INTER-UNIVERSITY RESEARCH INSTITUTE CORPORATION
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION
KEK

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KEK’s Roadmap（5 Year Plan）

＜The revised description on Super-KEKB is added to the original text of the KEK roadmap as the amendment No.1＞

1. Overview

At KEK, the construction of J-PARC will be completed shortly; the particle and nuclear physics experiments of a new era will soon begin utilizing its high power beams. Research in the material and life sciences with neutron and muon beams will also start. In addition, the integrated luminosity of the KEK B Factory (KEKB) will reach the important milestone of 1 ab^{-1}. Outside of Japan, the LHC will soon start operation and guide the future direction of particle physics. The development of the ILC conducted by an international collaboration is moving into a new stage of engineering design and industrialization. In the field of synchrotron radiation research, many third generation light sources are being constructed and replacing the second generation ones, while the next generation light sources beyond these are also being developed.

Facing such drastic changes, the establishment of the KEK roadmap is an imminent challenge for the accelerator science of our country. KEK has launched a task force whose members are listed at the end of this report to perform a study examining the research program of the 2010’s and to establish a detailed roadmap for the next five years (2009-2013).

The following goals have been taken into consideration in establishing this roadmap:

- To continuously produce top level world-class research achievements in the future by upgrading the internationally competitive accelerator facilities in a timely fashion, while taking the research directions of each field into account.
- To aim at the implementation of the future plans proposed by the various communities, while complying with the needs of the domestic communities as an inter-university research organization. For this purpose, the task force has taken into account the following recommendations given by the relevant communities; “Prospects for

Elementary Particle Physics" (Japan Association of High Energy Physicists, October 2006) and the recommendation by The Japanese Society for Synchrotron Radiation Research (2005).

As a result of the study by the task force, we established a roadmap with the following five main items, after the on-schedule completion and commissioning of J-PARC, which is currently the highest priority of KEK, as well as continuous operation of the Photon Factory. The five items are listed below, and details of the individual plans are described in Chapter 3.

I. Operate the J-PARC facility and undertake early realization of the design performance. Reinforcement of the proton beam intensity should also be undertaken.
II. Continue the Belle experiment after upgrading KEKB to realize luminosity at least 10 times higher than the present level and improve the Belle detector.
III. Continue operation of the PF/PF-AR with appropriate maintenance and improvement until the completion of the ERL described below in order to comply with the needs of the SR community.
IV. Promote our commitment to the experimental program at the LHC, which will begin soon at CERN.
V. Conduct R&D for advanced accelerator and detector technologies with the following goals:
    V-1. Construct a compact energy recovery linac (ERL) to establish component technologies necessary for a full-scale ERL, the next generation synchrotron radiation facility. KEK will also promote material and life science research using the compact ERL as a Tera-Hertz light source.
    V-2. Promote technical developments for the ILC accelerator. In particular, KEK aims at establishing/industrializing the technology for the superconducting accelerator system and establishing the control technology for the ultra-low emittance beams.
    V-3. Promote the development of advanced detector technologies applicable to various research fields and industries.

By conducting the research and upgrading the facilities described in the roadmap, KEK can continue to produce versatile research output and remain one of the world class accelerator science institutions in the 2010's.

This roadmap describes the research program for the next five years at KEK, which may eventually need to be reconsidered depending on the outcome of the research program, progress of the research in the relevant field and the financial situation. For example, if dramatic progress takes place in a future program such as the ILC, it will be necessary to navigate KEK toward this direction. Also in the research fields at J-PARC, this roadmap may need to be revised based on the accomplishments at this facility and discussion with the relevant communities.

2. Outlook for particle physics, nuclear physics and material/life sciences

Preface: Outlook for accelerator science

The microscopes and telescopes invented in the 17th century brought a great revolution in unraveling the secrets of life and the universe. In the 20th century, breakthroughs in technologies using quantum beams[1] such as X-ray photography, electron microscopy, high energy accelerators, synchrotron radiation, neutron beams and muon beams created new fields of research and industrial applications.

In the latter half of the 20th century, high energy accelerators have made a remarkable series of discoveries of new elementary particles and new physical laws, which led to the "Standard Model" of elementary particles. In the material/life sciences, the structures of proteins and new materials that were invisible with conventional microscopes were unraveled by synchrotron radiation; as a result, our understanding of material/life phenomena made dramatic progress. Synchrotron radiation, high power/high quality X-rays, provides industry with a research instrument indispensable to its development while proton and heavy nuclei beams have been successfully applied to cancer therapy. We expect that accelerator science driven by the most modern accelerator technology and detector technology will expand its domain of applicability and will contribute not only to our understanding of nature but also to a better quality of human life and a sustainable global environment.

KEK had successfully conducted research programs at the 12 GeV proton synchrotron, which included hadron experiments, neutrino oscillation experiments and material structure

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[1] Here "quantum beam" refers to beams of charged or neutral particles, synchrotron radiation and laser light.

studies with neutrons and muons. This machine was historically the predecessor of J-PARC and ended its operation at the end of FY2005. Meanwhile, TRISTAN, the predecessor of KEKB, realized the highest collision energies in the world at the time by adopting for the first time superconducting accelerating cavities on a large scale. Today, KEK is one of the world's unique "versatile accelerator science research institute" with its ability to conduct research that ranges from particle/nuclear physics to material/life sciences with a colliding beam accelerator（KEKB）for particle research, synchrotron radiation rings (the PF/PF-AR) and a high power proton accelerator to generate various secondary beams (J-PARC). It is the responsibility of KEK to continue developing and constructing accelerators with the highest level of performance in the world in order to provide researchers in accelerator science from all over the world with a place for their research. KEK has, in the past, established a track record for developing, constructing and operating advanced accelerators. Thus, the communities of related fields desire that KEK evolves further as an international research base for accelerator science covering the wide range of their research. In this roadmap, a five year plan is established to achieve this goal.

2-1 Outlook for particle physics

In elementary particle physics, it is widely believed that a new era is about to begin as physics enters the TeV (tera electron volt: 1 trillion electron volt) energy scale. It is expected that considerable progress will be made in unraveling fundamental problems in particle and astroparticle physics such as the unification of forces, the origin of neutrino masses, baryon number generation in the universe, and the nature of dark matter.

The various properties of the elementary particles that constitute matter were discovered by using particle accelerators. These discoveries allowed the fundamental laws of nature including gravity to be unraveled and allowed for attempts to understand the origin of the universe. Furthermore, in recent years, new ideas and models have been proposed that will change the concepts of time and space and lead to a new stage of understanding of elementary particles. We look forward with great anticipation to the next stage with experimental tests of these various new hypotheses at the TeV energy scale.

To take the initiative in research in this field, the LHC（Large Hadron Collider）is being constructed at CERN (European Organization for Nuclear Research ; Conseil Europeen pour la Recherche Nucleaire）. In elementary particle physics it is vital to directly observe the new particles and the new phenomena in the highest energy experiments: this will be done at energy frontier experiments at the LHC that will unravel the underlying fundamental laws. We will be able to understand the mechanism of electroweak gauge symmetry breaking by directly producing the long awaited Higgs particles as well as by making precision measurements of their properties to unravel the new laws of physics. Japanese researchers including those from KEK are playing an important role in the dawn of this new era by taking part actively in the LHC through the development and construction of the superconducting focusing magnets for the LHC accelerator and the ATLAS experiments.

Meanwhile, internationally it is a common understanding that the realization of a linear collider covering energies up to 1 TeV is indispensable in order to understand in detail the properties of the Higgs particles and the supersymmetric particles, which are anticipated to be found by the LHC, and furthermore to unravel the new laws of physics. For this purpose, the GDE (Global Design Effort: an international design team for the international linear collider project) for the global development of the collider has been organized to realize the International Linear Collider (ILC). Although Japanese researchers have already been playing important roles in this research and development effort, it is necessary to promote the activity further in the near future.

The fundamental symmetries of new laws and mixing phenomena of new particles are important aspects of the new physics laws, but it is not possible to study them entirely at the energy frontier accelerators. Research on leptons and quarks, called flavor physics, plays an important role in understanding this new physics and will lead to a complete picture of the new physical laws. Japanese scientists have made essential contributions in this field with the B Factory (KEKB) and neutrino experiments. At the moment, KEKB is the accelerator with the highest luminosity in the world.（Luminosity is one of the important parameters of the performance of a collider. The collision frequency is proportional to the luminosity）. The Belle group has played an important role in establishing the Standard Model by finding CP violation in the B meson system and by determining the parameters of the Kobayashi-Maskawa model, which is an important component of the Standard Model. The high precision measurements at this experiment were made possible by the large amount of data collected at KEKB.

If new physics exists at the TeV energy scale, it is quite conceivable that deviations from the predictions of the Standard Model will be observed in the decays of B mesons, D mesons and τ leptons. Although the Belle experiment has discovered CP violation and various rare decay modes of B mesons, the precision of the current measurements is not yet sufficient to see the effects of new physics. By increasing the luminosity of KEKB by a factor of 10 or more, the flavor physics of B, D and τ particles will enter a new era of precision measurements in which the possibility of detecting new physics effects will be greatly improved. Furthermore, combining precisely measured quantities will allow us to distinguish various theoretical hypotheses about the new physics. Therefore, detailed measurements at the upgraded KEKB facility can provide an excellent opportunity to examine the fundamental properties of CP violation and flavor mixing in new physics. Even if no new physics is found at the LHC, the upgraded KEKB machine provides a unique possibility for finding physics phenomena at a higher energy scale, which cannot be reached by the currently planned energy frontier experiments, through precise measurements of higher-order effects.

As a result of the discovery of non-zero masses of neutrinos by Super-Kamiokande as well as by the subsequent KamLAND and K2K experiments, the neutrino world so far veiled in mystery has gradually become clearer. This research is attracting global attention and is playing an important role in unraveling the old mystery of the physics of generations and their relationship, which is quite different from the physics of the energy frontier. At J-PARC, preparation for the T2K experiment is underway, which hopes to make the first observation of ν_e appearance from ν_μ by shooting a high power neutrino beam into Super-Kamiokande about 300 km away as well as measure the mixing angle θ_{13} for which so far there are only upper limits. Furthermore, the observation of the process of ν_e appearance from ν_μ will open the door to searches for CP violation in the lepton sector. In the neutrino field, in addition to the research at accelerators, there is fierce competition from research projects using neutrinos from nuclear reactors. Therefore, it is especially important to strongly promote domestic research in the future.

In addition, various research projects in flavor physics using the high power proton beam at J-PARC have also been proposed. Projects presently being considered include a K^0 rare decay experiment, a search for T-violation and a search for μ conversions to electrons. All of these experiments aim at discoveries of unique phenomena that cannot be searched for by the energy frontier experiments; if successful these experiments will have the potential to generate new directions in physics. These and other experiments, including the measurement of the electric dipole moment of the neutron, make use of the unique features of J-PARC and should be promoted.

As stated above, the research activities in high energy physics in Japan cover a very broad range with the aim of playing a leading role in finding new physics and then clarifying its whole picture in the midst of fierce competition from around the world. This roadmap is in line with the result of the discussions at the Japan Association of High Energy Physicists.

2-2 Outlook for nuclear physics

The frontier of nuclear physics today is research into extreme conditions of quantum many-body systems caused by the strong interaction. This includes, for example, the behavior of quarks and gluons at high temperature and high density, the behavior of nucleon systems with strangeness, the behavior of systems containing excessive numbers of neutrons. These research areas are also closely related to the evolution of the universe since the Big Bang. Depending on the energy scale, quantum many-body systems are understood either by treating quarks and gluons as the fundamental entities using Quantum Chromodynamics (QCD) or by treating hadrons as the fundamental entities. Nuclei exhibit quite different aspects depending on the properties of the surrounding environment such as energy. Therefore, both comprehensive research for a wide range of objects and focused research are necessary so that various experiments using many experimental facilities in the world and theoretical research can be conducted. In particular, a wide range of unique research can be developed at J-PARC, which has the highest power hadron beam in the world.

Research on strange nuclei generated by a high purity K meson beam has been adopted as a viable experiment from the initial stage of operation of J-PARC and will certainly provide a variety of useful data. High precision measurements can be made on hyperon-nucleus interactions and on hyperon-hyperon interactions based on these data. Theoretically, the development of numerical simulations based on QCD has led to an understanding of the characteristics of the nuclear force and the interactions of hyperons. Furthermore, the possibility of realizing a high nuclear density state with a stronger binding force from embedded K mesons has been demonstrated; this is expected to lead to an improved understanding of the formation of neutron stars where such a high nuclear density state is realized.

The hadron mass is theoretically expected to becomes smaller in the nucleus than in the vacuum due to the partial restoration of chiral symmetry. Measurement of the hadron mass in the nucleus is one of the interesting research subjects of J-PARC.

In order to understand the proton spin, one needs to take into account not only the spin of the quarks in protons but also the spin of the gluons and the contribution of orbital angular momentum as well as the contribution of the strange quarks. If the acceleration of polarized beams can be realized at J-PARC, this is expected to contribute greatly to resolving this issue. Furthermore, the study of neutrino-nucleus scattering can lead to an improved understanding of this issue.

In recent years, a series of hadron states that cannot be understood in the traditional picture have been found and thus hadron spectroscopy is undergoing a new evolution. At J-PARC, significant progress is expected in the search for bound states of quarks and gluons that are different from those of ordinary known mesons and baryons.

The research focusing on the strong interaction, which is the key to understanding the formation of the matter constituting nuclei can be developed substantially at J-PARC, which aims to achieve the highest level of beam power in the world. In order to make best use of J-PARC to develop such a wide range of research, experimental facilities superior to the ones currently available are indispensable. Since J-PARC is a joint project with the JAEA and since the establishment of its grand design is still underway, we do not include it in this roadmap. However, producing successful physics by making the best use of J-PARC remains one of the most important issues at KEK, and its overall program is being discussed in JAEA and research communities relevant to J-PARC.

2-3 Outlook for Material and Life Sciences

It is recognized that the material sciences and life sciences are precious intellectual assets of humankind; we also know that large numbers of research scientists are vigorously engaging in basic and applied studies in these fields in order to make people's daily lives more comfortable and happier. Although the research covers a very broad range, from fundamental to industrial applications, the essential theme of these research fields is exploring how molecular structures, their arrangement and electronic structure in the micro-world govern the characteristic properties of materials in the macro-world.

KEK pioneered in constructing unique quantum beam facilities such as synchrotron radiation, neutrons, muons as well as slow positrons. By stably providing them to 4000 scientists, research program has been carried out from basic science to industrial applications in various fields such as solid state physics, chemistry, material science, environmental science, biology, planetary science, medical science, pharmaceutical science, etc. For example, charge and orbital ordering, electronic properties including the Fermi surface, the magnetic state and the electron-lattice interaction have been studied in materials that exhibit high Tc superconductivity or giant magnetoresistance in order to clarify the underlying mechanism for these particular characteristics; these studies make complementary use of synchrotron radiation, neutron or muon beams. Furthermore, studies on the structure and electronic properties of magnetic recording materials, fuel cells, catalysts, environmental samples and proteins are being intensively carried out in order to clarify the origin of their material properties. Fundamental and pioneering researches of chemical reactions are also being conducted by using time-resolved measurements based on the pulsed synchrotron radiation from the PF-AR.

Forthcoming keyword is research on dynamics in order to directly clarify the functions of materials and organisms as well as investigations that directly clarify the functions in local areas such as interfaces or nano-structures. In the near future when J-PARC is in full operation and the synchrotron facility is upgraded, copious synergy will obviously appear in the material science research using synchrotron radiation, neutrons, muons and slow positrons. In order to fully realize this synergy, it is important for KEK not only to provide those quantum beams stably, but also to serve as a core of the network involving the research agencies and industries as well as universities.

In the field of research using synchrotron radiation, it is needless to say to make full use of the existing facilities to maximize the scientific accomplishments, furthermore a new light source that provides both ultra-short pulses and ultra-high brilliance is indispensable to meet the requirements of the material and life sciences. The former is needed for direct observation of each and every step of a reaction that leads to the manifestation of specific characteristics of a material. With the latter, scientists can observe and identify a specific local structure in a material. KEK proposes a 5 GeV level energy recovery linac (ERL) as an advanced ring-type photon source. An ERL is capable of analyzing the structure of a sub-micron scale protein crystal and is also capable of elucidating the functions of proteins in a cell by means of coherent diffraction microscopy. Thus, scientists will become able to explore substantially unprecedented domains in the life sciences. In material science fields, on the other hand, an ERL makes it possible to explore phenomena such as spin dynamics and photo-induced phase transitions by making use of ultra-short pulses while local electronic states such as quantum dots or nano-structures can be explored by means of nano-sized beams; these are also important to industry from the viewpoint of functional elements or fast switching elements. In basic science fields, an ERL makes it possible to launch studies of the behavior of materials under the extremely high pressures and high temperatures that exist in the deep interior of a planet. It may be worthwhile to mention that the Special Committee on the Advanced Ring-type Photon Source in The Japanese Society for Synchrotron Radiation Research (2005) concluded that an ERL is the most promising candidate for an advanced ring-type photon source.

J-PARC is capable of generating neutron and muon beams of several hundred times higher intensity compared with those at KEK-PS. By developing innovative technologies of neutron optics and neutron detectors, we construct new experimental facilities with unprecedented momentum/energy resolutions and beam polarization capability, and with ultra-fast data acquisition/processing system. These features allow us to clarify the mechanism of functional development; such as orbiton in colossal magneto-resistance, proton motion in biological activity, dynamics of high Tc superconductors, fullerene, and multi-ferroic compounds. New progress is also anticipated in fundamental physics including a measurement of neutron's electric dipole moment and various experiments using neutron interferometry.

Using muon beams and KEK’s surface/decay muon experimental devices, which has the world's highest pulse intensity, great progress is foreseen in experimental research on local electronic states in magnetic materials, superconductors and semi-conductors. Expected achievements include a clear observation of the inner structure of a vortex filament inside a superconducting electric current. This finding will be a key cornerstone in the coming development of innovative superconducting materials. Studies of muonic atoms, chemical reactions of muonic molecules, and muon-catalyzed nuclear fusion will make significant progress by using negative muon beams. Furthermore, the results of the advanced scientific research mentioned above might lead to innovative proposals not only in material science but also to a possible solution for energy resource problems. Development of advanced muon beams such as super slow muons will enable measurements with micro samples, and provides a powerful method to evaluate nano-technological material.

To carry out scientific research making best use of the capabilities of J-PARC, it is very important to fit the facility with state-of-the-art experimental equipment for use in connection with the neutron beams and muon beams. It is also necessary to keep upgrading and improving the existing facilities continuously and timely.

3. Research Program in the Roadmap

3-1 Operation of J-PARC, early realization of the design performance and reinforcement of the beam intensity

Needless to say, we must reiterate the importance of the completion of J-PARC construction and the start of the experimental program as scheduled. Here it should emphasized that a high intensity proton beam from the MR is essential to carry out any particle and nuclear physics experiments at J-PARC; continuous measures have to be taken to improve its intensity. T2K is especially determined to be the first to discover the neutrino mixing angle θ_{13} , which demonstrates mixing among the three generations. This discovery will be the key to the path towards exploring CP asymmetry in the lepton sector, which might be an essential element for understanding the baryon asymmetry of the universe. In this endeavor, the intensity of neutrino beams plays a decisively important role. Improvements to the intensity and stability of secondary beams such as the K-meson beam are also indispensable to the success of hadron experiments.

Changing the beam repetition rate of the J-PARC MR provides a realistic method to improve the intensity of the proton beam without major changes to the J-PARC facilities. The intensity of the proton beam will be increased from 0.36 MW (prior to the linac recovery to 400 MeV) to 1.7 MW by this method, which will allow improvement of the intensities of the neutrino and hadron beams as well. This has to be done without degrading the performance of the beam supplied to the Material and Life Science Facility.

Such an improvement of the beam intensity can be made by reinforcement of the RF system and the power supplies for the magnets in the MR. The equipment in the neutrino beam lines such as beam windows, targets, and horns presently being constructed can be used without any problem up to 1.7 MW beam power. The equipment in the hadron beam line should also be capable of handling such high beam power.

3-2 KEK B Factory upgrade

The KEK B factory has been operating with the highest luminosity in the world. Over the past eight years in the Belle experiment, CP violation in B to $J/\psi\ K_S$ decay, for example, has been measured very precisely, leading to a confirmation of the Kobayashi-Maskawa model. Upgrading the B factory to have much higher luminosity will enable precision measurements of other rare decays of B mesons, as well as D D-bar mixing and τ decays. It should be noted that there are already some results that hint at contributions from new physics in B decay such as the magnitude of CP asymmetry in B to $\phi\ K_S$ decay, for example. Detailed data analyses based on data samples of 10 ab^{-1} or more will provide a unique method to obtain a clear resolution of this issue. In addition, the Belle group has discovered several exotic resonances that are thought to be composed of four quarks. Physics of such multiquark states will also be clarified by accumulating data samples of 10 ab^{-1} or more. The program described in this roadmap is, therefore, an upgrade plan for the KEKB machine and Belle detector to collect 10 ab^{-1} for these purposes. This plan, however, contains the possibility of upgrading the machine further in the future, taking into account results from the LHC and the progress of other programs such as the ILC.

In the five years of this roadmap, we plan to shutdown KEKB for the first three years in order to carry out the major upgrades of the machine and detector. In the following two years, we plan to reinforce the RF system and related parts as well as operate the machine to achieve a luminosity above $2x10^{35}/cm^2/s$. It is also necessary to continue this mode of operation with additional RF installation for a few more years to integrate 10 ab^{-1}.

The upgrade plan in the first three years consists of:

- Replacing the current beam pipe by a beam pipe with an ante-chamber,
- An upgrade of the interaction region,
- An upgrade of the ground level RF facility,
- Improved crab cavities, and
- An upgrade of the Belle detector.

The continuing upgrade in the last two years will consists of:

- Installation of a damping ring,
- Installation of additional RF and
- Reinforcement of the cooling facility .

More details of the upgrade plan will be described below. To achieve the unprecedentedly high beam currents, the current beam pipes have to be replaced by newly designed and innovative beam pipes. The new beam pipes have been designed to handle extremely strong synchrotron radiation and higher-mode radiation, which are generated by the large currents and short bunches, and are also designed so that the generation of an electron cloud can be suppressed. In addition, we must renew the auxiliary facilities attached to the beam pipes such as the ultra-high vacuum pumping system and beam position monitors. Though the expected luminosity with the abovementioned replacements is only about 1.5 times as large as the present value, these are indispensable prerequisites for bunch compression and extensive increase of the beam currents, which will be done later.

In addition, we envisage that the luminosity will be doubled by modifying the beam optics system located close to the collision point so as to realize stronger beam focusing. RF cavities will be installed step by step to attain higher beam currents after the shutdown. For this purpose it is necessary to relocate ground level facilities and to install newly renovated acceleration units that will handle the larger beam currents.

Another key to further increasing luminosity is a crab crossing technology by which it becomes possible to practically realize head-on collisions while maintaining the crossing angle between beams. Crab cavities are already operating successfully in the present KEKB accelerator. Before the 2009 shutdown, by further intensive studies, it is anticipated that the luminosity will be 1.5-2.0 times as large as the luminosity without the crab cavities. After completion of the upgrade, an additional luminosity doubling is envisaged by further improving collision conditions. In this regard, new crab cavities that can accommodate a large beam current need to be installed at a certain stage.

After the completion of the above modifications and replacements, KEKB will be put back into operation. During the next period of operation, the following improvements will be carried out step by step to increase the luminosity further: 1) Improvement of the injection LINAC by installing a damping ring; 2) Improvements and reinforcement of the RF system; 3) Reinforcement of the capacity of cooling facilities to deal with heat generation accompanying the extensively increased beam current; 4) Replacement of power substations and air conditioning facilities. After these additional upgrades, the luminosity is expected to reach the level of $2 \times 10^{35}/\mathrm{cm}^2/\mathrm{s}$ or higher by the end of the five year program, and 10 ab^{-1} will be integrated after operation for an additional few years.

To carry out an experiment at the upgraded KEKB machine with the much increased luminosity, the detector system that measures decays of B meson and other particles also faces new challenges. The most important point among others is that the detector system should work stably with excellent performance in an extremely high counting rate environment that is brought about by the unprecedentedly large beam current and super-high luminosity. Other important requirements are excellent particle identification and event reconstruction capability that even allow us to detect events with multiple neutrinos. These capabilities are indispensable not to overlook very rare phenomena that might be observable with the super-high luminosity. Furthermore, data acquisition and analysis systems that allow us to process and handle the huge amount of data are needed. To meet the requirements mentioned above, the existing Belle detector must be substantially modified. The following technologies will play key roles.

1) Finer segmentation of detector elements: a) Finer space segmentation by adopting a device such as a fine pixel detector and b) attaining high time resolution by adopting high-speed sampling circuits.

2) A high-precision Cherenkov particle identification device based on the next generation photon sensor capable of detecting single photons with pico-second level time resolution.
3) A data acquisition system based on a ultra-high speed network, a massive-capacity data processing system based on a full-scale PC farm and an innovative GRID technology.

The development of the basic technologies needed to build the aforementioned detector has been nearly finished. A new international collaboration will be formed by leading scientists from all over the world. It is now anticipated that more than 600 scientists from around 20 countries will participate in the collaboration.

3-3 PF/PF-AR Operation and Upgrade

The existing synchrotron light sources, PF and PF-AR, have been in operation for more than 20 years, and still have room of upgrade. In these facilities, more than 3000 users carry out research in a wide variety of fields. It is anticipated that KEK continues to support the user community and to lead science using synchrotron radiation as an inter-university research institute. Particularly, it is necessary to undertake construction and renewal of the insertion devices beam lines to make full use of the performance of the upgraded machine. It is also useful to concentrate resources to upgrade beam lines and experimental facilities to keep competitiveness of science research in this field in Japan. In order to reinforce the competitiveness, it is a mission of the inter-university research institute to establish a platform including research organizations as well as universities, and play a central role in it. The advanced research here will involve initial steps to the research program anticipated in the 5GeV class ERL. The activities at PF and PF-AR will move to the new facility, when the 5GeV class ERL is completed.

3-4 Commitment to the LHC Experiment

The LHC accelerator is being constructed at CERN under an international cooperation agreement among the CERN member countries (20 European countries) and non-member countries including Japan, the USA, Canada and Russia. Two energy frontier experimental facilities are being constructed at the LHC; Japanese groups have had a strong commitment to the ATLAS collaboration from the very beginning. The ATLAS detector is a huge 7000 ton detector complex built by a collaboration of 1600 physicists from 35 countries. From Japan, 60 physicists participate in this group from 15 institutions, including KEK, the University of Tokyo and Kobe University. These groups have played important roles mainly in the construction of the muon trigger, silicon detector, superconducting solenoid, as well as in preparation of physics analyses. The experiment is expected to start in the summer of 2008 after a 13 year period of construction. KEK will play a leading role in the operation of the experimental facility and in the physics analyses.

3-5 R&D of Advanced Accelerator and Detector Technologies

3-5-1 R&D Program for the ERL

The next generation light source needs to satisfy a wide range of requirements. It must provide ultra-short pulses that enable direct observations of the functional characteristics of materials and ultra-high brilliance that enables identification of local structures of materials. At the same time, the light source has to support a variety of scientific research fields in the material and life sciences. A 5 GeV ERL will be a proper candidate for the next generation light source that provides improvement of three orders of magnitude over the present third generation light source in both beam intensity and bunch width. As there is no 5 GeV level ERL in the world at the moment, R&D is needed to supply stable synchrotron light to many users. Such activities should include R&D on electron beam dynamics and on accelerator technology elements. As the first step in the approach to the challenging tasks described above, we plan to build a compact ERL with a beam energy of around 60 MeV. A basic design has been completed already (CDR was published in March 2008), and R&D program has been initiated for superconducting RF cavity, electron gun and so on.

The synchrotron radiation generated from this compact ERL is very intense, very short (with a typical width of 0.1 pico-seconds) and has a high repetition rate (1.3 GHz). The compact ERL is a source of coherent synchrotron radiation (CSR) in the THz range with an intensity that is 7-8 orders of magnitude larger than that available from existing facilities. It will provide much important information on elementary excitation processes that are essential for material science; examples include lattice and molecular vibrations, the plasma oscillation frequency in conduction carriers, and the behavior of strongly-correlated quasi-particles. Furthermore, it is anticipated that the THz source will be used not only as a probe light source but also as an excitation light source taking advantage of its very intense and short pulse characteristics. Examples for this include selective diffusion of doped atoms in semiconductor process by selective excitation of lattice vibration mode, which draws attention of the relevant industries.

As the compact ERL uses a superconducting accelerating cavity, the amount of heat generated from the ERL is very small compared with that from a normal-conducting cavity. Taking advantage of this fact, a superconducting accelerating cavity can accelerate an electron bunch with an extremely high repetition rate. As such, we anticipate using this system as an X-ray imaging apparatus based on a micro light source that makes use of laser inverse Compton scattering. It can also be used as a femtosecond pulse X-ray source for imaging ultra-high speed phenomena. In particular, an ERL will allow us to carry out high-precision X-ray refraction imaging diagnostics, which presently can be done only at a large synchrotron radiation facility.

As an important step towards realizing the ERL, R&D on accelerator technology elements will be carried out and a compact ERL (with energy exceeding 60 MeV and beam current above 10 mA) will be built in the East Counter Hall in the coming 5 years (2009-2013). The innovative technology elements include: 1) an input coupler for a superconducting cavity, 2) an electron gun, 3) a drive laser and 4) an RF power source. Thereafter, from around 2013, we will aim to construct a full-size 5 GeV class ERL. This research project is promoted as a joint nation-wide effort with the JAEA, the Institute of Solid State Physics, the University of Tokyo, SPring-8, the Institute for Molecular Science, the National Institute of Advanced Industrial Science and Technology, Hiroshima University, and so forth. It will also involve international collaboration with Cornell University and the Argonne Advanced Photon Source.

3-5-2 R&D Program for the ILC

The GDE (Global Design Effort), an international team for design and development organized under a world-wide agreement, is the core body promoting the ILC project. As one of the major participating research institutes, KEK participates in the R&D effort of the GDE, organizing university-based activities in Japan, and leads the relevant scientific research studies. The Reference Design Report (RDR) for the ILC was completed in Mid-2007. The

GDE has now entered a new stage of engineering design and of promoting industrialization (technology transfer to industry). In the present schedule the GDE will complete the Technical Design Report (TDR) in 2012. From the purely technical viewpoint, the earliest start of construction work for the ILC is expected to be around 2014. Thus, the 5-year span of our roadmap corresponds to the period of establishing industrialization for the ILC. KEK's R&D programs in the next 5 years for ILC will be comprised of the following three pillars:

A) Continuation of present R&D activities;
B) Engineering design;
C) Technology transfer to industry.

For A), basic solutions have to be found for some items where specifications are not yet fully satisfied; examples include the high field gradient in the superconducting acceleration cavities and beam instabilities in the damping rings.

For B), it is necessary to carry out engineering design work based on the conceptual design in the RDR.

For C) the goal is to transfer the manufacturing technologies developed in laboratories to industry, as well as establish a scheme for mass production. This technology transfer has to be promoted in all the three regions, Asia, North America, and Europe.

The new technologies for ILC are classified into two categories:

- technologies relevant to the superconducting acceleration, and
- technologies relevant to precise beam control.

KEK will carry out development of the former at the Superconducting RF Test facility (STF) while the latter will be done at the Accelerator Test Facility (ATF/ATF2).

Research at the ATF has been conducted for more than 10 years; its scientific achievements are greatly appreciated by scientists throughout the world. The remaining items for development and investigation include: 1) establishment of a tuning methodology for low emittance beams, 2) research into beam instabilities such as the fast ion instability, 3) development of extraction kickers, and 4) development of diagnostic instruments such as laser-wires. KEK is now constructing the ATF2 as a prototype of the beam delivery system (BDS) for the ILC by extending the ATF extraction line; commissioning is expected to start in fall 2008. The operation of ATF2 will continue until the start of the construction of the BDS in order to contribute to the improvement of the design.

The plan for the Superconducting RF Test facility (STF) consists of three stages. The purpose of STF1, the first stage, is to construct a prototype of the L-band superconducting acceleration system being planned for the ILC, and to develop experience with its technology. Two cryostats will be built to house 8 acceleration cavities. Their assembly and testing are being done at KEK, and will be completed in JFY2008, prior to the 5-year roadmap plan.

In stage STF2 following STF1, KEK will build one acceleration unit having a structure close to the one currently planned for ILC. The unit consists of 3 cryostats each containing 8-9 accelerating cavities, a 10 MW klystron, and an electron beam source needed for the test. The program at STF2 will contribute not only to improving the technical level in Japanese laboratories and industries, but also is useful to ensure the technical consistency of the ILC design. This stage is being planned for the early years of the 5-year research program.

In parallel to these, KEK will conduct development of a high gradient cavity. In the basic ILC design, the accelerating gradient of the cavities is required to be higher than 35 MV/m in vertical tests, and 31.5 MV/m on average after being installed in cryostats. KEK plans to construct 20 or more cavities in the early years of the 5 year program, to establish the technology of surface processing and to guarantee a high production yield.

STF3 will be constructed following STF2. The purpose of this stage is to transfer the manufacturing technology of important components to industry, and to establish industrially proven manufacturing procedures. For manufacturing the critical components such as the superconducting cavities, it will be necessary to build a production line technically close to the ones that will be used for actual mass production. It is thought to be necessary to build three acceleration units before starting ILC construction, and to meet this requirement, one unit will be constructed in the latter half of the five year program. This must be preceded by civil construction work to extend the existing housing and construction of the cavity manufacturing facility in the first half of the five year program.

3-5-3 R&D for the Particle Detectors

Innovative technologies in particle accelerator and detector play a fundamental role in the science of the next generation. In some cases, innovation provides important breakthroughs for the progress of basic science such as particle physics. An example well-known to many physicists is the development of semiconductor detectors, which allowed the precise measurement of decay vertices of particles and consequently brought epoch-making progress in the physics of heavy quarks. Another famous example is the development of ultra-large aperture photomultipliers that greatly contributed to the experiments done at Super-Kamiokande.

The future “perfect detector” system would be one that enables the reconstruction of every particle trajectory in three spatial dimensions in conjunction with time information of sub-nanosecond resolution (thus reconstructing the phenomenon completely in four dimensions) to be used in an experiment to search for dark matter, double beta decay or proton decay. This type of “perfect detector” can be constructed with a liquefied gas such as xenon, which provides both scintillation light and an ionization signal in an integrated manner as is used in medical tomography. Such a detector system may evolve into a next generation water Cherenkov detector or liquid argon detector that is larger than Super-Kamiokande in size and more precise, and plays a key role in the next generation of neutrino experiments.

To realize the “perfect detector” mentioned above, the following technologies have to be developed intensely: 1) time projection chambers (TPC) together with micro-pattern gas detector (MPGD) technology and pixel detector technology, 2) photon detection technology to measure scintillation photons with good time and energy resolutions, 3) sophisticated cryogenic technology to handle liquid xenon or argon, 4) ASIC technology that enables high-speed processing of mega-channel signals, 5) very fast software to reconstruct space-time trajectories of particles in four dimensions, and 6) generic technology to integrate all those advanced technologies into a large-scale detector system without degrading the quality of the measurements.

Whereas innovative accelerator technology is, in a sense, a ray of light that shines ahead for the science of the future, novel detector technology is, so to speak, the sharp eye that scrutinizes what the ray of light reveals. In this context, KEK would like to emphasize that the development of synchrotron radiation based imaging technology or next generation electron microscopy, and progress in neutron beam-based basic physical sciences in the material and life sciences can be accomplished only with successful development of novel detector technologies.

4. Conclusions

The High Energy Accelerator Research Organization (KEK) has successfully designed, constructed and operated: 1) a 12 GeV proton synchrotron, 2) a 8 GeV electron-positron Linac, 3) a 2.5 GeV Photon Factory (PF) and a 6.5 GeV Photon Factory Advanced Ring for pulsed X-rays (PF-AR), 4) a 32 GeV electron-positron collider (TRISTAN), 5) a 3.5 GeV + 8 GeV asymmetric energy collider (KEKB), and 6) the ATF. These accomplishments have been carried out in close collaboration with researchers dispatched to KEK by universities and other research institutes. As a result of these scientific achievements at KEK in the past 20 years in the fields of particle accelerator and particle beam technologies, KEK is now recognized as one of the centers in the world. Now KEK is continuing its sustained efforts as it completes the construction of the J-PARC facility. Also KEK is expected to play an important role in the international research program.

Furthermore, KEK has decided to conduct the future research program contained in the aforementioned five year plan proposed in the Roadmap (Operation and early achievement of the design performance as well as beam intensification at J-PARC, upgrade of KEKB, operation and upgrade of PF/PF-AR, commitment to LHC experiment, R&D for ERL, R&D for ILC, and development of innovative detector technologies) so as to allow the past history of scientific studies to evolve into a significantly new phase of science; the upgrade of KEKB will allow us to explore fundamental problems such as flavor mixing and CP violation in the new physics at the TeV energy scale, the compact ERL will provide us with a new tool for research in the material and life sciences, the development of ILC technologies will allow us to take an essential step towards the realization of the accelerator of the future, improvement of the beam power at J-PARC will provide further competitiveness for the neutrino program while the detector development program proposed here will lead to new technologies that will in turn lead to progress in various fields of science. Conducting these programs, therefore, will allow KEK to continue to play an important role as one of the centers of accelerator based science in the world.

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In Section 3-2, "KEK B Factory Upgrade," of the previous Roadmap, the plan presented for upgrading KEKB was based on high beam currents and crab crossing. Since that time, it has been requested that the construction and operation costs be reduced. In addition, due to increased luminosity requirements from physics considerations, and in light of developments in accelerator research, we have changed the upgrade scheme. In this section of the KEK Roadmap we present the new Nano Beam Scheme for the Super-KEKB.

KEKB is a B factory boasting the highest luminosity in the world, having achieved a peak luminosity of $2.11\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$, and a total integrated luminosity exceeding 1 ab^{-1}. With the data accumulated so far, the Belle collaboration has succeeded in proving the Kobayashi-Maskawa theory, and has obtained experimental results that provide hints of physics beyond the Standard Model. At present, the search for "new physics" is considered an urgent problem in particle physics; upgrading the present KEKB to Super-KEKB, and carrying out detailed experiments with the greatly improved luminosity is the shortest and best path to that end.

For this purpose, we will conclude operation of KEKB and completely rebuild the machine on the basis of the Nano Beam Scheme, aiming for a 40-fold increase in luminosity, to $8\text{x}10^{35}$ $\text{cm}^{-2}\text{s}^{-1}$. In this scheme, the vertical beam size at the collision point will be squeezed down to 50-60 nm (as compared to approximately 1 μm in the current KEKB), and at the same time the stored beam currents will be approximately doubled. The upgrades needed to carry out these improvements will require a shutdown of at least 3 years. Once beam operation has been restarted, the goal is to accumulate 50 ab^{-1} over approximately 6 years.

The principal elements of the Super-KEKB upgrade plan are as follows:

- Rebuild the interaction region and Tsukuba straight section;
- Improve optics in the arc and wiggler sections;
- Change the energies of both rings;
- Change the beam pipes in both rings;
- Strengthen and reconfigure the accelerating RF system;
- Upgrade Linac, including the construction of a positron damping ring, strengthening the positron source, and installation of a new, low-emittance RF gun for electrons;
- Implement speed and resolution improvements to the beam monitor and control systems; and
- Strengthen the cooling facilities.

There are three ways to improve luminosity: 1) reduce the beta function (increase the beam focusing strength) at the interaction point; 2) increase the beam currents; 3) increase the beam-beam parameter. In the Nano Beam Scheme, a factor of 20 increase in the luminosity comes from squeezing the vertical beta function at the interaction point (IP) to about 300 μm, with another factor of 2 coming from the increase in the beam currents, for an overall target increase of a factor of 40. For the beam-beam parameter, we assume the same value that has already been achieved at the present KEKB.

In order to squeeze the vertical beta function at the IP, we will construct a new final focus magnet system comprising both superconducting quadrupole magnets and permanent quadrupole magnets. A large horizontal crossing angle between the beams at the IP will be introduced to shorten the longitudinal crossing region, which will reduce the "hourglass effect," and make it possible to reduce the vertical beta function at the IP to around 300 μm.[See Note, below] In addition, to maximize the dynamic aperture, local chromaticity correction sections will be installed in both rings.

To realize extremely small beam sizes at the IP, not only must the beta functions there be reduced, but the horizontal emittances must also be reduced to 1/5-1/0 of their present values. For this purpose, the arc sections of both rings and the wiggler section of the Low Energy Ring will be greatly modified. In addition, the energies of both rings will be changed for lower emittances, from 8 GeV and 3.5 GeV to 7 GeV and 4 GeV.

To cope with the increased beam currents, the beam pipes in both rings will be replaced with a new design capable of withstanding the increased heat loads due to synchrotron radiation and higher order modes, as well as suppressing the build-up of electron clouds. The RF system will also be strengthened, and the accelerating cavities modified and rearranged. Along with this, there will be speed and resolution improvements made to the beam position monitors, bunch-by-bunch feedback system, beam profile monitors and other beam instrumentation and control systems. The cooling systems will also be strengthened to cope with the heat loads associated with high beam currents.

Upgrades to the injector linac and beam transport system, including a new, low-emittance RF electron gun, improvements to the positron source, and installation of a 1 GeV positron damping ring, are designed to improve the rate and quality of injected beams to deliver the required beams with increased injection efficiencies.

Note:

The luminosity is inversely proportional to the value of the vertical beta function at the IP. The length of the beam crossing region sets a lower limit on the vertical betatron function (the “hourglass effect”). I.e., because the beta function increases rapidly with longitudinal distance from the collision point, squeezing the beta function at the crossing point to below the length of the crossing region does not generate any further increase in luminosity. At Super-KEKB, the horizontal crossing angle (83 mrad) is larger than in the present KEKB, and the horizontal beam size is smaller (about 10 μm, 1/10 of that in KEKB); with this design, the length of the beam crossing region is about 300 μm. Accordingly, the vertical beta function can then be squeezed to around 300 μm.