its low-emittance e^- source is the leading candidate for the realization of the free electron laser, which is regarded as the dream light source of the next generation. The free electron laser programs are close to be realized at several Linear Collider test facilities. Some of the basic technologies such as fast computing with a large memory capacity, fast electronic circuits and high precision machine crafting technology, have been sharpened by demands from the high energy experiments.

The essence of fundamental science, which includes high energy physics, is the pursuit of the truth, and it is a creative cultural activity which stems from one of the basic human instincts, namely, the curiosity towards the Nature. In the past, the origin of mass and the beginning of the universe were questions whose very scientific meaning was doubtful. The establishment of the ‘Standard Model’ in the 1970s and the 80s enabled us to describe the interactions between particles almost completely, and we now recognize that the origin of the masses of fundamental particles is the key to understand the next layer of Nature. The origin of mass will be probed and clarified by experiments at LHC and the e^+e^- Linear Collider. Furthermore, the development of particle physics has brought insight into the particle interactions at high energies, allowing us to deduce the sequence of events in the high energy early universe. Together with the development of the big bang cosmology, this led to the advent of the modern cosmology. The understanding of the origin of mass, the understanding of the matter vs. anti-matter asymmetry of the universe, the discovery of the origin of the cosmic dark matter, are amongst the anticipated results in particle physics which will profoundly affect our understanding of Nature and the universe. Thus high energy physics is an active area of science whose major progress in the 21st century is anticipated, and it should be strongly supported together with the other areas of progressing sciences.

Chapter 1

The Value of Fundamental Science

For mankind to continue its progress in harmony with Nature, it is a necessity to develop a deep understanding of Nature and to have a scientific view of Nature.

In its origin, the pursuit of the truth is the creative cultural activity of the self-enlightening mankind with active intellectual curiosity, and the intellectual asset of mankind, which is the amalgamation of the record of this pursuit, has in itself a value in providing us with intellectual wealth and further progress. Fundamental science has influence over our thinking and the view of the universe, the physical world and life. It can thus greatly influence philosophy and thought, as well as even literature and art.

Furthermore, fundamental science is strongly linked with the society via technology for industry. The year 1997 has seen the centenary of the discovery of the electron. Only with the discovery of the electron have the inventions of the electronic computer and the electron microscopy become possible; the development of the quantum mechanics and the theory of relativity led to the progress of the present day sophistication of electronic technology, machine technology and material technology. The examples are innumerable.

Thus the progress in fundamental science has brought technological revolutions in later eras, and has contributed to the human society through the dramatic development of industry. It is an undeniable fact of history that the apparently useless pursuit of the truth, which perseveres to find the essence of Nature and of matter, has brought about the technological revolutions directly related to the society. It might even be regarded as an inevitable consequence of the history of mankind who has achieved the enrichment of living through the effectual utilization of the knowledge of Nature.

In this light, the history of mankind in promoting fundamental science is of a just cause, and this positive attitude towards fundamental science should to be relocated in the human society in a more clarified manner.

The striving of fundamental science has a facet which immediately motivates the progress of industrial technology. In particular, the experimental study of fundamental science is ever supported by the latest technology of the era and demands higher technological targets. One notable example is the progress in the capacity of electronic computers motivated by the demand for instant analysis of huge amounts of data, which came hand in hand with the progress of high energy physics. Thus fundamental science and engineering share a mutual supportive development, and the promotion of the two as a whole is an essential necessity.

Today, the investigation of the origins of matter and the study of the fundamental laws of Nature is a task of high energy physics which, through its role in challenging the most fundamental questions of natural science, has been a leading branch of fundamental science. And now high energy physics aspires to find the essence of matter, the origin of mass and the unified picture of the forces.

In addition, the recent progress in high energy physics and the development of big bang cosmology have brought to light the intimate connection between high energy physics and cosmology. It can be said that the future developments of high energy physics holds the key to the mystery of the creation of the universe, the evolution of the matter universe, and the mystery of the end of the universe. Thus high energy physics, in not only purposing to clarify the fundamental laws of Nature and of matter, but in purposing to find the origins, the evolution, and the end of matter, is clearly a branch of science challenging the fundamental questions. There is thus purpose in further promoting high energy physics, given the value of the pursuit of the truth in creating the new culture of mankind, and given that it enriches the knowledge of the origin of the universe, which underlies the existence of mankind.

We cannot hope for progress in high energy physics without the progress in accelerator science which is its experimental methodology. As the object of research turns to the infinitesimal regions, the accelerators searching the regions become larger and more sophisticated. This tendency to greater scales is beginning to appear in other branches of fundamental science, and in dealing with the sophistication and size, high energy physics is a leading model. As the tendency to sophistication and enormity develop further in many branches of science, a task for the future is in creating a large-scale research organization capable of projecting creative research activities scientifically in an organized fashion, for fruitful achievements. Big sciences should hence be promoted rigorously.

Today, with a high anticipation for global contribution, the role of Japan towards the 21st century is in actively tackling the unexplored regions of fundamental science and to take part in the creation of the intellectual asset of mankind in a global collaboration and sharing of roles. In order for our country to establish a true scientific and technological national foundation, it is clear that we need a capacity for developing new technology with a unique and long-term perspective. This developmental capacity can only be nurtured through a backbone of fundamental science, and from this perspective too, efforts in fundamental science needs to be encouraged further.

Chapter 2

The Status of Particle Physics and the Challenges at the Energy Frontier

2.1 The Status of Particle Physics and Perspectives

Particle Physics, having pursued the understanding of the ultimate structure of Nature, is facing a grand transition at the establishment of the Standard Model. With the discovery of the top quark at the Fermilab TEVATRON in the US, the six quarks and leptons that represent the three generations of basic constituents of matter have all been discovered. The particles that mediate the interactions between them, the photon, the gluon, the W boson and the Z boson, have also been discovered. The interactions among these elementary particles have been studied experimentally with great accuracy to verify the predictions of the Standard Model. The success of the Standard Model, which is dictated by the Quantum Field Theory based on the principle of local gauge invariance, has established the gauge principle as the principle governing the fundamental dynamics of Nature. This has provided a framework for theoretical studies of the infinitesimal world beyond the Standard Model, and has led to numerous theoretical conjectures. Most attractive of such conjectures include the grand unified theory which attempts to unify the strong, weak, and electromagnetic interactions, the technicolor model and other models based on strong-coupling gauge theories, the supersymmetric models, and, in seeking the unification of all forces including gravity, the supergravity and superstring theories.

As well as further confirmation of the Standard Model and understanding of its entirety, the current task of high energy physics lies in the construction of our view of Nature towards the understanding of the physics of the infinitesimal world beyond the Standard Model. In particular, the immediate focus of attention is in the origin of the masses of the fundamental particles, in other words, in the mechanism that breaks the electroweak gauge symmetry which unifies the electromagnetic interaction and the weak interaction. The Standard Model has born many great successes, but they are limited to the domain of gauge interactions that are completely described by the gauge principle. Our knowledge of the interactions of the Higgs boson, which plays an essential role in the electroweak gauge symmetry breaking and the origin of fundamental particle masses, is experimentally completely missing. The discovery of the Higgs boson and the study of its properties, as well as the study of the origin of the Higgs boson, has a role not only in the complete understanding of the Standard Model but is also essential in the pursuit of the 'hidden principle' which governs the infinitesimal world beyond the Standard Model.

There are roughly two possible scenarios for the nature of the Higgs boson, which have been proposed through theoretical attempts to understand the Standard Model more deeply.

First, according to the ideas as represented by the technicolor model, the spontaneous breaking of the electroweak symmetry is realized as a consequence of a new strong-coupling gauge theory. The Higgs boson has a composite structure constructed through its dynamics. The energy region from a few TeV up to 10 TeV will be colorfully decorated by many new particles which are consequences of this new dynamics. While there is no complete theory which describes the origin of the quark and lepton masses based on this scenario, the possibility of the dynamical breaking of the gauge symmetry needs to be continually assessed.

The other scenario, which has been increasingly considered more likely recently, is the solution of the problems associated with the Higgs boson in the framework of the supersymmetry theory. According to this theory, all particles in Nature are accompanied by supersymmetric particles, partners differing in spin. Interactions of these particles are constrained strongly by supersymmetry. Supersymmetry is the only fundamental symmetry which can extend consistently the symmetry of the four-dimensional space-time. Based on the results amassed in the study of the unified theories such as the supergravity and superstring theories, it is believed that whatever the fundamental mechanics may be, supersymmetry will play an essential role in Nature.

The Minimal Supersymmetric Standard Model, which is the supersymmetric extension of the Standard Model, predicts new particles in the mass range of a few hundred GeV to 1 TeV as supersymmetric partners of the Standard Model particles. In addition, it has a prediction which is of utmost importance for the planning of future projects: The Higgs boson will have a mass below about 150 GeV. The phenomenological viability of this theory has been studied from many aspects, and it is gaining an increasingly solid support as the most promising candidate for the next level of theory beyond the Standard Model. In particular, the recent precision measurements in the gauge coupling constants strongly indicate that in the presence of supersymmetry, the strong, the electro-magnetic and the weak interactions will be grand unified at the energy of the order of 10^{16} GeV. The discovery of supersymmetry, which is the key to the understanding of the ultimate unified theory which includes the gravity, is the most important task for high energy physics.

2.2 The Challenges in the Energy Frontier

As discussed in the preceding section, the progress in our understanding of Nature critically requires the understanding of the mechanism for spontaneous gauge symmetry breaking in the Standard Model, that is, the origin of mass. In order for the current and future accelerator and non-accelerator particle physics experiments to lead to the discovery of the 'hidden principle' underlying the infinitesimal world beyond the gauge principle, it is necessary that the mechanism of mass generation is understood. For example, the B-factory challenges the origin of matter in the universe by exploring the matter–anti-matter asymmetry in the quark-mass matrix, but for this insight to lead to a more profound understanding of Nature, it is necessary to understand the mechanism which leads to the quark-mass matrix. Similar statements can be made concerning the Kamioka and other non-accelerator underground experiments exploring the neutrino masses and the lepton mass matrix, and the cosmological observations aimed at studying the dark matter which holds a principal part in the mass of the universe. The understanding of the gauge symmetry breaking mechanism, the origin of the particle masses, is the key leading us to the final understanding of Nature.

The mechanism for spontaneously breaking the gauge symmetry and giving masses to the gauge bosons, such as the W and Z bosons of the Standard Model, is generically called the Higgs mechanism. It has a general consequence that there exists one or more electrically neutral spin-zero particle (the Higgs boson). The exploration of the origin of mass thus resides in the discovery and the analysis of the Higgs boson(s) and its (their) properties. This is the most important task for experiments in the energy frontier.

Thus the pursuit of the Higgs boson is placed a spirited emphasis in the current experiments at the energy frontier. The CERN e^+e^- collider LEP has shown that the Higgs boson mass is above 65 GeV, and the effort is channeled into searching for the Higgs boson of masses up to 90 GeV at the second phase project LEP2. The CERN pp collider LHC will greatly expand the discovery potential for the Higgs boson. In this project which starts operation around 2006, the Higgs boson of all allowed mass range is expected to be discovered in the 'Minimal Standard Model' which assumes just one Higgs boson.

Figure 2.1 shows the allowed ranges of the Higgs boson and the top-quark masses in the Minimal Standard Model, according to the energy scale Λ where new physics emerges. In the Minimal Standard Model, the Higgs boson gives masses to the W and the Z bosons as well as to all quarks and leptons. From TEVATRON experiments the top-quark mass is known to be 175 ± 6 GeV (the oblong area). So, there are upper and lower limits to the Higgs boson mass. If new physics beyond the 'Minimal Standard Model' does not emerge below $\Lambda \sim 1$ TeV, then the Higgs boson mass must be less than about 500 GeV. If the Higgs boson is heavier, above 700 GeV, its mass exceeds the scale of 'New Physics' and the Higgs boson must be taken as a composite system made by new strong interactions rather than as a fundamental particle. On the other hand, if new physics does not emerge up to $\Lambda \sim 10^{16}$ GeV where the grand unification

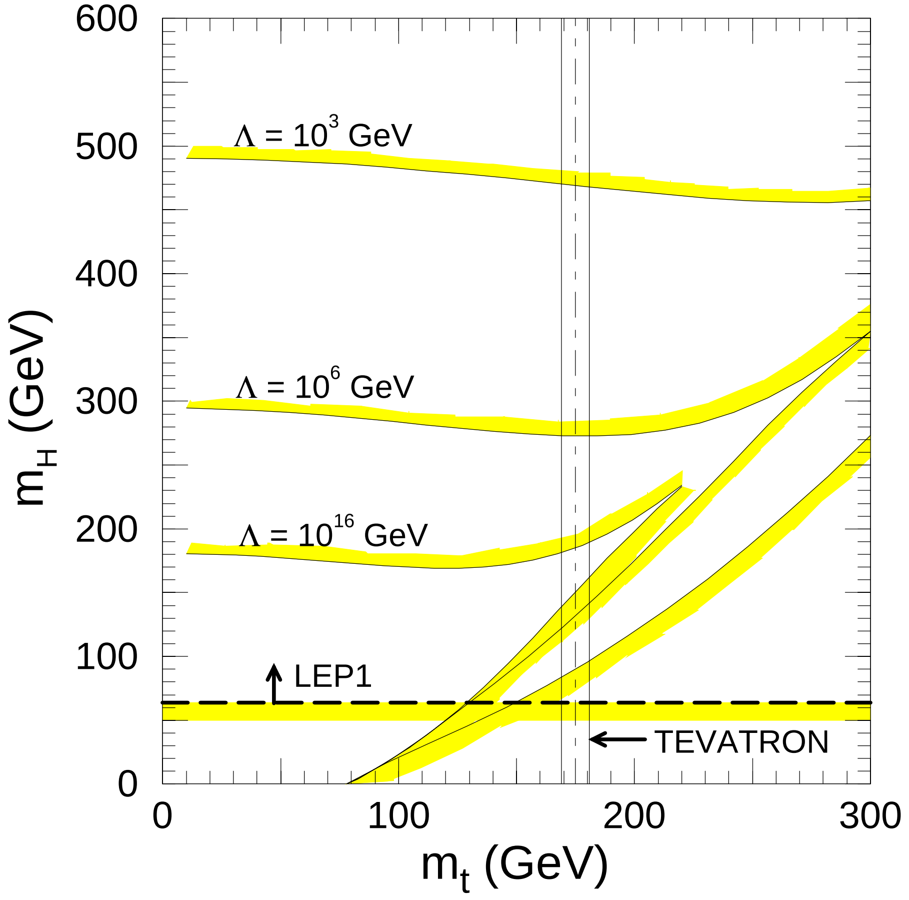

Figure 2.1: The theoretically allowed range of the Higgs boson mass m_H as a function of the top quark mass m_t in the Minimal Standard Model where a single Higgs boson is responsible for the masses of all particles including the W and Z bosons and the top quark. Λ is the scale at which new physics beyond the Standard Model emerges. The lower limit on m_H from LEP1 experiments and the range of m_t measured at the Fermilab TEVATRON experiments are also shown.

of the electromagnetic, the weak and the strong interactions is anticipated, the Higgs boson must have a mass between 130 GeV and 190 GeV. Assuming this ‘Minimal Standard Model’, the LHC experiments will be able to find the Higgs boson at all allowable mass range.

2.3 The Necessity of an Early Construction of an e^+e^- Linear Collider

In the previous section we summarized the scenarios for Higgs boson searches according to the ‘Minimal Standard Model’ where a single Higgs boson is responsible for the mass generation of all fundamental particles. However, the latest results in particle physics theory strongly suggests that the ‘Minimal Standard Model’ is not realistic. For example, on one hand, according to the technicolor model and other models where new strong interactions break the gauge symmetry, the Higgs boson may not be found clearly as a fundamental particle. On the other hand, according to the supersymmetric models there are at least four scalar (spin zero) Higgs bosons. In these more attractive models the discovery of the Higgs boson is generically more difficult, and there is possibility that even the LHC experiments will not find them.

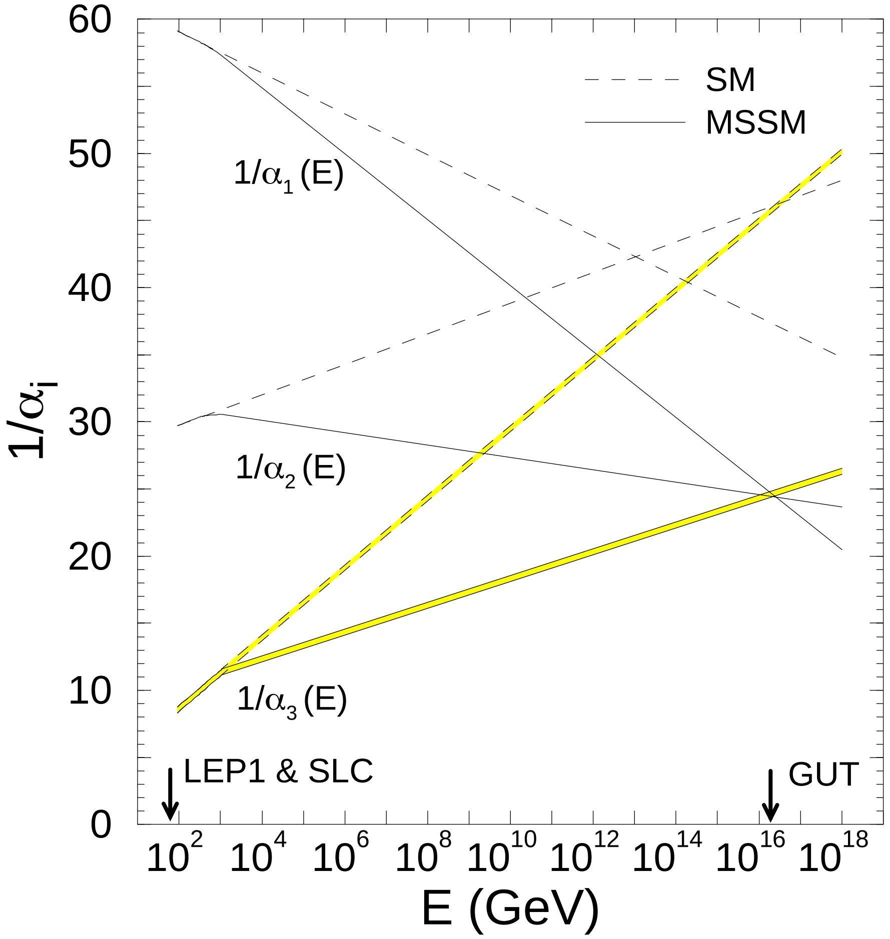

Figure 2.2: The high-energy scale running of three gauge couplings α_1, α_2 and α_3 inferred from the precision measurements at 100 GeV. If only the Standard Model particles exist (dashed lines), the coupling do not unify. In the supersymmetric Standard Model (continuous lines), due to the effect of many supersymmetric particles with masses below 1 TeV, the grand unification of the three interactions is realized at an energy scale of about 10^{16} GeV.

In particular, due to the theoretical development of the 1980s and the precision experiments in the early 1990s the supersymmetric Standard Model has become the leading candidate for explaining the origin of the Higgs boson. According to this theory, the spontaneous gauge symmetry breaking mechanism is understood naturally in connection with the breaking of supersymmetry. It also successfully explains the non-observation of proton decay at underground experiments such as the Kamioka experiment. Furthermore, the grand unification predictions on the electromagnetic, weak and the strong gauge couplings have agreed quantitatively with the precision experimental measurements. In figure 2.2 we show the prediction on the three running gauge couplings at high energies according to the Minimal Standard Model, and its supersymmetric version, with the most precise inputs from measurements such as those at LEP1. It can be seen that due to the effect of the many supersymmetric particles with masses below about 1 TeV, which are expected in the supersymmetric theory, the three gauge couplings converge at the energy scale $\Lambda \sim 10^{16}$ GeV. Because of this high grand unification energy scale, the proton lifetime becomes sufficiently long. Whether the decay will be observable at, for example, the super-Kamiokande experiment depends on the details of this grand unification model. On the other hand, if the supersymmetric particles do not exist (dashed lines), the grand unification of the three gauge couplings is not realized.

One of the most important consequences of the supersymmetric Standard Model is that in the general model which does not jeopardize the grand unification of the three gauge couplings, there is at least one Higgs boson with a mass below 150 GeV. In the Minimal Supersymmetric model, the Higgs boson can be found at the LHC in some cases but there is a significant possibility that it is not detectable. According to the latest theoretical calculations and the simulations, an e^+e^- Linear Collider with a center-of-mass energy of $250 \sim 500$ GeV can definitely find the Higgs boson predicted by the supersymmetric grand unified theory, and can determine its quantum numbers and its coupling to the Z boson. In this regard, the Linear Collider is capable of determining whether this boldest and most attractive theory of modern particle physics is related to our world. If the Higgs boson of mass below 150 GeV does not exist then, however theoretically attractive the supersymmetry theory is, the generation of mass in this world is not directly related to it and we must find a completely different mechanism which involves a new strong interaction for the origin of mass. On the other hand, if the Higgs boson is discovered in the anticipated mass range, we can immediately direct our attention to the search for the supersymmetric particles and the testing of supersymmetric models involving gravity as well. The Linear Collider will determine the direction of particle physics research.

Although the LHC has an enormous potential including the possible discoveries of supersymmetric particles, if the Higgs boson mass is less than about 150 GeV, it is difficult for the LHC experiment to determine model independently the presence or the absence of the Higgs boson. Indeed, for a Higgs boson of a mass less than 150 GeV such as the one predicted by the supersymmetric grand unified theory, its discovery demands a very difficult analysis even if its properties happen to favor its detection at the LHC. If the colored supersymmetric particles are heavy and the signals are not distinct, there is a significant possibility that after some time since the beginning of its experimental operation, no decisive evidence of either the Higgs boson or the supersymmetric particles is to be found. If, at this time, the results of Linear Collider experiments are available, the great discovery potential of the LHC can be maximized. If the Linear Collider discovers that there is no Higgs boson of any type below 150 GeV, the LHC can devote its attention to the detection of a new strong interaction involving the W and the Z bosons at still higher luminosities. On the other hand, if the Higgs boson is found below 150 GeV, the LHC can aim at detecting the supersymmetric particles. It should be remembered that in the past, when new particles were discovered in hadronic collisions, as in the case of the J/ψ, Υ, the W and the Z bosons and the top quark, the masses and electronic charges of their decay products such as the electron, the neutrino, the b-quark, the W-boson and so on, were already known. The colored supersymmetric particles to be produced at the LHC, the gluino and the scalar quarks, will generally decay into colorless supersymmetric particles such as the gauginos and the scalar leptons. The masses and properties of these decay products will not be determined without resorting to specific model assumptions. Therefore, the search for supersymmetric particles at the LHC is associated with a new kind of difficulty. If the Linear Collider can discover these colorless supersymmetric particles and can determine their masses, the discovery capacity of the LHC for the gluino and the scalar quarks will be dramatically improved, and accurate measurements of their masses will become possible. Indeed, unless the numerous signals of gluino and scalar quark production match the predictions of the existing models of supersymmetry breaking, the 'discovery of supersymmetry' by the LHC alone may be a difficult task. In addition, since the mass spectrum of the supersymmetric particles is considered to be the key in searching for the ultimate model of particle physics including gravity, the concurrent operation of the Linear Collider and the LHC has an immeasurable value in order to discover supersymmetry and search for the ultimate unified theory.

2.4 The First Phase and the Second Phase of the Linear Collider Project

As stated above, the Linear Collider will make the greatest contribution to the progress of particle physics if it operates concurrently with the LHC at the center-of-mass energy $250 \sim 500$ GeV. Reflecting upon the recent dramatic progress in the accelerator technology, this is considered realizable. Therefore, we recommend as the first phase of the Linear Collider project (LC1) an experiment concurrent with the LHC at $250 \sim 500$ GeV. The aim of LC1 is to determine the presence of a Higgs boson with a mass below 150 GeV and thereby determine the relevance of the currently most promising supersymmetric unified theory, and thus determine the future direction of particle physics. In addition, through precision studies of the W^+W^- production and the top-quark-pair production, model-independent information concerning the origin of mass can be obtained. Together with the possibility of the detection of relatively light supersymmetric particles at LC1, these information obtained at LC1 will increase the physics discovery potential of the LHC significantly. In order to attain the physics goals above, LC1 must achieve an annual integrated luminosity of above 10 fb^{-1}.

In order to clarify the origin of the Higgs boson in addition to its discovery, other scalar Higgs bosons and the supersymmetric particles, or if the Higgs boson is a composite state, the effects of the new strong interaction, must be searched for. To this end, a center-of-mass energy of about 1 TeV is necessary, and this should be achieved in the second phase of the Linear Collider project (LC2). At 1 TeV energies, LC2 experiments dramatically improve the discovery potential of the colorless supersymmetric particles, which parallels the ability of the LHC to search for the colored supersymmetric particles. In addition, the precision measurements of W^+W^- production at around 1 TeV will provide complementary information to the strong interaction studies of the W boson at the LHC which is considered difficult. Furthermore, although no theoretical model which explains its origin is known, a Higgs boson with a mass about 700 GeV or below can exist in principle, and LC2 can determine its properties and clarify its origins. An integrated annual luminosity of a few 10 fb^{-1} is necessary in the LC2 project.

The Linear Collider project aims at the first phase to determine the direction of particle physics and at the second phase to clarify the picture of new physics beyond the Standard Model. Through the entire project an effective collaboration and competition with the LHC project should be pursued. Based on the capability for accelerator technology and particle physics experiments developed in the TRISTAN project, and based on the rapidly developing research on Linear Collider construction technology by international collaborations, it is the most important and pressing task for the high energy physicists of Japan to realize the Linear Collider project with the support of international communities. With the numerous theoretical evidence in mind, we are firmly convinced of the fruitfulness of the Linear Collide project as our contribution to the world in fundamental science.

Chapter 3

Directions of High Energy Physics in the World and Future Projects in Japan

3.1 The History of High Energy Physics in Europe and the United States

The advances of research in high energy physics was led by the United States during and after World War II by making a number of discoveries through constructing accelerators one after another. After the war, many European and Japanese high energy physicists moved to the US and have joined research activities at laboratories such as the Fermi National Accelerator Laboratory (Fermilab), the Brookhaven National Laboratory (BNL), and the Stanford Linear Accelerator Center (SLAC). In Europe CERN (the European Laboratory for Particle Physics) was established in 1953. CERN has not only promoted collaborations within the western Europe but also accepted researchers from the US and other areas. In Germany the Deutsches Elektronen-Synchrotron (DESY) was established independently. Experiments at DESY has led to many achievements through the international collaborations with CERN and with physicists of countries outside the western Europe.

In the mid 1970s, a state of healthy competition began between the US and Europe, and many accelerators of similar types have been constructed in the two regions at around the same time. SPEAR (SLAC, 1972) and DORIS (DESY, 1973), PETRA (DESY, 1978) and PEP (SLAC, 1980), $\mathrm{S}p\bar{p}\mathrm{S}$ (CERN, 1981) and TEVATRON (Fermilab, 1987), and SLC (SLAC, 1989) and LEP (CERN, 1989) are examples of these. Regarding the electron–positron experiments at SLC and LEP, the experiment at SLAC SLC accelerator began first but the LEP experiments at CERN swiftly caught up, and overtaken SLC in the statistical precision of the Z boson samples. From Japan, an experimental group at first joined LEP, and then other groups joined SLC when the polarized electron beams became available, thus being actively involved in the frontier electron–positron experiments.

Since the beginning of the 1980s, the well organized researchers in Europe have brought fruits such as the discovery of the gluon at DESY and the discovery of the W and Z bosons at CERN. A plan was then laid out at CERN for the construction of the LHC pp collider in the LEP tunnel. Challenged by the European successes in the early 1980s, the US physicists planned an unprecendented pp collider SSC as a huge national project. The SSC project was aiming at the construction of a 40 TeV pp collider in a circular tunnel of 87 km circumference. Although it was once approved by the U.S. Congress, its construction was halted when the funding for the continued project was turned down by the 1993 Congress.

In the meantime, the Soviet Union built accelerators at several laboratories including those in Dubna and Novosibirsk, and conducted researches in collaboration with the East European nations, as well as having collaborative links with CERN. However, its research environment has been changing significantly since the dissociation of the Soviet Union.

3.2 An Analysis of the Current Status of High Energy Physics in Overseas

An analysis of the current future plans in North America and Europe is presented below:

After the termination of the SSC project in the United States, the U.S. future plans currently include (1) participation in the LHC project (including the support for the accelerator construction), (2) the upgrade of the TEVATRON (the main injector), (3) the SLAC B-factory (PEP–II). The projects (2) and (3) have been approved. The participation in the LHC project is a natural path to take after termination of the SSC project. Talks are under way with CERN for the funding arrangements.[1]

It is possible in the US for an approved project to be overturned by the Congress as in the case of SSC, a scheme should be found for ensuring the execution of the projects involving international collaborations. Such a scheme should be examined carefully when collaborating with the United States in the future.

In addition to the existing plans above, SLAC has a plan of the NLC (Next Linear Collider) project centered around it. SLAC has made many achievements until now such as the construction of the Two-Mile Linac which is a central laboratory for linear accelerators, construction of the world's first Linear Collider SLC, and the R&D for the next generation Linear Collider. However, the relative population of researchers who have historically been involved in hadron collider experiments is large in the US, and there are those supporting a hadron collider of an energy higher than the LHC, as well as those supporting the muon collider project.

In Europe, the future plans are currently converging on the LHC project. Capability for

---

[1] *Note added on the English translation (Jan/23/1998):* After the present report was accepted by the High Energy Committee in May 1997, the agreement was reached by the end of the year 1997 between the US government and CERN for the US participation in the LHC project.

extending the other projects are therefore limited, and this applies equally to the case of LEP2 which is currently running. There is a strict limit to the annual operation hours of LEP2, and even if the LHC project will be delayed, the extension of the LEP2 project for a few years is difficult, unless there is a clear discovery of new physics or definite signs of it.

Plans other than the LHC includes Linear Collider projects (TESLA with a superconductor linac, and SBLC with an normal-conductor linac) for which DESY has taken a central role. The R&D for TESLA is made in collaboration with, for instance, the United States. DESY has research carried out simultaneously, for example, on free electron lasers (FEL) together with researchers in the fields of nuclear physics and synchrotron radiation, with the hope of gaining supports from scientists of those fields for the TESLA project. This is in the same vein as our Linear Collider project in Japan. However, since the European central project is the LHC, Germany must collaborate with the LHC and make a significant contribution to CERN at the same time as the Linear Collider project. CERN has itself a plan for a two-beam Linear Collider called CLIC, and there has been much active R&D work. However, this is considered as a project next to the LHC. Therefore, if there is a possibility abroad, e.g. in Japan, for a Linear Collider such as the first phase project presented in this report, it is expected that CERN will collaborate with us rather than making objections. However, they still hope to construct a Linear Collider in the energy range above 1 TeV by themselves. Thus, both in Europe and in North America, the importance of a Linear Collider is highly recognized.

In Asian countries other than Japan, an e^+e^- collider with a center-of-mass energy of 3 GeV was constructed in China in 1988 and began operation. In 1995, the Asian Committee for Future Accelerators (ACFA) was established amongst Japan, China, South Korea, Taiwan, India and Thailand. ACFA promotes organized collaboration in accelerator-related fields in Asia. In 1996, Malaysia joined the ACFA. Here, too, the Linear Collider project has received strong interests, and the ACFA regards the Linear Collider as a project for the Asian–Pacific region, hoping that Japan will play the leading role in the establishment of an international organization for this purpose.

3.3 The History of High Energy Physics in Japan

After the World War II, a 1.3 GeV electron synchrotron was built in the Institute for Nuclear Study of University of Tokyo after overcoming many difficulties, reviving the research in nuclear physics and particle physics. This accelerator had its purpose as a trial machine for a more large-scale high energy accelerator, but it had also served as a training ground for scientists who have later led the field of high energy physics in Japan. At the same time, many scientists went over mainly to the United States until the 1960s as an arena of frontier physics research, and during the 1970s onwards we have participated in international collaborations in Europe as well as in the US. Research activity overseas has, thus, taken an important part. However, there arose a movement for the construction of a frontier research institution in Japan as well, and in

April 1971, KEK (then National Laboratory for High Energy Physics, Japan) was founded. In KEK the proton synchrotron and the synchrotron radiation facility (the Photon Factory) were constructed. In the Fall of 1986 the e^+e^- collider TRISTAN started operation, which brought KEK to the energy frontier. The fruit of the construction of TRISTAN is overwhelming, and it signifies the end of an era where Japanese scientists sought for major research bases abroad and we have gained ability to carry out top-level researches also in Japan. In particular, through the construction of TRISTAN, the Japanese accelerator technology has dramatically improved, becoming abreast with the top level technology in the world. Thus, our country, especially on the e^+e^- collider, has achieved world class results. In 1994, we began construction of a high luminosity e^+e^- collider B-factory, KEKB, as the extension of the then principal project TRISTAN. It is expected to be completed in 1998. KEKB is expected to produce results which can lead to a great progress in the research on the particle–anti-particle and space-inversion asymmetry.

As stated in chapter 2, the most important and pressing task in high energy physics, namely the understanding of the mechanism of the electroweak gauge symmetry breaking, or the origin of particle masses, has led to huge hadron collider projects LHC and SSC. However, for the discovery of the light Higgs boson, as expected, for instance, in supersymmetric theories, the e^+e^- Linear Collider has more advantage. Thus, from mid 1980s the R&D on the Linear Collider has taken place throughout the world. Japan has led the frontier together with the United States, Germany, France, Russia and CERN. The following is a history of the formation of the consensus that 'the Linear Collider is the next principal project in Japan' in the Japanese high energy physics community.

The first Subcommittee on Future Projects of High Energy Physics in Japan (chairman Yorikiyo Nagashima) was formed in 1984. After two years of discussions it was concluded in 1986 that the key to a breakthrough for new physics beyond the Standard Model is in experiments at the energy frontier, recommending two main objectives (1) to immediately begin R&D on the TeV range Linear Collider to be built in Japan, and (2) to promote the participation in SSC.

Based on this report, the first-term 5-year project for the Linear Collider research and development was carried out, and the summary was published in January 1993. In the meantime, the analysis of LEP precision data and the theoretical research have sharpened the recognition that an early construction of an e^+e^- Linear Collider at center-of-mass energies in the range $300 \sim 500$ GeV is essential for discovering the light Higgs boson predicted by the supersymmetric models. Active discussions and detailed analysis of the scientists throughout the country were compiled into the report JLC–1 (KEK Report 92–16, JLC: Japan Linear Collider) which summarizes the possible accelerator design and physics at the Linear Collider. Reflecting upon the urgency of the construction of a Linear Collider at $300 \sim 500$ GeV, the High Energy Physics Committee of Japan proposed in April 1993 a plan for the second-term 3-year project. Here, the years $1993 \sim 1995$ were set the second-term development planning period, aiming at the development of the prototype main equipment and the optimization of the parameters and design, leading to the completion of a conceptual design. In particular, the completion of the ATF (Accelerator Test Facility), which is a miniature version of the JLC, was given a central position, and at the same time participation in foreign research and development was made and the participation of foreign countries in the R&D in Japan was invited.

As stated in the Preface, the High Energy Physics Committee of Japan set up this current Subcommittee in 1994. The Subcommittee submitted an Interim Report in July 1995 on the urgent topic of an early construction of the e^+e^- Linear Collider, thus consolidating the consensus of the academia. The basic statement in the report of the first Subcommittee: "the key for the breakthrough towards new physics is in the experiments at the energy frontier" has equally been supported by the current Subcommittee. The backbone for the evolution of this current report from the first report lies in the following two factors; first, the demand of physics and technological capabilities leading to an increased desire for an early construction of a Linear Collider, and second, the termination of the SSC project.

In Fall 1995, the Basic Law of Science and Technology was enacted by the Japanese parliament through multi-partisan support. This has a major impact on the future plan of high energy physics in Japan. As stated in the Basic Law, our country should play a leading role in the investment in fundamental science based on long-term perspective. However, if our contribution is centered on overseas research facilities, the foundation in basic science in Japan will not be improved, leading to a poor research ground as compared to the economic power. That the research funding for fundamental science should be doubled, as the Basic Law dictates, is reasonable since fundamental research in the past was based almost entirely in Europe and the United States. It is through the development of science and technology that our country can maintain the active economy also in the future in a society with an increase of the higher age population. The investment for the future should hence be given the highest priority even when the national budget is limited. The investment into high energy physics, in particular, should be seen in a long-term perspective as a part of the investment in fundamental science. It should be stressed that high energy physics is an area of fundamental science where a great scientific progress is expected in the near future, and that it is an area where the frontier research is expected to give rise to numerous technological offsprings which could contribute directly to the economy.

The development in high energy physics should be considered as one of the central themes of the frontier research areas, and now is the time for us high energy physicists to make the idea permeate into the academia, the political world and the industry. We believe that there is an exceptionally strong case for hosting the Linear Collider in Japan as our international contribution, since it is an academic project of fundamental importance, where our contribution has been most wanted, and since it is certain to attract many frontier researchers from overseas.

Thus looking at every aspect, the scientific importance of experiments to be carried out at the e^+e^- Linear Collider, the high quality of Japan's accelerator technology, the presence of a developed industrial basis for its realization, the consensus in the high energy physics community, and the status of the high energy physics projects overseas, it is clear that there is a well-founded need for the construction of the e^+e^- Linear Collider in Japan where Japanese scientists and industry play a leading role.

Chapter 4

The Principal Project

4.1 The Linear Collider Accelerator

4.1.1 The Principles of a Linear Collider

Electron–positron collider accelerator of the past have mainly been based on a storage ring system. The electrons and positrons are converged into bunches of particles with lengths of a few millimeters and widths of a few hundred microns, and they orbit around at the speed of light under the control of magnetic fields produced by electromagnets. The electrons and positrons emit synchrotron radiation in the forward direction and lose their energy, and in order to compensate for it there are radio frequency (RF) cavities placed in the ring. Since the bunches pass the cavity at a great frequency, a small number of low accelerating gradient in the cavity allow to store and preserve the beams with energies up to a few tens of GeV. However, the energy loss per unit time due to synchrotron radiation is proportional to the fourth power of the beam energy and inversely proportional to the square of the orbital radius of curvature. In order to keep the electric power supplied to the accelerating cavity constant and raise the energy, the orbital radius of curvature must be increased as the second power of the beam energy. The number of the various equipment comprising the accelerator is roughly proportional to the length of the accelerator, and thus the construction cost increases as the second power of the target energy. This storage ring system has contributed to many glorious achievements for energies up to that of the CERN LEP2 (center-of-mass energy 200 GeV maximum) which is currently in operation. However, the realization of energies greatly surpassing LEP2, which has a circumference length of 27 km, by an increased ring size is not realistic. This has led to the invention of the Linear Collider concept which utilizes the linear accelerator because it does not suffer from the synchrotron radiation loss. The Linear Collider accelerates electrons and positrons separately by two opposing linear accelerators and collides them at the center. By this system the accelerator length is approximately proportional to the target energy. We list the properties of the Linear Collider and the problems necessary to be resolved for its realization.

4.1.2 The First Challenge: High Power RF Technology

At the Linear Collider, the beams must be accelerated at once in a single cycle of the linear accelerator from the generation of the electrons and positrons to a few hundred GeV. This requires far more accelerating equipment than the storage ring system. Indeed, in order to realize the center-of-mass energy of $0.5 \sim 1$ TeV, linear accelerators of total length $20 \sim 30$ km is required even if a high acceleration electric field of ~ 50 MeV/m is utilized. The linear accelerators are composed of as many as a few thousand RF sources and accelerating cavities. The first challenge for the design of a Linear Collider lies in operating these numerous and high-electric-field accelerating cavities, as well as the high-electric-power RF sources driving them, with a good power efficiency and reliability.

4.1.3 The Second Challenge: Collisions

The frequency of the repeated collisions at the Linear Collider is determined by the repetition frequency of the accelerating pulses of the Linear Collider. Due to the upper limit for electric power and the technical issues in high electric power RF sources, this is limited to several hundred times per second. This is less than a thousandth of the case of a typical storage ring. On the other hand, the typical reaction cross sections in electron–positron collisions are inversely proportional to the square of the center-of-mass energy, and so a luminosity a hundred times greater than that of TRISTAN is required at a thousandth lower collision frequency. Due to the limit on the electromagnetic energy which can be stored in the cavities, it is impossible to raise the number of particles beyond the storage ring system in order to raise the luminosity. At the Linear Collider, the luminosity must be raised by powerfully focusing the colliding beam size to a thousandth that of the ordinary storage rings, namely, to the order of nanometers. The second challenge for the design of a Linear Collider is thus in realizing the emittance conservation during the acceleration and in realizing the small beam size and a stable running of collisions.

4.1.4 The Third Challenge: The Optimization of Parameters

When two bunches at the nanometer scale collide, in addition to the electron–positron particle reactions, the Beamstrahlung radiation is emitted due to the strong electromagnetic field created by the powerfully focused bunches. A large number of low energy electron–positron pairs are generated there. These will become the noise for the physical experiments. The number of their occurrence is proportional to the number of particles per bunch and inversely proportional to the width of the bunch. In order to perform meaningful experiments the pair-production noise must be kept below a certain level. Thus, the number of particles per bunch and the beam size at the collision point create a boundary condition for the design of the Linear Collider. In reality, these two parameters are also related to numerous parameters in the operation of the Linear Collider such as the operation conditions for the linear accelerators and the beam emittance. For this and many other reasons, numerous parameters are mutually interrelated, and their optimization is the third challenge in the design of the Linear Collider.

4.1.5 The Fourth Challenge: Reliability and Cost

For an efficient running of the experiments, it is important to raise the yearly integrated luminosity. To this end the maximum luminosity of the accelerators needs to be improved and be kept stable simultaneously. Therefore, in the designing of the accelerators, in addition to the beam acceleration, the beam focusing and the parameter optimization listed above, considerations must be made towards the reliability, the operational rate, the maintenance and the conservation. In other words, the long-term stable operation of the equipment is a necessity which requires a sufficient design margins. Another important problem is in keeping the production cost low, while keeping the quality of the equipment high. Indeed, in the construction stage of the Linear Collider, the manufacturing of the various and numerous equipment will be assigned to the industry. The viability of the production scheme to be taken up by the manufacturers, as well as the incorporation of the existing technology tested for reliability, should be considered carefully. This is the fourth challenge in the design of the Linear Collider.

4.1.6 Approaching the Problems

The development of the Linear Collider began throughout the world after the ICFA (International Committee for Future Accelerator) Workshop near the end of the 1980s. Various explorations were made regarding: for instance, the assessment of the accelerator technology. The First International Linear Collider Workshop in 1988 at SLAC marked the beginning of an organized study of the next generation Linear Collider systems. The first Linear Collider SLC at SLAC (center-of-mass energy $\sim$ 92 GeV) began its operation in 1986 and the experiments were started in 1989. The basic construction of a Linear Collider, apart from the capacity of each subsystem, can be found in SLC. The operational experience obtained there will be a basis of the next-generation Linear Collider. Due to the geographical limit, SLC accelerates both electrons and positrons in the same linear accelerator. The acceleration of electrons and positrons in two separate linear accelerators is a system which will be realized for the first time in next-generation Linear Colliders. Next-generation Linear Colliders have been studied and proposed in various forms in Japan, the United States, Europe and Russia. The possibilities contain, first of all, the choice in whether the main accelerators are made of superconducting or normal-conductors. For the case of the normal-conductors there is further choice in terms of the frequency and the bunch structure. There is also a proposal for the two-beam system, where one accelerator creates and amplifies RF power and supplies it to the other accelerator which is placed parallel to it. The groups in countries mentioned above have each from their own standpoint assessed the realistic possibilities regarding the various hardware in order to resolve the above four challenges, and have worked at wide-range constructional parameter optimization in the presence of friendly competition. In the 1990s, the laboratories KEK, SLAC, CERN, DESY and Protovino have each proposed as Linear Collider systems including the JLC (Japan), NLC (SLAC), CLIC (CERN), TESLA (international collaboration based in DESY), SBLC (DESY) and VLEPP (Protovino). The constructions of test accelerators such as ATF (JLC), NLCTA (NLC), CTF (CLIC), TTF (TESLA) also began at this time. In the first half of the 1990s the SLC luminosity went up and the polarized electron beams have come into use. In 1994, the international collaboration FFTB at SLAC succeeded in realizing a 60 nm beam spot size and its measurement. 1995 onwards has seen the outcomes of the test accelerators such as ATF, which includes the generation of the multi-bunch beam at ATF, the development of the acceleration and measurement techniques, the steady progress of the SLAC X-band klystron towards the realization of NLC, the development of the RF electron gun at CLIC and the progress in high electric field superconducting cavity. Thus the four problems described above are gradually being resolved, and today we are entering the practical designing stage after the conceptual studies.

4.2 The Basic Construction and Development of the Linear Collider

As mentioned in the third chapter, the Linear Collider research and development in Japan began in 1986 following the report of the first Subcommittee on Future Projects of High Energy Physics in Japan. The results are described in detail in the report submitted to the High Energy Physics Committee of Japan. As described in that report, we have adopted for the main linear accelerator a system where the peak voltage is raised by the temporal compression of the RF source from the pulse-operated klystron. This is supplied to the normal-conducting accelerating structure, which accelerates the electron–positron multi-bunch beam. Given this direction, the theoretical study of the beam dynamics and the parameters was organized in parallel with the hardware development including the detector equipment. Here we describe the conceptual design of the Linear Collider accelerator from the beam source to the collision point according to the above choices (see figure 4.1). The Linear Collider accelerator consists of: the electron/positron source generating a multi-bunch high-current beam, the damping ring which produces ultra-low emittance beam, the bunch compressor which reduces the bunch length, the main accelerator structure which accelerates electrons and positrons effectively while keeping the low emittance of the beams, high-electric-power RF source, the final collision unit which focuses and collides the nanometer scale beams, and the monitor system which operates and adjusts the system steadily and efficiently.

4.2.1 The Electron and Positron Sources

Although the electrons are usually generated by the thermionic-cathode electron gun, systematic study of the supersymmetric grand unified theory requires polarized electron beams. An electron source combining GaAs strained layer super-lattice photo-cathode and circularly polarized laser beam is the most promising for this purpose.

Positrons do not exist by themselves in Nature, and for their generation we shoot electron beams at energies of the order several up to ten GeV onto a heavy metal target such as tungsten alloy, and choose positrons out of the electromagnetic shower of particles generated. In order to improve the positron yield, a powerful focusing unit and improved acceptance will need to be developed. While the experience at SLC provides the data on the endurance of the metallic target against the heating by the incoming electron beam, there is much still requiring development, such as the radiation safety measures in an high beam current environment, and construction of the target with improved maintainability. More research and development should be strongly promoted.

4.2.2 The Damping Ring, the ATF

A beam generated at the electron and positron sources is accelerated up to a few GeV, and is injected into a small storage ring called the damping ring. By allowing the beam to emit synchrotron light for a few tens of milliseconds, the emittance is reduced. Here, great care must be taken over the precision in the location of the equipment such as the electromagnets and in the electric properties of the vacuum chamber and the accelerating cavities, in order to achieve the low emittance. The beam injection and extraction units and the feedback technology are also important. The lower limit for the emittance is governed by the beam optics of the ring. It is necessary to examine this limit early on and reflect this in the overall design. This was the motivation for the ATF project. The ATF is a development project which is important not only for simulating the damping rings but also in simulating parameters as closely with the actual Linear Collider as possible. The ATF can thus be said to be the miniature version of the accelerator equipment necessary for the Linear Collider.

4.2.3 The Bunch Compressor

The bunch length of the low emittance beam provided by the damping rings is a few millimeters, and this is too long for the focal depth which is about 0.1 mm. Also, the conservation of the emittance through the main linear accelerator would require the bunch length to be short in order for the RF acceleration to uniformly accelerate the particles within a bunch. The bunch length of a few millimeters is too long and this is compressed by a special beam line which comprises of beam optical units and accelerating equipment. There are several methods in the bunch compression, but all methods require a few hundred meters of equipment. It is necessary to experimentally assess the resolution of problems associated with the bunch compressor, and the prototype testing of the connections between the damping ring, the bunch compressor and the main linear accelerator with or without using beams needs to be analyzed.

4.2.4 The Main Linear Accelerator

The main linear accelerator is the largest part of the accelerator facility. A few thousand units of the radio frequency (RF) source, the RF power compression unit and the accelerating structure set with a unit length of about 10 m, are aligned through a tunnel of a total length $20 \sim 30$ km, and the units are operated at $50 \sim 150$ Hz. The peak output of the RF source is 50 MW or more, and after the pulse compression this becomes a few hundred MW. The electric field strength in the accelerating structure will be ~ 50 MV/m. In order to accelerate the multi-bunch beam without emittance degradation, the unprecedented development of a new type of accelerating structure which does not cause beam instability is necessary, as well as the precision location and the beam control technology. As mentioned above, it is important to develop a practical construction plan based on considerations of the reliability, operation rate, lifetime and the cost of the few thousand accelerator units.

Currently in Japan, as a central technology in the development of the main accelerator, we are studying the X-band linac. As a back-up technology, we have also begun investigating the C-band linac. The development of the X-band linac is carried out in close collaboration with SLAC and the Protovino laboratory. SLAC has succeeded in extracting 60 Hz output of 75 MW peak output power and 1.1-microsecond pulse width in 1996. SLAC has also succeeded in focusing the beams using permanent magnets for the sake of saving the operating power of the klystron. These provide a milestone for Linear Collider development alongside the experiments at FFTB. At the Linear Collider it will be necessary to install at least 5000 such klystrons and operate them stably. The methodology in mass-production and the improvement of the reliability are amongst the most important issues in the next step. The modulator power supplier for supplying pulsed power to the klystron has a large number of components and is an important item governing the reliability and the cost of the accelerator, and this requires more development too. The development of the C-band linac, including the hardware technology, has been started. As a back-up technology, evaluation of its reliability and cost is urgently needed. The possibility of the energy upgrade is another important factor.

There are currently multiple methods studied for the temporal compression and division of the klystron output, which effectively raises the peak electric power, and feeds it to the accelerating structure. The decision on the technology choice will have to be based on a broad range of factors including the results of the low and high RF power tests, and the stability and reliability of the entire systems.

There are various types of accelerating structures which have been developed. Generally, the mechanical precision of the individual accelerator cell can be achieved within the current industrial standard. In addition to the development of the component technology, the next outstanding tasks will include the further experimental studies, the mass production of high precision accelerating structures, the reduction of cost, and the development of the technology for installation of these components in the accelerator tunnel.

We are also developing the L-band superconducting cavity in Japan. Here we are establishing the cavity production and processing technology for a stable output of 40 MV/m high electric field based on the superb experience with superconducting cavity gained at TRISTAN.

4.2.5 The Final Focus Unit

The electron and positron beams which have been accelerated by the main linear accelerator to a high energy, while keeping the emittance low, are focused at the final focus unit to the nanometer scale and are collided at the interaction point. The considerations of the issues associated with the strong focusing, and the technological development of the precision control of the collisions and the measurements are essential in order to achieve and preserve a high luminosity. The collimators and the masks near the collision point, which will reduce the background to the experiments, will require special considerations, distinct from those in the conventional ring-type accelerators. The SLAC FFTB experiments which started in 1992 have studied the beam focusing and the control near the collision point. This is an experimental project pursued by an international collaboration. A Japanese group has also participated in it, leading to important achievements in beam optics design, the focusing magnet and the beam monitor instrumentation. As a result, the beam optics design, required for the final focus unit of the Linear Collider is in principle already demonstrated, and the monitoring technology for the nanometer-scale beam cross-section size appearing at the collision point has almost completely been established.

4.2.6 Other Factors

Design considerations on the accelerator control and beam diagnostic tools, autonomous feedback systems *etc* have much to learn from the experience from the operation and development of SLC. However, the beam control technology at the Linear Collider needs to be much more advanced than that at SLC in many respects, and concrete studies based on the specific design of the Linear Collider is urgently required.

4.3 Organization for the Linear Collider Development and Construction

The first Subcommittee on Future Projects of High Energy Physics in Japan pointed out in 1986 that research at the energy frontier is the most important task. As a national project, the development of the Linear Collider was proposed, and participation in international collaborative SSC project was supported. The current Subcommittee recommended that the Linear

Collider should be hosted by Japan, and while the construction will be realized by international collaboration with Japan playing a key role, the experiments will be done on an international and open collaborative basis. The field of high energy physics in Japan has so far reached the current stage by learning from Europe and the US, but this Subcommittee believes that through this construction of the Linear Collider and through its role in providing research opportunity to scientists throughout the world, Japan will make an international contribution affecting many facets in the future of Japan.

In the Linear Collider research and development, the various international collaborations of the past have functioned well. The early construction of the Linear Collider from now on will have to motivate such collaborations further and aggregate the wisdom both within the country and overseas. The determination of the technological methodology adapted for each part of the accelerator, and the detailed selection of the parameters, will need to be organized scientifically on the basis of the technological and practical merits, judged by the development groups centered on the laboratories in charge. The Linear Collider needs to be constructed according to the technological design which will stand up to international reviews, and for this reason an open environment for the research and development is essential. In realizing these activities, the Subcommittee truly realizes that Japan, in being the host country for the construction of the Linear Collider, is undertaking a great task and responsibility. To be the host country of the Linear Collider means that this could be the first Japanese opportunity to build a large-scale international center in fundamental science. This will be a long-term base which will be handed over from the current generation to the next generation. This will be a national and international contribution not only in the area of high energy physics but also in raising and keeping the level of particle beam accelerator science and other related fields. This naturally brings out the necessity for high energy physicists and accelerator scientists of Japan to pursue further their respective studies in accord with the status thus acquired. At the same time, this will be an extremely good opportunity in forming a model for the future of big science in Japan.

We must also actively promote the collaborative structure with the national and overseas industry. Our primary anticipation for the industry is in their combining of the industrial high-level technology with the knowledge of accelerator amassed so far, leading to a improved reliability of the various hardware for the Linear Collider and optimized mass production. Since the technology in demand are often of a standard unprecedented in the conventional accelerators, the research institutions and the industry should both analyze the technological problems and their solutions, and sharing the results as a team. For many cases the collaborative involvement of researchers both in the industry and in the academia is called for from the initial stages of development. This Subcommittee recommends the leaders of high energy physics community and of KEK to keep promoting this collaborative research and development structure.

In order to clarify the structure of international technological collaborations, the technological necessities in the development and construction of the Linear Collider must be found out in their entirety, and this information must be made a common realization of the researchers involved. Furthermore, the presence of the facility, equipment and human resources in the countries involved which are available for the Linear Collider project should be clarified through straight communication, and the utilization of these resources in the early realization of the Linear Collider should be sought. The strategy necessary in the construction of the new facilities and the development of the human resources should be actively discussed. In the past, various test facilities throughout the world and the KEK ATF have been utilized for collaborative development, and will continue to be utilized internationally. Given the progress in research and development, a structured analysis of the new facility required for the experimental studies should be made rapidly. In addition, the analysis of the tunnel facility for the Linear Collider accelerator as well as the site evaluation work need to be made.

For the smooth execution of the principal project, the e^+e^- Linear Collider, it is important for the high energy physics community as a whole to support the project, and the opinions of the community should be reflected sufficiently in it. To this end, a committee comprising of the leaders of the Linear Collider project in the universities and KEK should be created, which will take in the opinions of the community and discuss the strategies to be adopted. In order to respect these strategies and to execute the project with due responsibility, KEK should host the ‘LC promotion office’, which will be the center for the promotion of the research and development, construction and experimental preparation. The strategies in executing the project and the debates leading to the decisions should be made public, and efforts must be made for improved communication, for which the LC promotion office and the committee described above are responsible. In addition, it is of course necessary to form an international assessment committee which continuously assesses the progress of the project. These organizations for the promotion of the project need to become internationalized as the project itself will become international.

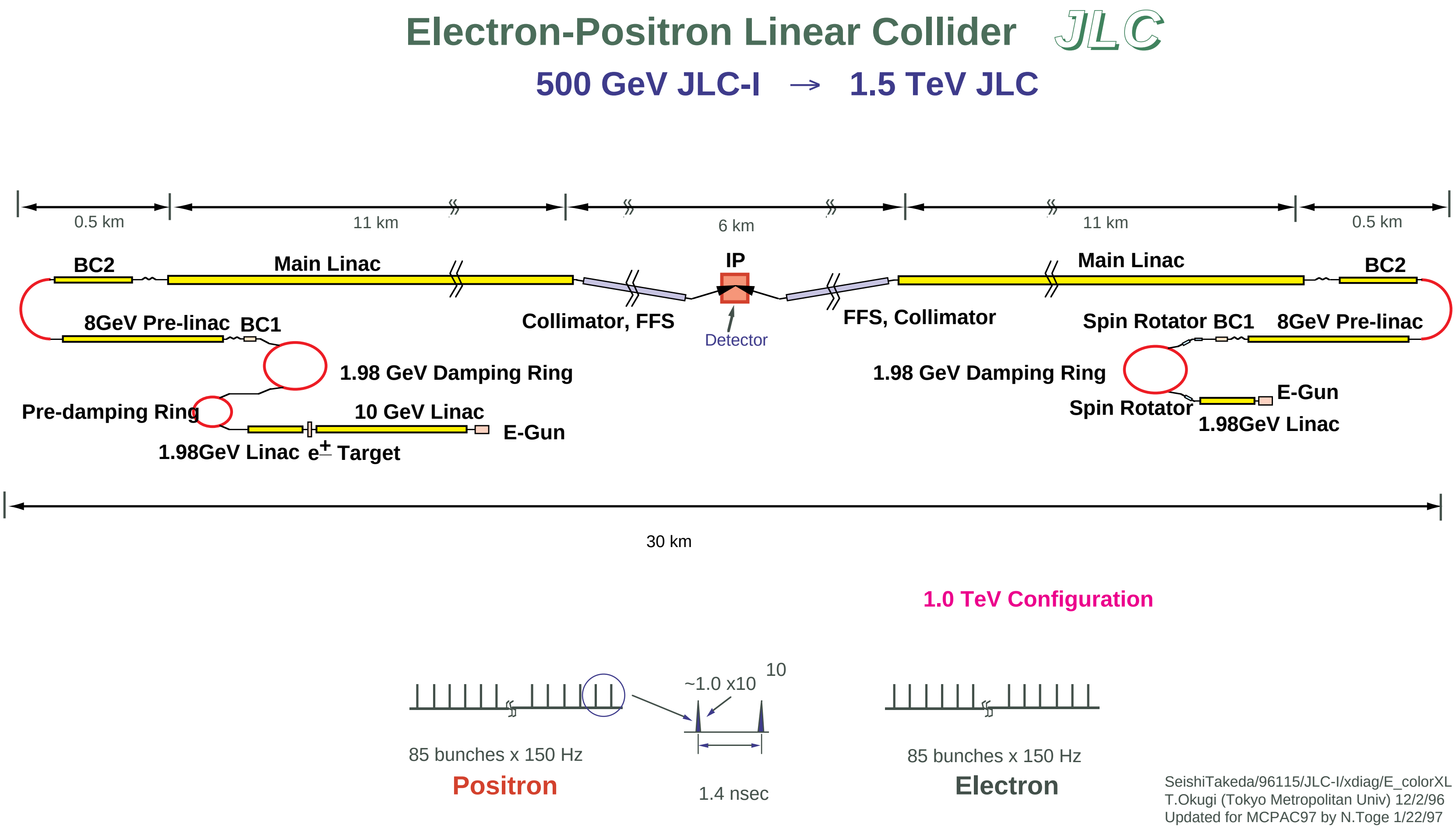

Figure 4.1: The conceptual design of the e^+e^- Linear Collider.

Chapter 5

Other Projects

5.1 An Overview

A large part of progress in high energy physics has so far been brought about from accelerator experiments which are directed at the energy frontier. This is because the purpose of particle physics is in the exploration of the infinitesimal world, and the measurements of reactions at higher energies are the most direct method for studying material structure at smaller scales. The experimental research at large accelerators has successfully confirmed predictions of the unified electroweak theory, contributing greatly to the establishment of the Standard Model. Now, the current theoretical research focuses on the grand unified theory which unifies the strong, the electromagnetic and the weak interactions, the supersymmetric grand unified theories which are based on supersymmetry, the supergravity and superstring theories which unify all forces including gravity. Phenomenological predictions of these new models are calculable for various measurable and observable processes, and the methodology in particle physics have become numerous and diverse. Given this diversification in the particle physics methodology, we believe that unique focus of individual research group should be valued, and that research plans other than the Linear Collider project should also be promoted.

For example, diversification of the research projects in the energy frontier is shown by the TRISTAN experiment in Japan, the international collaborative experiments at LEP and SLC studying Z^0 physics at electron–positron colliders, the discovery of the top quark in proton–anti-proton collision experiments at the Fermilab TEVATRON, the *ep* collision experiments at HERA and so on. The Japanese experimental groups have chosen the suitable projects from programs at these various types of accelerators, and have made impressive achievements. In particular, the university research teams have actively taken part in the overseas large-scale collaborative projects through for instance the US/Japan Cooperation in High Energy Physics, advancing further on their research achievements. Japanese researchers are also playing an active role in the participation in the 10 TeV energy range large proton–proton collider project LHC.

Complementary with the energy frontier experiments, projects in Japan such as the low energy high-luminosity electron–positron colliding beam accelerator KEKB and the high-intensity proton accelerator JHF are making a steady progress. These projects aim at studying CP-violation and other problems in the fundamental symmetries and at studying physics at high energy scales through the study of the rare decays. In terms of non-accelerator experiments such as the proton decay and the neutrino experiments, Japanese physicists have produced top-class results superlative in the world.

The Japanese high energy physics researchers have made achievements merited internationally in various research projects. The environment supporting the diverse research topics should hence be maintained in the future.

Such diversification of research in particle physics is important not only in promoting research achievements, but also in nurturing researchers possessing long-term perspective. In recent years, the future plans in high energy physics experiments have become large-scale in their scope, requiring a considerable number of years towards their realization. In this era, continuous generation of young talented people requires the continual experimental activities, especially at universities, which are provided by experimental projects other than the Linear Collider project. The steady build-up of young generation of researchers, with the experience and knowledge obtained through the various large and small experiments both inside and outside the country, is essential for the future success of the Japanese high energy physics.

In other words, the execution of the diverse projects promotes the national personnel development, while the acquisition of depth and variety in research leads to long-term success of the Linear Collider project. Thus, while emphasizing the importance of the Linear Collider project, we believe that the other projects also need to be promoted steadily at the same time.

The projects other than the Linear Collider project can be categorized roughly into the projects in Japan and the international collaborative experiments. They range from researches as extensions of the currently operating research projects, to the energy frontier projects such as the LHC project. They also vary in scope, from the large-scale domestic projects such as KEKB and JHF, down to university level international collaborations. Furthermore, there will need to be flexibility enough to accept programs based on new ideas which are not in the list below. We summarize below the goal, the current status and future perspective for each of the projects in Japan and overseas.

5.2 Projects in Japan

As for the projects in Japan, the three ‘branches’ of the first Subcommittee on Future Projects of High Energy Physics in Japan of 1986 have developed into three pillars at the core of the projects in Japan. The first pillar, the low-energy high-intensity electron collider project, is currently in progress in the form of the high-intensity electron–positron collider KEKB built on the success of the TRISTAN project. The preparations are under way at KEK and at other national and foreign research institutes. The KEKB project aims to study the origin of the violation of the CP symmetry. The second pillar, the high-intensity proton accelerator, is being developed in the form of the 50 GeV 10 μA high-intensity proton accelerator project JHF. This takes the form of an extension of the present 12 GeV proton synchrotron at KEK. As for the third pillar, non-accelerator particle physics experiments, there are various experimental plans such as the Superkamiokande which has already begun operation. As a completely new form of particle physics experiments, there is the long-baseline neutrino-oscillation experiment which is to begin operation in the Japanese Fiscal Year 1998, where neutrino beams, created at the KEK 12 GeV proton synchrotron, are projected towards the aforementioned Superkamiokande detector which is located 250 km away. These projects are all complementary with the Linear Collider project in the energy frontier, and are pursued as extensions of previous or current projects. We describe the physics and the perspective for each of the projects in the following.

5.2.1 The KEKB Project

The violation of the CP symmetry is one of the most important subjects in particle physics, since it is related to the origin of the matter universe. However, there has been no definite experimental evidence for CP symmetry violation other than in the $K^0\bar{K}^0$ system where it was discovered in 1964. In 1972, Kobayashi and Maskawa investigated possible sources of violation of the CP symmetry in the unified theory of the weak and the electromagnetic interactions based on the gauge principle. They concluded as follows: the observed violation of the CP symmetry requires the presence of either six or more quarks or several new particles such as scalar bosons and new interactions. This first possibility is attractive for not requiring any new interactions, but was too revolutionary to be immediately accepted at the time, when only three quarks u, d, s were known. However, the subsequent progress in high energy physics led to the discovery of the c (charm) quark in 1974, the b (bottom) quark in 1976 and the t (top) quark in 1994, leading to a wide acceptance of the Kobayashi-Maskawa model as the standard theory for CP violation.

As pointed out in the original paper of Kobayashi and Maskawa, there are several other possibilities for the origin of the CP violation, and experiments capable of distinguishing between these have become desired. In particular, the Kobayashi-Maskawa model predicts the CP violation effect, whose strength is only one part in a thousand in the neutral K-meson system, to be as great as one tenth in the neutral B meson system. This should be verified experimentally.

From this perspective, the KEKB project has been launched as an electron–positron collider experiment which aims to deepen the understanding of CP violation through the detailed investigation of the decay processes of the B mesons. KEKB adopts a scheme where B mesons are created in high-luminosity collisions of electron and positron beams of asymmetric energies. In addition to the potential discovery of CP violation at systems other than the neutral K mesons, this project is capable of measuring the complex phase of the Kobayashi-Maskawa matrix elements, and can provide a clear resolution to the choice between the two possibilities proposed in the 1972 Kobayashi-Maskawa paper for the origin of the CP violation.

The construction project of the KEKB accelerator began in 1994 reusing the old TRISTAN MR tunnel. The KEKB has beam energies of 8 GeV on 3.5 GeV and design luminosity goal of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Its design is based on the technology developed further upon experiences cultivated at the TRISTAN project, such as the RF-cavity technology, is adopted. KEK also possesses medium scale electron accelerators which are currently operational, such as the accumulation ring (AR) and the Photon Factory ring. One advantage at KEK is that KEKB can be constructed, while tests are being made at these accelerators.

There is only one beam collision point at KEKB, where the BELLE experiment is to be installed. The detector is a spectrometer comprising the silicon strip detector, the drift chamber and the CsI calorimeter. A special attention is paid in providing high-precision measurements of low energy particles. The detailed design for the detector is already complete, and the construction is in steady progress.

There are several other projects at institutes throughout the world which aim to study CP violation in B meson systems. At SLAC, the construction of an asymmetric electron–positron collider (PEP–II), similar to KEKB, is under way. Its experiments are due to begin simultaneously with KEKB. At Fermilab, experiments utilizing B mesons from TEVATRON are planned. At DESY, the HERA–B project is planned, which utilizes B mesons created in collisions of the HERA proton beam with a fixed target. CERN is planning on the LHC–B project, where similar measurements will be made using B mesons produced at LHC.

Numerous simulation studies have been made on the physics potential of the KEKB project. The following scenario is being considered. Firstly, according to the Kobayashi-Maskawa model, CP violation in the decay mode $B \to J/\psi K_s^0$ should be observed within one or two years of initial experiments at an accumulated integrated luminosity of between 20 and 60 fb^{-1}. If the signal is detected, not only will this be the first discovery of CP violation outside of the K meson system, but it will be a verification of the mechanism of CP violation based on the mixing of six quarks, which was the principle behind Kobayashi and Maskawa's prediction on the existence of six quarks in 1972. If the CP violation is not observed during this period, it will strongly indicate that the CP violation in K mesons cannot be explained in the framework of the Kobayashi-Maskawa model.

In the second stage of the project, the maximum luminosity of the KEKB accelerator will reach the target value $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and an integrated luminosity of 200 fb^{-1} will be accumulated. The measurement of all parameters of the unitarity triangle will become possible then, and all matrix elements of the Kobayashi-Maskawa matrix, including their complex phases, will be made, except for V_{ts}. This will allow the confirmation of the consistency of the unitarity triangle, the comparisons with the decays of the K and the D mesons, and tests of all other processes involving the Kobayashi-Maskawa matrix. Later on, the measurement precision can be improved, and if any contradictions are discovered in any of these, they will be a basis for studying Physics beyond the Standard Model. Furthermore, by raising the KEKB energy by 5

%, the CP violation in B_s decays can be discovered and the decay modes can be studied.

In any case, KEKB is expected to continue producing important results for more than ten years after its starting operation, and the pursuit of the KEKB project will be an integral part of the progress of high energy physics in Japan.

5.2.2 The Long-Baseline Neutrino-Oscillation Experiments

While neutrinos are assumed to be mass-less in the Standard Model, the possibility that they may possess small masses and induce the quantum mixing of the three generations of leptons, is an important subject of particle physics. It is contrasted with the quark mixing through the Kobayashi-Maskawa matrix. It has been discovered recently that the number of solar neutrinos observed at Kamiokande and other underground experiments is considerably smaller than predictions of the standard solar model. It is conjectures that this is likely due to neutrino oscillations. Furthermore, Kamiokande and other experiments have observed an anomaly in the ratio between the muon neutrino and the electron neutrino in the atmospheric neutrino flux, and this indicates that the muon neutrinos created in collisions of cosmic rays in the upper atmosphere turn into other neutrinos before reaching the underground detectors.

Whether the anomaly in the atmospheric neutrinos is due to neutrino oscillations can be verified in terrestrial experiments. The long-baseline neutrino-oscillation experiment which connects KEK and Superkamiokande, was planned in this vein. Its preparations are under way ahead of other similar experiments in the world. This experiment uses muon neutrinos created by the 12 GeV proton synchrotron at KEK and measures their flux at Kamioka, 250 km away from KEK, using the Superkamiokande detector which is the largest water Čerenkov device in the world.

If the muon neutrinos turn into electron neutrinos, Superkamiokande will detect electron neutrinos, and if the muon neutrinos turn into other particles, Superkamiokande will detect a reduction in the number of muon neutrinos. In order to detect the conversion into the tau neutrinos directly, a higher energy for the neutrino beam is necessary. An upgrade to the neutrino source which utilizes the 50 GeV proton synchrotron of the Japan Hadron Facility (JHF) is currently planned, and is described in the next subsection.

5.2.3 The Japan Hadron Facility (JHF)

The Japan Hadron Facility (JHF) is a project for constructing a high intensity proton accelerator complex, comprising the 50 GeV 10 μA proton main ring (50 GeV PS) and the 3 GeV 200 μA proton booster ring. This project is being promoted mainly by researchers in the field of nuclear physics, but it is also an inter-disciplinary project which can serve high energy physics and solid state physics through the use of its secondary neutron and meson beams.

The 50 GeV proton synchrotron of the JHF project will exceed the AGS accelerator of the Brookhaven National Laboratory (BNL) in the United States both in beam energy and intensity, making it the most powerful machine in the world in this energy range. The high energy physics experiments to be carried out at JHF can be considered as extensions of the particle physics experiments which are currently carried out at the 12 GeV KEK proton synchrotron accelerator (KEK–PS).

The research in particle physics studied at the JHF project can be characterized as pursuit of the 'Intensity Frontier' with high-intensity proton beams, as opposed to experiments at the energy frontier. In particular, the precision measurements of the K meson rare decays, such as the $K \to \pi\nu\bar{\nu}$, will allow tests of the Standard Model and the determination of the Kobayashi-Maskawa quark mixing matrix elements. The search for the decay modes forbidden in the Standard Model will allow the study of new physics beyond the Standard Model. Another important topic will be the search for the hints of new physics through the investigation of new modes of CP symmetry violation and time-reversal symmetry violation, and through the studies of fundamental symmetries in the K meson system.

Another important application is the upgrade of the long-baseline neutrino-oscillation experiment, mentioned in the previous section, using the JHF 50 GeV proton synchrotron. By using neutrino beams with higher energies, direct measurement of τ lepton appearance in the final state through neutrino oscillation will become possible at Super-Kamiokande, besides higher precision and statistics are expected in studies of neutrino oscillations in general. Furthermore, if oscillations are seen, it will also be possible to investigate the CP violation in lepton mixing, analogous to the Kobayashi-Maskawa mechanism in quark mixing. It is hoped that the long-baseline neutrino-oscillation experiment will provide a key to the understanding of the still mysterious properties of the neutrinos.

By using the high intensity muon beams generated from a proton beam, it will be possible to investigate lepton-flavor violating processes such as $\mu^+ \to e^+\gamma$ and $\mu^- - e^-$ conversion in nuclei with an unparalleled sensitivity. Many models, which are extended from the Standard Model, such as the Supersymmetric Grand Unified Theory, predicts lepton-flavor violation at the order of a tenth or a hundredth of the current experimental lower bound. They will become within the reach of experiments at JHF. The rare muon processes, along with the proton decay, are considered to be the most appropriate experimental measurement in the testing of the Supersymmetric Grand Unified Theory.

Considering the fact that hadron accelerators capable of fixed target experiments have become scarce throughout the world, it is hoped that the JHF project will attract international interest as a facility open to the world. The Japanese experimental groups which have taken part in the fixed target international collaborative experiments in the United States and Europe will gain a ground for research activities based in Japan. We consider it necessary from now on for Japan to take up a leadership in international research collaborations and to promote the collaborative experiments at JHF.

5.2.4 Non-Accelerator Particle Physics Programs

The current directions in particle physics capitalize on the success of the electroweak unified theory and formation of the Grand Unified Theory which involves also the strong force, and theories which also unify the fourth force, gravity. The experimental verification of these unified theories have become essential for the progress of particle physics. Non-accelerator particle physics programs aims at finding the proton decay, events induced by finite neutrino masses, and magnetic monopoles and so on, which are predicted by Grand Unified Theories. Since most of these are difficult to study in the accelerator environment, non-accelerator particle physics programs are complementary to accelerator particle physics programs. The simultaneous execution of both types of experiments is hoped to bring further progress in particle physics.

Particle physics deals with fundamental laws of nature that governs the creation, the evolution and the end of the universe. The detection of the signals from particle interactions which took place during the creation of the universe, the creation of the elements and the formation of galaxies, holds the key to clarifying the picture of the universe. Another important topic in non-accelerator particle physics is detection of particles originating from the Earth, the Sun and the active galactic objects, and the detection of the particles which have been produced through the evolution of the universe. Discoveries in such studies can bring revolutions to cosmology and particle physics, and this field has attracted much attention recently.

Non-accelerator particle physics research in Japan has been playing the leading role in the world. Particularly outstanding research achievements have been accomplished at experiments, such as, the Superkamiokande experiment which chiefly aims to detect the proton decay, the solar neutrinos and the atmospheric neutrinos, the search for the double beta decay and the cosmic dark matter at Osaka University, the search for the cosmic anti-matter and the cosmic dark matter at University of Tokyo, and the search for the axion at Kyoto University have cultivated important results. They deserve continued support in the future.

As described above, Nature and the Universe are themselves a great laboratory for particle physics. Non-accelerator particle physics, which explores a new aspect in particle physics and cosmology, deals with much that is still unexplored, and it is important to promote unique original research activities which cultivate this field. The development of devices for detecting ultra-weak particle interactions, based on high capacity liquid scintillator planned at Tohoku University, and various experiments involving ultra-cold neutrons planned by the physicist group supported by Grant-in-Aid for Scientific Research on Priority Areas are amongst the most promising future projects.

For the sake of progress in particle physics, while the advancement of accelerator particle physics at the energy frontier is the most pressing topic, smaller-scale and original research in non-accelerator particle physics will also be important. Such research activities lead not only to the progress in particle physics, but also to the training of researchers and to the advancement of the experimental technology, which lead to improved general research capability.

5.3 Projects in Overseas

The prime motivation for participating in international collaborative projects is in allowing the researchers to take part in large scale projects whose execution is impractical for one country alone, and in contributing to ingenious experiments which are not carried out in Japan. At the same time, the participation will also bring about positive influence towards the cultivation of the human resources. For instance, by providing young people, such as the graduate students and the assistants, with opportunities of participating in experiments overseas, even at smaller scale ones, personnel can be nurtured with a global orientation who are capable of carrying out research in collaboration in an international environment, and their personal relationships with overseas researchers and experience will be essential for promoting future large scale collaborative projects.

We examine below the current status and the future perspective of the international collaborative experiments where Japanese high energy physicists are participating.

5.3.1 The LHC Project

LHC (Large Hadron Collider) is a 14 TeV next-generation proton–proton colliding beam accelerator at CERN, which will be constructed inside the LEP tunnel after the termination of the LEP2 program. LHC will begin the proton-proton collision experiments in 2005, and its final target luminosity will be $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The Japanese contribution will consist of participation of researchers from KEK and the universities in the proton–proton collision experiment ATLAS, as well as in the construction of the accelerator.

As discussed in chapter 2, the biggest objective of the LHC project is the discovery of the Higgs particle. The collider is capable of finding not only the Standard Model Higgs particle but also the Higgs particles in a wide mass range predicted by the supersymmetric theories. It will also search for colored supersymmetric particles, explore new phenomena which are predicted by the technicolor model, and look for other unknown phenomena beyond the Standard Model at the energy frontier. In addition to the search for new particles, it will also allow us to study a rich set of phenomena such as the precision measurements of the top quark properties and the measurements of CP violation in B mesons decays. The LHC project can also support various options such as the LHC-B project which focuses on the measurement of CP violation, and the collisions of heavy ions such as lead ions.

5.3.2 The SLC/SLD Experiments

SLC, which began its high energy physics program in 1989, is the first Linear Collider in the world which accelerates electrons and positrons to 50 GeV, splits them via arcs and collides them. High energy physicists from Nagoya and Tohoku Universities have been participating in the SLD detector experiment as a part of the US/Japan Cooperation in High Energy Physics. The acceleration of polarized electrons became possible in 1992, and the measurement of the electron polarization asymmetry in Z boson production cross section led to the measurement of the Weinberg angle of the electroweak interaction at an accuracy comparable to the LEP data. The SLD group has been considering an option where the final focus unit will be modified and the experiments continued in order to observe about three million polarized Z boson events. The experience gained at SLC and SLD is hoped to play an essential role in the development of the accelerator and the detector at the future Linear Collider project.

5.3.3 LEP

The European Laboratory for Particle Physics (CERN) constructed the Large Electron–Positron Collider (LEP), which is the largest and the highest energy electron–positron colliding beam accelerator in the world, and began experiments in 1989. Out of the four detectors, the OPAL experiment has a group of Japanese researchers mainly from the University of Tokyo, which has taken a central role in the project since the design stage of the detector.

LEP began experiments with the center-of-mass energies near the Z boson mass (LEP1). In addition to carrying out precise verification of the Standard Model such as the determination of the quark and lepton generation numbers, LEP experiments searched for new particles such as the Higgs boson and supersymmetric particles and new phenomena. In the second stage (LEP2), the beam energy was upgraded and in 1996 the center-of-mass energy exceeded the W boson pair production threshold, reaching 172 GeV. LEP will continue upgrading the beam energy and will carry out precision tests of the electroweak interaction using W boson pair production. In addition, the Higgs boson of mass up to about the Z boson mass can be discovered. There is also much hope towards the discovery of the supersymmetric particles.

Ever since the initial experimental program, LEP has been at the energy frontier, and the physics studied at LEP is of the same nature, albeit at smaller energies, as the physics of the next generation energy frontier at the Linear Collider. Thus, it is hoped that the physics results gained at LEP2 will provide crucial information for the Linear Collider project.

5.3.4 Fermilab TEVATRON

TEVATRON is a proton–antiproton colliding beam accelerator of the highest center-of-mass energy in the world (1.8 TeV) built at the Fermi National Accelerator Laboratory (Fermilab) in the United States. Its operation began in 1987. The characteristic feature of a hadron collider at the energy frontier is that it is capable of discovering new phenomena at energy ranges which are out of the reach of the contemporary electron–positron colliders. A Japanese group of researchers from University of Tsukuba and other institutes has participated in the CDF experiment, which is one of the two collider experiments at TEVATRON, since the preparatory stage. An integrated luminosity of 0.11 fb^{-1} has been acquired by the February of 1996, which led to the evidence for top-quark production in 1994.

In 1999, the main injector ring, currently under construction, will be completed, and it will allow the data accumulation of 2 fb^{-1} per year. This will enable precision measurements of the top-quark and W-boson masses, as well as precision measurements of the parameters in the Kobayashi-Maskawa matrix involving B mesons. As for future programs, the TeV33 project will involve construction of a recycler ring around 2004, which will be used as the storage ring for antiprotons. It will enable improvement of the luminosity to $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is anticipated that the discovery of the Higgs boson up to the mass of 120 GeV will then be possible.

5.3.5 DESY HERA

The Deutsches Elektronen-Synchrotron (DESY) operates the only existing electron–proton colliding beam accelerator (HERA) in the world, which began its operation in 1992. There are two international collaborative experimental groups organized for the collision experiments, and members of the Institute of Nuclear Study at University of Tokyo (currently a part of KEK) and Tokyo Metropolitan University have been participating in the ZEUS collaboration.

Electron–proton scattering experiments at high energy is effectively a huge electron microscope which utilizes the electrons as the probe for studying the quarks inside the proton. The center-of-mass collision energy is about 300 GeV, and is more than ten times higher than the corresponding fixed target experiments in the past. Using the data obtained up to 1995, precision measurements were made on the distribution of quarks and gluons inside the proton. The results provided a good test of Quantum Chromo-Dynamics (QCD) which constitutes a core of the Standard Model.

After 1998, scattering experiments using a polarized electron beam will become possible, and an upgrade towards a higher luminosity will be made in 2000. It is hoped that this will enable various precision studies of the electroweak interactions such as the search for the right-handed W-boson and right-handed neutrinos.

In addition to the collision experiments described above, there is the HERMES experiment which studies the scattering of a polarized electron beam off a stationary nuclear target. The experiment has been in operation at HERA simultaneously with the collision experiments since 1995. Members of Tokyo Institute of Technology have participated in this experiment. Furthermore, an approval has been given to the HERA-B project, which produces B-mesons using the HERA proton beam on a stationary nuclear target. The detector for the HERA-B project is currently under construction.

5.3.6 Fixed-Target Experiments

There are several noteworthy fixed-target experiments carried out abroad as international collaborative projects. Examples include the KTeV experiment carried out at the Fermi National Accelerator Laboratory (Fermilab) and the E787 experiment at the Brookhaven National Laboratory (BNL), which study the weak interaction through the precision measurements of the K meson decays. The Osaka University group has participated in the KTeV experiment, carrying out the measurement (E832) of a direct CP violation parameter Re(ϵ'/ϵ) and the search (E799) for the rare decay modes such as $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$. Physicists from KEK and Osaka University have participated in BNL E787 and have searched for $K^+ \to \pi^+ \nu\bar{\nu}$. [1]

After the year 2000, there are plans under way for experiments involving the decays of the K mesons using the Fermilab main injector ring and the BNL AGS. One of the principal topics in the study of the K meson decays will be the detection of the direct CP violation in $K_L \to \pi^0 \nu\bar{\nu}$ to determine the η parameter in the Kobayashi-Maskawa matrix. This experiment will be carried out concurrently with the B-factories and will play a complementary role in the search for the origin of CP violation.

At the CERN Super Proton Synchrotron (SPS), there are two neutrino experiments currently in progress which aim to detect the neutrino oscillation $\nu_\mu \to \nu_\tau$. A Japanese group based mainly in Nagoya University has participated in the CHORUS experiment, being responsible for the emulsion target which is the essential part of the experimental setup. We await the experimental results. The Nagoya group is also running an experiment (E872) which searches for ν_τ at Fermilab by using the emulsion target technique.

As for the next-generation neutrino experiments, CERN and Fermilab have plans for long-baseline neutrino-oscillation experiments, which are due to start operation at the beginning of the 21st century. These long-baseline experiments will allow the detection of neutrino oscillations $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ for a broad parameter range which has not been covered before, thus leading to clarification of the nature of the neutrinos.

In addition, there is the COMPASS experiment that has been proposed through a consolidation of research programs on glueball and other hadron spectroscopy. Japanese groups are participating in this and also in the study of the nucleon spin structure functions at SPS by using the proton and muon beams.

5.3.7 The Tau-Charm Factory

At the Institute of High Energy Physics (IHEP) in China, the Beijing Tau-Charm Factory (BTCF) is currently under construction. This is an electron–positron two-ring accelerator collider with a beam energy of 1.5∼3 GeV and the target luminosity of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. BTCF aims at studying the scalar glueball, the particle–antiparticle mixing in the D-mesons, and the CP violation in the decay of the tau. KEK has announced its support for the BTCF accelerator and detector development, and the Asian Committee for Future Accelerator (ACFA) also supports the pursuit of the R&D. This project is the only accelerator project for high energy physics programs in Asia outside Japan, and may become an important corner stone in the China-Japan collaboration in the future.

---

[1] *Note added on the English translation (Jan/23/1998):* The first candidate event was observed in the summer of 1997.

Chapter 6

Human Resources Development and Organization

6.1 An Overview

High energy physics is a field which utilizes a variety of frontier scientific technology. In order to achieve progress in the research of particle physics through acclerator and non-accelerator experiments, it is desirable to raise a broad interest and to aggregate a wide range of personel.

High energy physics is a field based on large-scale projects with long term perspective. For the success of the principal project, the e^+e^- Linear Collider, it is essential to clearly define the direction of the project and to exploit fully the collective capability of the community. At the same time, it is very important to have a research system which encourages the creativity and the enthusiasm of the frontier researches. The successful execution of such projects requires the nurturing of the younger generation researchers.

However large the project might be, the driving force of research lies in the creativity and enthusiasm of the individual researchers, and the key in pushing ahead the project resides in extracting such indivusual capability. The role of the leaders of the organization is not only to show the direction of the project in general, but also to provide a creative environment, in which unique ideas can be introduced to the system after a scientifically fair evaluation.

The next principal project e^+e^- Linear Collider is a project of the Asia–Pacific region which is open to the rest of the world. Efforts should be made toward the build-up of an environment which is suitable for promoting an adequate international set-up. This is required for aspects of both the project organization and encouragement for personnel, from the R&D and construction phase of the project.

6.2 The Roles of KEK and the Universities

As a result of discussions on the interrelationship between the universities and inter-university research institutes, the High Energy Committee of Japan founded the Subcommittee for enhancing the activities of university high-energy-physics groups in 1996. The Subcommittee on Future Projects of High Energy Physics in Japan expresses its support for the important activities to be carried out by the Subcommittee for enhancing the activities of university high-energy-physics groups, and hopes that discussions from broad perspectives there will be reflected for the benefit of the next-generation researchers who would be responsible for future developments of high energy physics.

Japanese high energy physics experiments so far have been carried out mainly in the form of collaborative work in constructing experimental facilities and conducting experiments which utilize the infrastructure of central laboratories, most typically KEK. Many research projects have been conducted in the framework of such collaborations between universities and central laboratories. Training of the next-generation researchers has also been taking place in such an environment. It should be noted that a superb work environment, where top-class research activities are conducted, is indispensable for educating competent scientists who would carry on the research leadership of tomorrow. The TRISTAN project has played a great positive role in this respect. Namely, the Japanese high energy physics community has seen a vast growth in its population and competitiveness, and an increasing number of universities, previously with no high energy physics groups, have come to join TRISTAN experiments. Naturally, this trend should be maintained and encouraged through the B-factory project, eventually passing on to the Linear Collider project.

At present, more than a half of the entire Japanese high energy physics researchers at universities belong to a group with approximately 10 or more members each, where graduate students are included in the count. However, the rest of the high energy physicist population is distributed in much smaller groups with only one or two staff members each, and they are facing difficulty participating in large collaborations. On the other hand, the researchers at universities have an advantage of having a greater access to undergraduate students, and are in a position to give more positive impacts on them towards high energy physics. It is imperative that the efforts of researchers under varying conditions be coherently consolidated for promoting the principal project. The importance of building up structured collaborative links among universities, and between KEK and universities, must be underlined.

While promoting the Linear Collider project, the university groups have a specific responsibility for raising the next-generation researchers, as well as for spearheading the work in new, advanced research topics. In this context, an important aspect of their task lies in R&D efforts on accelerator and detector technologies, which are driven by flexible thinking and long-term perspectives. For this purpose, suitable research infrastructure needs to be steadily accumulated in universities so that they have their own R&D capabilities for developing pioneering experimental technologies for the future. This definitely allows universities to have more effective collaboration with KEK.

Due to the government policy for efficient execution of the budget, the funding and human resources for those research programs which utilize the KEK facilities have so far been preferentially allocated to KEK. Although the current system is in a way efficient, it is recognized that there are rooms for improvement. A point to be noted here is that the system has to be operated in a way that individual university groups are encouraged to exercise their research capability to its full extent, with a sufficient degree of self discipline and long-term perspective and commitment. This is particularly important for creating an even more solid collaborative relationship between universities and KEK. For these reasons, this subcommittee considers it important to explore the possibility of a revised system that allocates budgets to universities based on clarified responsibilities and commitment in high energy physics projects.

6.3 Diversity of the Human Resources for the Principal Project

The realization of the Linear Collider requires the aggregation of the frontier technologies. In addition to technologies specific to high energy physics, those from various other frontier areas related to materials and manufacturing need to be collectively used. Therefore the project should attract the attention of researchers from a broad range of communities, and the personnel cultivation and the formation of the experimental organization need to be made more broadly, while extending the bounds of the high energy physics community. The progress in the field of accelerator science has generated a variety of users, for example in solid state physics through the use of synchrotron radiation and neutron beams, in radiation therapy through exploiting various particle beams, and in the study of future energy source problems. It is desirable to activate communication among scientists in these fields, especially with the young researchers who are interested in accelerator technology and high energy experiments.

The number of engineering and technical staffs at universities and research laboratories has been small as compared to those in the US and in Europe, and it is decreasing further as a result of the general reduction of civil servants in Japan. It is necessary for the entire high energy physics community to keep trying to obtain the support of the public and the bureaucratic sectors for stopping this trend and also for making the salary structure more attractive to the engineering and technical staffs.

Concerning the development and the construction of accelerators and detectors, Japan has created a unique scheme of collaborating with many industrial engineers and researchers. This system of collaboration with industry which possesses a large number of technical staff has the benefit of mutually raising the ability in accelerator science and frontier technology, and of effectively securing the personnel. This should be encouraged further in the future. In doing so, a collaborative research basis which allows for the accumulation of technology regardless of the personnel movement should be developed. The universities and KEK should also organize a system for inviting these industrial engineers and researchers as visiting researchers, graduate students or research students. CERN, in constructing LHC, also is organizing the research and development in collaboration with the industry, and utilize the capability of the industry in the manufacturing of components such as the superconducting magnets. When the project scale exceeds a certain limit, this system is advantageous for securing a broad range of personnel, for the large scale production system and for the quality control of a large number of components, and should be further promoted.

6.4 The Structuring of a Suitable Environment for an International Laboratory

At an international laboratory there should be no national, racial and other discriminations in the personnel management and membership of executive committees.

For Japan to function effectively as the host country for the Linear Collider, it is essential to prepare an environment suitable for inviting researchers from throughout the world. In particular, the housings, the medical care, the education of children, the language education and the employment of the spouses are amongst the very basic needs which should be provided to the foreign researchers. At the same time sincere care should be made concerning the cultural environment for the long-term visitors. Not only amongst the researchers but also the relevant departments of the government and the local communities should welcome the presence of different cultures and to help resolve various difficulty faced by the foreign researchers and the students who will participate in the project. There should be a permanent section at the central institute created specifically for helping foreign researchers and their family members.

In order to promote collaborative research nationally and internationally as an international laboratory, international personnel exchange programs are essential, and they should be more strongly encouraged. In particular, the mobility of temporary and staff scientists into and from Japan with respect to overseas institutes is still low, and its promotion will be essential for the creation of a truly international research institute. Furthermore, for the sake of an active promotion of the research internationalization, efforts should be urgently made such that both short-term and long-term visitors can utilize KEK as a base for their research.

Chapter 7

Interdisciplinary Aspects

7.1 An Overview

What is science? This question, concerning both natural and social sciences, have been discussed for years from various standpoints, including, philosophical, religious and ideological and other perspectives. However, it would be safe to characterize one aspect of scientific endeavors as organization and categorization of the total knowledge of human being. While the progress of science induces development of deeper and more specialized branches of research, it also creates another stream of efforts whereby attempts are made to understand Nature from a more consolidated and unified standpoint. Such trends are naturally expected from the nature of science itself. There are quite a few cases where a progress in one field of science, while contributing to accumulate the intellectual asset of its own field, ignited a revolutionary transition of methodology or paradigm in other fields. Interdisciplinary efforts made by researchers of multiple fields have opened a number of new branches of science, and helped enrich science as a whole. This history indicates that the most desirable form of progress in science should be found in active and balanced interactions among many research fields, including applied sciences.

High energy physics, while rapidly absorbing the fruits of other fields and applying them, directly or indirectly, to its advancement of accelerator and experimental technologies, is in an excellent position to promote development of a new interdisciplinary field, as well as to contribute to the progress of other branches of science. The general observations on the scientific research above strongly corroborates such an expectation. Moreover, it is felt that this trend will be more evident in the near future. This chapter attempts to examine the mission of high energy physics in such a global scientific context.

7.2 High Energy Physics as a Branch of Science and its Relationship to Other Fields

When one examines Science as the systematic aggregation of accumulated human knowledge, each field of natural sciences is found to have two facets. One facet is characterized by the objects or phenomena that the field of science specifically deals with. They are characteristics which are distinct to each field. The other facet is represented by abstract principles or a general paradigm which dictate the methodology and the laws that the field deals with. Interdisciplinary interactions of different branches of science, including high energy physics, takes place through the link that is provided by this second facet.

In terms of the first facet, according to the analysis above, particle physics is a field of natural sciences which attempts to disclose the fundamental particles and their interactions. The high energy experiments at the LHC and at the Linear Collider are hoped to bring answers to the question of the origin of mass. This, in turn, is expected to bring hints to more fundamental questions, such as, why the specific particles exist in the specific pattern and how the space-time structure of our universe allows these particles to exist. For instance, the supersymmetric theories, which are considered to be the most promising candidates for new physics, indicate that our space-time is not in fact 4-dimensional (i.e., one time dimension and three spacial dimensions). Rather, they suggest that our space possesses extra dimensions which is related to the existence of particles with different spins, super-partners. Some of the more ambitious attempts to build a truly unified theory, which includes the gravity and all particles, have led to the superstring theory. There, the very question as to why the present space-time is apparently four-dimensional is considered to be one of the major research topics.

The research topics of particle physics have always been our most fundamental questions concerning Nature, the fruits of which have influenced our views of Nature and the universe profoundly, and will continue doing so in the future. On the other hand, because the scales of energy and space-time distances in particle physics research is so much different from the rest of the objects in natural sciences, it is difficult to imagine that the new laws of particle physics that will be discovered in the future will affect research in the other fields directly. The only exception may lie in the relation between particle physics and cosmology, because the origin of the universe through big bang cosmology is thought to be an ultra-high-energy phenomenon relevant to particle physics. Thus cosmology and particle physics are now beginning to fuse into one field of science. Through this fusion of the infinitesimal and the infinite, particle physics and cosmology will continue having great influences on our view of Nature.

The other facet of particle physics is that the laws of Nature found in the world of particles may be abstracted and applied to other fields of natural sciences. Conversely, the laws of Nature discovered in the macroscopic world may be rediscovered as laws governing the interactions between fundamental particles.

Through this second facet, the research in particle physics will develop jointly with the research in other fields. This is the facet which allows particle physicists to actively participate in the interdisciplinary approaches which are beyond the conventional classification of scientific fields. There are numerous examples of such interdisciplinary developments. Some well-known examples include the application of a theoretical framework developed in electric engineering onto the quantum mechanical world, and a well-known concept in the theory of superconductivity which plays a fundamental role in the understanding of the origin of the mass of the fundamental particles. The study of complex systems, and research areas described with keywords such as chaos, catastrophe and non-linearity, which have recently met strong interests, have large overlap with particle physics research when faced with such fundamental questions as the origin of the universe and the space-time.

There are numerous other examples, but in more abstract terms, the entire cultural background, including art, can promote the introduction of new concepts in science. The modern days are said to be an era of scientific technology. This is not only because the technological development has been a driving force behind the entire era but also because the DNA and other genetics research as well as other branches of biology including the study of the brain, have created a profound influence on the spirit of the era. The origin of mass and the creation of the universe, as described in chapters 1 and 2, were questions whose scientific value was under scepticism in the past. The great transitions in particle physics such as the understanding of the origin of mass, is about to be triggered by the Linear Collider experiments. Since the concept of mass is so fundamental to matter, our understanding of its origin will lead to the revolution in the human view of matter, the universe and Nature, as well as science. Since such great transition can be expected now, it is crucial further promoting particle physics research and the Linear Collider project.

7.3 Other Fields of Accelerator Science

The field currently known as High Energy Physics can be defined historically as the research concerning the fundamental units of matter and the fundamental particles, and the interactions governing them. It has been called particle physics for this reason. At the beginning of the 20th century, the smallest units of matter were the atoms, and then they became the nucleus of the hydrogen atom, that is, the proton, and now the constituents of the proton, the quarks, are considered the fundamental particles (the constituents of quarks are also speculated by some theorists). Starting from the discovery of the atomic structure where the positive electric charge is condensed at the center of the atom, the study of particle physics in the 20th century has taken as its central methodology the utilization of higher and higher energy particles collided with matter for studying their structure and interactions. In particular, the study of the elementary particles as the constituents of the nucleus obtained the name High Energy (Nuclear) Physics since higher and higher energy accelerators have led to the discoveries of particles of higher and higher masses. Thus the naming came from the study of the properties of nuclei at high energies, but more generally, it is the experimental science utilizing high energy accelerators. While particle physics in the traditional sense has developed by high energy accelerator experiments, the study of the nuclear properties at ‘low’ energies using low-energy accelerator is now called the low-energy nuclear physics and it is also a developing field. As high energy physics continually shifts its attention to higher energies, there is now a new field at an intermediate energy, called the medium-energy nuclear physics.

The historical circumstance that the invention of the particle accelerator had its purpose in the study of particle physics has its natural consequence that high energy physics has been the driving force behind the progress in accelerator technology. Since high energy physics now demands yet higher energy accelerators and demands more sophisticated accelerator technology, this role as the driving force is becoming ever more important. On the other hand, the particle accelerator, which have been developed along with the progress of high energy physics not only finds applications in particle physics in the broad sense described above, but also has provided revolutionary research methodology in many other fields. There are now developments in accelerator technology specific to the research of each corresponding research field. As a result, there are now cases where developments in accelerator technology with objectives outside high energy physics have been applied to high energy physics research. Thus accelerator-based research has spread over a broad range of science and engineering, and it has found broad industrial applications. We are observing the advent of the common scientific interdisciplinary field of Accelerator Science.

As for the industrialized applications of the accelerator, there is the radiative isotope production for medical and manufacturing purposes. The use of the proton and heavy ion accelerators for the treatment of cancer is currently becoming a practical method after the experimental preparatory stage. The industrial application in material processing using primary beams is expected to become more abundant.

The research and development, and the construction and operation of particle accelerators for high energy physics have contributed to other fields of accelerator science. One example is the synchrotron radiation. The synchrotron radiation, for its brightness and other properties, have attracted much attention from various other scientific and engineering fields as soon as the high energy electron–positron accelerator rings were constructed. As a result, many synchrotron radiation rings have been built, and currently, the so-called third generation rings are built and being operated. On one hand it is already regarded as an everyday research methodology in science, and on the other hand there is much anticipation towards its industrial application such as the semiconductor manufacturing. The improvement of synchrotron radiation brightness requires the improvement in the beam characteristics. These are precisely the characteristics required by the B-factory and the Linear Collider damping rings. The progress in synchrotron radiation rings has gone hand-in-hand with high energy electron accelerators.

In addition, the most promising electron beam source of the free electron laser, which is expected to become the dream light source of the future, is the high-luminosity Linear Collider.

There are several test facilities of Linear Collider which are about to realize X-ray free electron lasers with high coherence.

On the other hand, the high energy proton accelerators have attracted attention as the pulse neutron source, and KEK has the history of constructing KENS ahead of the world which utilizes the proton beams from the 500 MeV booster. As a result of the recognition of its usefulness, ISIS was constructed in Britain which has a hundred times greater power, and LANSCE was constructed in the United States. These proton beam accelerators have also become an important technique for a broad range of sciences. In particular, neutrons are sensitive to the presence of hydrogen, and it has been regarded as a powerful tool in the structural analysis of biological polymers. Since a neutron has roughly the same mass as a hydrogen nucleus, and since it is possible to explore various properties of materials which cannot be explored by light, it is the most promising probe in the study of material structure. The high-intensity high-energy proton accelerator can also create muons, which can be considered as heavy electrons, in large quantities. The muons are also attracting attention in the study of materials utilizing its unique characteristics, similarly to the pulse neutron source. Because of such wide and diverse interests, the JHF project in Japan, the ESS project in Europe, and the ORNS project in the US are about to be constructed as the third generation neutron and muon source. The construction of these high-intensity high-energy proton accelerators requires the development of the high electric-power RF accelerator equipment, the minimization of the beam loss and the beam instability, and other sophisticated accelerator technology. These are precisely the extension of the accelerator technology which has been developed so far for the high energy physics accelerators.

In particular, at KEK, the 12 GeV proton synchrotron (including the 500 MeV booster), the accelerator PF (photon factory) for the synchrotron radiation, and TRISTAN were constructed and operated. Currently KEKB is under construction, and in the near future JHF will be constructed. Furthermore ATF has been built and has just begun operation. These accelerators at KEK show precisely the history of the development of the accelerator technology driven by the development, research, construction and operation of the preceding accelerators. They clearly demonstrate the necessity of progress in high energy physics accelerators for the progress of accelerator science. On the other hand, there are recently applications of technology developed for the sake of other accelerators in high-energy-physics accelerators.

Considering the energy and environmental problems of the 21st century, it is beyond question that a clean and safe energy source is necessary to minimize environmental pollution. The potential of the super-high-intensity high-energy proton accelerator for processing radioactive waste from nuclear-power plants, and also in the nuclear-power generation based on a new concept, has recently obtained much attention. This will play a central role in the neutron science research project planned at the Japan Atomic Energy Research Institute. For its realization, the superconducting accelerating system which was developed for the first time at TRISTAN is a necessary element. Furthermore, the high-power RF system developed at KEKB, ATF and for JHF to accelerate high-current beams, and other aspects of the accelerator science as a whole, including the accelerator theory, will be needed. For the nuclear fusion reactor, which is expected to be a dream energy source of the future and whose development is under competitions throughout the world, the super-high-current deuteron source will be an essential element to be used in the materials research for the reactor. It is planned to be built on a collaborative basis (IFMIF).

Reflecting upon these historical circumstances, and from the viewpoint of accelerator science, the progress in high energy physics will be essential as a driving force in exploring the technology of the 21st century.

7.4 The Relationship between Accelerator Science and Other Fields

As described above, Accelerator Science is an interdisciplinary science by itself and it has deep connections with many other advanced technologies. The success of accelerator science in Japan, including high energy physics, is based not only on its economic power but in its high technological capability. On the other hand, high energy physics has promoted progress in frontier advanced technology through the research, development, construction and operation of advanced accelerators. High energy physics accelerators should be designed and constructed by utilizing the highest standard of advanced technology available and exploring the limits of the achievable characteristics, and should hence be called the energy frontier for that reason. Thus its research, development, construction and operation require the continual effort to find even one small step for the advancement of frontier technology. The fruits of such efforts will naturally contribute to further improving the technological standards. For example, the super-high-precision machine processing, the superconducting technology, and the surface processing technology necessary for the RF accelerator technology, as well as the high-precision computer network, the high-speed electronic circuits and the high-speed measuring technology are amongst the innumerable examples of the technology promoted by accelerator science.

(End)

This English language version of the HEPSC Final Report is a translation, prepared by the HEPSC members, of an original, authentic document produced in Japanese. Any questions that may arise about the interpretation of the report should be resolved with regard to the original Japanese document.