May 31, 2021
KEK Roadmap 2021

Inter-University Research Institute Corporation, High Energy Accelerator Research Organization

1. Introduction

The High Energy Accelerator Research Organization (KEK) has been formulating the KEK Roadmap since 2007 as a guideline for promoting its research programs. The most recent Roadmap is the KEK Roadmap 2013 Update, which was formulated in May 2013 and republished in April 2019 with minor revisions. It was decided to revise and formulate the roadmap with a view to the fourth medium-range goals and mid-range plans period beginning in FY2022. This is the new “KEK Roadmap 2021”.

The importance of scientific research using accelerators has been increasing in recent years, and KEK, as an inter-university research institute corporation, promotes research in the fields of particle and nuclear physics, materials science, and life sciences. KEK provides research opportunities for researchers in Japan and abroad, both from academia and industry. To this end, KEK has been developing, constructing, and operating state-of-the-art accelerators and has played a role as an international center of excellence for accelerator research. In addition, KEK has focused on research and development of accelerator technology for industrial and medical applications. This Roadmap is designed to further develop the role of KEK and to make it a world center of accelerator science.

In developing the Roadmap, inputs based on the future plans of the research communities of particle, nuclear, synchrotron radiation, neutron, muon, and other related research areas were obtained through the four research institutes and research laboratories that constitute KEK, namely, the Institute of Particle and Nuclear Studies, the Institute of Materials Structure Science, the Accelerator Research Laboratory, and the Applied Research Laboratory. The formulation process began in December 2019 with KEK’s Research Steering Committee; a KEK Roadmap Open Symposium was also held in July 2020 with the participation of researchers from KEK and other research institutes. Based on these discussions, an "Interim Summary" was prepared and published at the Research Steering Committee Meeting in September 2020 to solicit opinions from the research community. Taking into account the opinions received, the Research Steering Committee carefully considered KEK’s goals and direction and compiled the “KEK Roadmap 2021”.

Chapter 2 of this Roadmap describes the long-term prospects of KEK-related research fields and the role that KEK should play. This includes research in the fields of particle and nuclear physics, materials and life sciences, accelerator and related technologies, detector development, and the role of KEK as a center for international cooperation, human resource development, and social contribution. Chapter 3 describes the research strategy for the period from FY2022 to FY2027, which corresponds to the fourth medium-range goals/plans period, for the six items outlined below.

・J-PARC

All experimental facilities including neutrino, hadron, and materials and life science experimental facilities will be pushed to meet their design beam intensities, while maintaining an appropriate balance between beamtime availability and facility upgrades. For upgrades, the beam enhancement for Hyper-K, the muon g-2/EDM experiment, the extension of the Hadron Experimental Facility, and phase II of the COMET experiment will be steadily carried out. In addition, the development and research plans of the second target station, which is a major future plan of the Materials and Life Science Facility, will be materialized.

・SuperKEKB/Belle II

The operation of the SuperKEKB/Belle II facility will continue while its performance is improved, and physics analyses, such as the search for new physics, will be carried out. Aiming to accumulate 50 ab^{-1} of data by 2031, the major accelerator and detector upgrade will take place around 2026, which will enable significant performance improvement thereafter.

・LHC/ATLAS

KEK will continue to carry out the ATLAS experiment and will actively promote the upgrading of accelerators and detectors to increase the luminosity of the LHC through international cooperation.

・ILC

Under the leadership of the International Development Team set up in August 2020 with KEK as the host, KEK will work on research and development of the accelerator and physics/detectors, while developing the organizational design for the establishment of the ILC Pre-Lab, an international preparatory body. Promptly starting the operation of the ILC Pre-Lab, KEK will lead the ILC project together with the international community within the framework of the ILC Pre-Lab.

・Photon Factory

As an advanced science platform, the exploration of matter and life using the two light sources currently in operation will continue. In the short term, the facility will be equipped with a set of one-of-a-kind beamlines and a beamline dedicated to R&D, utilizing the improved performance of the light source to carry out cutting-edge research and development. In addition, the conceptual design of the new light source facility with much more flexibility and the R&D of related technologies will be carried out as part of the long-term plan.

・Promotion of other important projects

In addition to the five major projects mentioned above,

(1) Under the newly established Center for Applied Superconducting accelerator (CASA), KEK will promote the application of its accelerator technologies to industrial and medical applications, including the superconducting high-frequency accelerator, which can accelerate high intensity beams with high power efficiency.

(2) The Slow Positron Facility leads the world in the development and application of positron diffraction techniques to meet the needs for development of functional surfaces.

(3) The KEK Wako Nuclear Science Center will operate its own short-lived nuclear experimental facility for the study of astrophysical nucleosynthesis processes in the universe. The next-generation facility will utilize new technology to elucidate the origin of uranium.

(4) The neutron electric dipole moment search experiment (TUCAN), precise observation of polarization of the CMB (LiteBIRD), and the Large-Scale Cryogenic Gravitational Wave Telescope (KAGRA) project will be promoted in collaboration with other institutions and fields.

This Roadmap presents an overview of the research projects to be pursued at KEK based on the input solicited from the relevant research communities. In order to ensure that the research described in this Roadmap is carried out in a timely manner, a steady implementation plan, including the securing of human and financial resources, must be developed and implemented based on the progress of related research fields and technological developments. In June 2016, the KEK Project Implementation Plan (KEK-PIP), an implementation plan for advancing specific research plans listed in the Roadmap, was established based on Roadmap 2013. With the new KEK Roadmap, it is necessary to develop an appropriate implementation plan to implement research strategies in line with the Roadmap.

Any plan or project to be positioned in the KEK Roadmap must be steadily carried through the long process from conception to technical development, design, and implementation in collaboration with the relevant research communities. KEK encourages the development of new proposals for the future. If any significant development occurs during the period of this Roadmap that will have a particularly large impact, including on the projects listed within it, this Roadmap itself must also be updated.

2. Long-term Prospects for Each Sector and the Role of KEK

2.1 Elementary Particle and Nuclear Physics

Prospects for particle and nuclear research

Understanding the nature of atomic nuclei and elementary particles that make up matter in nature is one of the central tasks of basic science, and since the discovery of radiation at the end of the nineteenth century, our understanding of atomic nuclei and elementary particles has advanced at an accelerating pace, thanks primarily to the invention and development of particle accelerators.

The discovery of new particles and precision measurements by accelerator-based experiments have led to the establishment of the so-called "Standard Model" of particle physics, which has enabled precise predictions about many phenomena involving elementary particles. At the same time, various discoveries made during this period have given rise to new mysteries. Dark matter, which is known to exist, is clearly a missing element in the Standard Model, and is expected to be discovered in future experiments and observations. Many questions remain, such as why matter overwhelmingly dominates over anti-matter in the universe, the mystery of the generational structure of elementary particles, the mystery of the accelerating expansion of the universe, and the mystery of the beginning of the universe. It is believed that the exploration of these questions will lead to the clarification of the ultimate laws of elementary particles, including the structure of spacetime, and is a grand challenge to physics that aims to understand the whole picture of matter and the universe.

It is difficult to say for sure at this point where the next breakthrough in particle physics will come from. For this reason, various approaches are important, and the search for phenomena beyond the Standard Model is centered around accelerator-based experiments in the uncharted high energy region and ultra-precision experiments at low energies.

In 2012, the Large Hadron Collider (LHC) experiments at CERN, in which KEK also participated, discovered the Higgs boson, which had long been a pending issue in particle physics. The most important challenge to future particle physics posed by this discovery is to understand the mechanism of electroweak symmetry breaking and to elucidate the new physical laws behind it. The measurement of the properties of the Higgs boson at the LHC using high-statistics data will continue. The International Linear Collider (ILC) project is eagerly awaited, since electron-positron collisions are essential for more precise investigations. In these energy frontier experiments, the search for more unknown new particles will continue in order to open up a frontier of physics beyond the Standard Model.

The multi-faceted search for cracks in the Standard Model will continue, combining precision measurements of all generations of elementary particles and results obtained from cosmological and astrophysical observations, thereby developing a theory that goes beyond the Standard Model. KEK's facilities serve as a world hub for the promotion of such studies through precision measurements of B meson and tau lepton decays in the SuperKEKB/Belle II experiment, through precision measurements of rare decays of K mesons and muons at J-PARC, and through collaborative measurements of inter-generational oscillations of neutrinos with J-PARC and Super-Kamiokande. The strength of KEK is its comprehensive searches and measurements using all generations of quarks and leptons, which no other institute in the world can offer. There are also areas that KEK is exploring in close collaboration with other institutions, such as the search for the electric dipole moment (EDM) of neutrons and the observation of the polarization of the cosmic microwave background (CMB).

An atomic nucleus consists of nucleons, which are in themselves bound states of quarks and gluons called hadrons. The major goal of nuclear and hadronic physics is to understand the structure of hadrons and the properties of a nucleus which is a complex many-body system of hadrons on the basis of quantum chromodynamics (QCD), the fundamental theory of the strong force, and to elucidate the overall evolution of matter from the quark-gluon plasma in the early universe to the formation of heavy elements.

In general, the properties of hadrons and atomic nuclei are investigated through spectroscopy or through their transitions. For a more in-depth understanding based on QCD, however, it is effective to study states of atomic nuclei injected with exotic particles (e.g., strange quarks or charm quarks). The beams available at J-PARC, such as high-energy proton and kaon beams, are used to study hypernuclei containing strangeness, kaonic atoms, and mesons in atomic nuclei to provide a deeper understanding of the structures of hadrons and nuclei.

Recent advances in cosmological and astrophysical observations have led to the observation of many neutron stars and provided information on their masses and other properties. The gravitational and electromagnetic waves emitted by neutron star mergers have been measured, and the need to understand the properties of high-density nuclear matter is increasing. In order to understand high-density nuclear matter, it is necessary to know the nature of the "generalized nuclear force" for systems containing strangeness, which can be obtained from the study of hypernuclei. In addition, heavy elements such as xenon, gold, and uranium are thought to be produced by rapid neutron capture in explosive events in the universe, and it is becoming increasingly important to characterize the short-lived nuclei involved in these events in accelerator-based experiments. Since astrophysics and nuclear physics are closely co-evolving, information from accelerator-based experiments plays an important role.

The increasing precision and statistics of particle-nuclear experiments require increasingly sophisticated measurement techniques and analysis. The explosive increase in the amount of data, as well as improvements in the accuracy of individual detectors, requires faster data processing and analysis. Experimental data analysis using machine learning methods has become a standard tool for high energy experiments. KEK can play a leading role in the development of the required technologies. The refinement of experimental results also requires correspondingly improved theoretical calculations. For example, the data obtained from the SuperKEKB/Belle II experiment have implications for the search for phenomena beyond the Standard Model only when the effects of QCD are evaluated theoretically, while spectral and other information obtained from hypernuclear experiments at J-PARC can be compared with the theoretical calculations of QCD to obtain more basic information regarding the nuclear force. Theoretical calculations using supercomputers will achieve theoretical accuracy commensurate with experimental accuracy.

Elementary particle and nuclear research at KEK

With input from the domestic research community and paying attention to global research trends, KEK carries out a number of projects and has become a major international center for particle and nuclear physics research. At the energy frontier, in order to elucidate the Higgs boson and new laws of physics, KEK will continue to participate in the LHC experiment and to pursue its activities towards the realization of the ILC. KEK will further strengthen its role as an international hub for the preparation of the ILC. Meanwhile, a unique research program that uses high-intensity frontier accelerators, SuperKEKB and those at J-PARC, will be planned and implemented. KEK is a key research hub in the search for a complete picture of matter and the universe, and aims to be an attractive research center with sufficient resources to realize these plans in a timely manner and to produce rich research results.

The most important challenge in the short term is to secure the long-term stable operation of the experiments already in operation required to produce their research output, taking into account realistic resources and their careful allocation. The goal is to provide sufficient beamtime to achieve the targeted integrated luminosity by Belle II to advance research into quark and tau-lepton flavor physics, to clarify neutrino CP violation in T2K using the high-intensity proton beam from J-PARC, to develop K meson flavor physics, to promote nuclear physics including strange quarks, and to realize the COMET Phase I experiment to search for muon-to-electron conversion, thereby leading the world in these research fields. It is also important to promote well-balanced R&D geared towards future research facilities and projects desired by scientists from both inside and outside Japan. KEK will also take advantage of synergistic effects in current projects based on close cooperation with other institutions to produce research results. For Hyper-K and HL-LHC, future projects already under construction, a prompt transition to the post-construction phase of producing research results will be prepared for.

The projects for expanding the existing KEK facilities, namely the muon g-2/EDM experiment, the J-PARC Hadron Hall expansion and the construction of a new secondary beamline, COMET Phase-II, and KISS-II, which are described in the next chapter, have been studied for a long time. The internal timeline of each project, including phased implementation, will continue to be refined and prioritized among the projects taking their correlations into account in order to promptly realize these facilities. In addition, by making appropriate investments in computer resources, KEK will promote its own distinctive research projects in the fields of computational particle and nuclear physics and lead the relevant research communities toward coherent progress with experimental research projects.

In exploring new particle and nuclear physics from multiple perspectives, it is increasingly important to undertake a variety of new experiments. It is important to solicit ideas from both the international and domestic communities for new experiments which make the best use of the existing accelerator facilities at KEK, as well as to consider new developments that are not limited to the use of existing accelerators, taking advantage of the development of existing research and accumulated technologies. Theoretical researches undertaken at the Theory Center cover a broad range of fields including particle phenomenology, hadron and nuclear physics, cosmology and string theory. They are important as an exploration of new opportunities to understand the origin of matter and space. The Theory Center plays the central role for deeper collaborations between experimental projects and theorists as well as for the generation of new ideas based on an overall view of particle and nuclear physics, the investigation of their feasibility in collaboration with experiments, and the sharing of ideas with other fields.

Prior to the formulation of the KEK Roadmap, the Institute of Particle and Nuclear Studies convened a Research Planning Committee with a wide range of members from the Japanese community and asked them to extensively discuss the future expansion of research. The community requested KEK’s involvement and support for a number of projects beyond the current KEK-led projects, indicating that KEK plays a role larger than just a user facility for the community. KEK already supports the activities of Japanese research communities both domestically, through a university collaboration program, and internationally through, for example, Japan-US and Japan-France joint projects.

2.2 Materials and Life Science

Research in materials and life sciences covers a wide variety of materials, and this research will lead to an understanding of their diversity, the creation of basic principles and concepts for the expression of functionality, and the creation of new functional materials that are useful for the realization of a sustainable society. In recent years, the use of quantum beams has become indispensable for the study of materials with widely different length and time scales of fluctuations, because the cohesion, interaction, and hierarchy of electrons, atoms, and molecules play an important role in the functionality of materials. In particular, to understand the diversity and multifaceted nature of materials and life sciences, it is important to utilize various quantum beams in a combined and collaborative manner.

Quantum beam research in materials and life sciences

Synchrotron radiation is an indispensable tool for the precise determination of structural and electronic properties of materials in a wide range of academic fields such as physics, chemistry, materials science, life science, and earth and planetary sciences. Recently, not only the static structure and electronic state, but also its time evolution can be determined. In addition, local structure and electronic state can be determined with high spatial resolution in the nanometer range and high energy resolution in the meV region by using high brilliance light from vacuum ultraviolet soft and hard X-rays and highly coherent light in the soft X-ray range. This enables the elucidation of the mechanism of functional expression in heterogeneous systems, which often play an important role in functional materials. In particular, the clarification of the structure and electronic state specific to different phases and their interfaces, which inevitably occur in heterogeneous systems, is a major breakthrough in the search for the origin of function.

Since neutrons interact with nuclei and electron spins, they are used to determine the details of the position and magnetic structure of light elements and to elucidate the motion of atoms, molecules, and molecular assemblies. In particular, the use of isotope substitution and polarized spin analysis is a powerful tool for the cross-correlation analysis of multicomponent systems. The development of brilliant beams using focusing mirrors and magnetic field gradient devices and the use of polarized neutrons has made it possible to freely select an observation area from near-surface to bulk depending on the research purpose, enabling quantitative comparisons with information from other quantum beams such as synchrotron radiation and multi-probe analyses. These instruments, with features such as high resolution, high intensity, and sample environment, will be utilized to develop next-generation research on materials and life sciences using neutrons, such as near-interface dynamics, microscopic materials structure analysis, and charge excitation observation.

The muon is a complementary method to synchrotron radiation and neutron, which relate in terms of wavenumber and energy space, and the spin rotation, relaxation and resonance (μSR) technique can be used to study the spatial structure of matter and its fluctuations. It is important to improve the availability of the world's highest-intensity pulsed muon beam, especially an ultra-low energy tunable beam, as well as to develop the μSR system with a pulsed beam by improving its temporal resolution and making it practical for the observation of transient phenomena. With this improved μSR technique, the origin of various interesting phenomena in the vicinity of surfaces and interfaces, which is one of the major frontiers of materials science, will be elucidated at the atomic scale. Furthermore, nondestructive elemental analysis using negative muon characteristic X-rays, materials research for industrial applications, and a wide range of applications as a probe for soft matter and life-related materials are also planned.

With the slow-positron beam, precise and surface-sensitive diffraction methods are used to determine the atomic arrangement of a few topmost layers of a materials' surface. The determination of the structure of one-dimensional atomic chains and two-dimensional molecular layers on the surface of a single crystal, including the settlement of the 30-year-long debate on the rutile-type $TiO_2(110)(1\times2)$ surface atomic arrangement, has been achieved. In addition the determination of the atomic arrangement of Ca-intercalated bilayer graphene on SiC, which is a two-dimensional superconducting material, has recently been realized. It has been shown for the first time that they are completely different from what was originally believed. Such surface structure analysis of materials is important for the development of advanced catalysts and novel electronic devices. The research will be enhanced, using positron diffraction on the relationship between the surface structure and the properties of these materials. The surface electronic state will also be studied by measuring the time-of-flight of positronium, which is an exotic atom composed of a positron and electrons.

Multi-quantum beam probe research in KEK materials and life sciences

The Institute of Materials Structure Science (IMSS) established the Structural Biology Research Center (SBRC) in 2003 and the Condensed Matter Research Center (CMRC) in 2009, to take advantage of its unique and unparalleled availability of four different quantum beams (synchrotron radiation, neutrons, muons, and slow positrons). In 2020, contributions from the CMRC were reorganized and the Center for Integrative Quantum Beam Science

(CIQuS) was established to expand the scope of multi-probe research to materials science. The main objective of materials structure science is to comprehensively elucidate the structure and function of materials by investigating the surface structure, internal structure, and inhomogeneous structure of materials using the four quantum beams, the observation techniques of which include absorption/transmission, scattering/reflection, diffraction, etc. The IMSS mainly covers four major research fields: surface science, solid state physics, materials science, and structural biology. In addition to the above, the use of quantum beams will be expanded to other fields.

(1) Promotion of quantum beam research

At the Center for Integrative Quantum Beam Science (CIQuS), a "Cultivated Joint Usage" system has been established, whereby staffs who are familiar with the multi-probe application system will not simply wait for applications for use of the probes from external researchers, but will work together with co-users to examine the research content and guide them toward a multi-probe application system, from sample preparation to experiments. CIQuS will provide guidance, advice, and support at every step of the research process, from research on surface science, solid state physics, and materials science to analysis. In addition, by establishing a "Theme-driven Joint Research" system, the staff of IMSS will take the lead in setting up a grand challenge to be solved in about five years to contribute to the innovation of 1) surface science, 2) solid state physics, and 3) materials science, which should be solved through industry-academia-government cooperation and international collaboration. In advancing these efforts, CIQuS will promote the automation and remote-controlled operation of the experimental apparatuses to respond to the research style of the post-corona era, unify the sample environment control system among the probes so that even novice users of multiple probes can obtain data quickly and reliably, and develop a system to control the large amount of data obtained by different quantum beams. CIQuS will improve the sophistication and efficiency of analysis methods using data-driven science and high-speed computation technologies, including AI and machine learning, to comprehensively analyze the data of the research areas.

1 Surface Science

Information on the atomic arrangement and surface magnetism of the top surface of solids and layered materials is indispensable for the development of new materials such as high-speed, low-power information and communication devices, low environmental impact catalysts, and new superconducting materials to achieve a super-smart and sustainable society. It is necessary to measure them in-situ by surface-sensitive quantum beam techniques while producing the materials. In the field of surface science, where the preparation and characterization of materials are directly connected, a unique joint research program for quantum beam applications will be established.

2 Solid State Physics

A new trend in solid-state physics is the emergence of new properties that cannot be understood by elemental reduction-type analysis, such as the emergence of new properties from the combination of different types of properties. In addition to the development of functional materials from pure to heterogeneous systems, the use of quantum beams is essential for both fundamental and applied research. In addition to deepening our understanding of physics, such as mesoscopic structures, cross-correlation, spin-correlation, and hydrogen-induced properties, a joint research project for quantum beams that will lead to the development of spintronics devices, high-retention magnets, low-energy-loss motors, and high-speed optical switches will be set up.

3 Materials Science

In recent years, the development of materials with a strong consideration for a sustainable society, low-carbon society, green innovation, eco-materials, and printable electronics has been accelerating. Although it is linked to the trend of surface science, the field of materials development and multi-probe materials evaluation using quantum beams are very close, and the development of quantum beam evaluation technology based on close collaboration between industry and academia is also indispensable. For example, in-situ multiscale observation technology is necessary for high-performance organic electronic materials, high-performance storage batteries, and high-performance thermoelectric materials, and microscopic observation technology is necessary for highly fracture-resistant structural materials. A quantum-beam cooperative research program that includes the development of such advanced measurement techniques to solve these problems will be set up.

(2) Promotion of structural biology research

The Structural Biology Research Center (SBRC) is taking on the grand challenge of 1) correlative structural analysis, 2) trans-scale structure analysis, and 3) advanced automation of hardware and software of their analysis techniques. In addition, SBRC tries to play an important role in the next generation of biology by expanding the scope of their research from biological macromolecules to organelles and cells.

1 Correlative structural analysis

With the establishment of the macromolecular X-ray crystallography method in the 20th century, complex and intricate elementary processes inside cells for supporting life have been analyzed based on atomic-resolution tertiary structures of biological macromolecules. Since the beginning of this century, combination usage of X-ray crystallography with solution scattering and cryo-electron microscopy methods have been widely employed to obtain information about multiple-state solution structures at ambient temperatures rather than single-state crystal structures at cryogenic temperatures. To further pursue the understanding of dynamics of biological macromolecules, not only quantum beam techniques including XFEL and neutron scattering methods, but also spectroscopic techniques, such as Raman spectroscopy and NMR, and computational methods are necessary. Since the correlative structural analysis is a multidisciplinary method, SBRC will expand cross-organizational collaborations. The correlative structural analysis is a basis for the rational design of molecules, such as low-molecular-weight protein inhibitors, and contributes to biological and pharmaceutical sciences.

2 Trans-scale structural analysis

Conventional biology research has mainly focused on the decomposition of cells to the level of biological macromolecules and analyzed them to explain mechanisms of elementary cellular processes. At present, however, there is an emerging trend to integrate information about biological macromolecules. For example, the high-resolution structural information of various structural levels in cells, from biological macromolecules to the organelle and cell, should be integrated (trans-scale structural analysis) to understand the functional mechanisms of biological networks in cells. For organelle and cellular level structure analysis, it is indispensable to use the cryo-electron microscopy (cryo-electron tomography), which enables the study of intracellular structure at near-atomic resolution. With the method of trans-scale structural analysis, SBRC will establish a research strategy that can go beyond the conventional framework of the structural biology. In addition, the collaboration with omics research, which can provide comprehensive information about gene expression and the amount and type of proteins and metabolites in cells, will be extended. The collaboration of the two advanced methods will bring us closer to understanding the living state of the cell.

(3) Promotion of interdisciplinary research

Extremely challenging research, such as “non-destructive elemental analysis of archaeological materials and cultural heritages using negative muons” as a fusion of humanities and science, "Multiscale characterization of earth/planet/environmental materials: historical analysis" as a new interdisciplinary research project involving synchrotron radiation, neutrons, and muons, "pioneering research on feV science by cold neutron interferometry" as a new interdisciplinary research project in the field of particle-nuclear physics, "fundamentals and applications of exotic atoms and molecules" for muon-catalyzed fusion, and "positronium laser cooling research for Bose-Einstein condensation", will be embarked upon.

2.3 Development of Particle Accelerators and Related Technologies at KEK

As an international center of accelerator science, KEK has, in each era, pioneered basic science and related fields of application using particle accelerators that incorporate state-of-the-art technologies. On the basis of its achievements in the design, development, construction, and performance improvement of particle accelerators built up through various projects, KEK will continue to lead the research and development of accelerators for academic and all other purposes within and outside of Japan, including various applications, as well as the methods of utilization. For further exploration, it is vital to realize accelerators and their support infrastructures with higher performance, higher stability, and higher efficiency. For this purpose, the various cutting-edge technologies listed below will be exploited to promote the sophistication of accelerator technologies well suited for experimental purposes and to contribute to producing experiment results.

In the RF technology field, the superconducting cavity technology, put to practical use in the TRISTAN Project ahead of the rest of the world, is now widely used worldwide. The superconducting cavities developed for KEKB and SuperKEKB also apply to the BEPC-II Project of China's Institute of High Energy Physics (IHEP) and the TPS Project of Taiwan's National Synchrotron Radiation Research Center (NSRRC). In technology development for the ILC, a superconducting accelerating cavity with the highest-class acceleration gradient was manufactured and used to achieve successful stable beam acceleration: one of the successful results achieved to lead domestic and overseas research on superconducting cavities. The magnetic alloy-loaded cavity developed at J-PARC was adopted by CERN for the PS Booster (PSB) upgrade in the HL-LHC project, for PS's longitudinal damper, and for antiproton deceleration. The crab cavity demonstrated at KEKB is soon to be applied at such facilities as the LHC. The demanding specifications in the past have yielded unique and creative solutions such as ARES cavities at KEKB and SuperKEKB, ACS cavities at J-PARC, and damped cavities at the PF and Accelerator Test Facility (ATF), all of which turned out to be keys to the success of the respective accelerator systems. Building upon these achievements, the promotion of developments aiming for next-generation accelerators will continue. Moreover, the R&D for enhanced performance of superconducting acceleration cavities will be reinforced for the ILC and industrial applications. Furthermore, to meet the increasingly advanced requirements for large-power RF generation, transmission, and control, the pursuit of higher precision and efficiency through developing advanced digital RF controls and semiconductor devices will continue.

In the magnet technology field, to achieve state-of-the-art experiment results, the three-dimensional magnetic field design of the superconducting magnet system for the interaction region of SuperKEKB with nanometer-level three-dimensional beam dynamics analysis will be combined. Moreover, the development of the superconducting magnet for precision measurements of muon anomalous magnetic moments and electric dipole moments (g-2/EDM experiment) toward the early implementation of the experiment and to improve three-dimensional high-precision magnetic field design and measurement technologies will be pursued. The construction of superconducting magnets for the muon-to-electron conversion search experiment (COMET) will be completed and developed into the rad-hard superconducting magnet technology for future large-intensity accelerator applications, including the MLF second target station. Development of the superconducting beam separation magnets for the LHC upgrades will continue and they will be further advanced to contribute to the development of high magnetic field superconducting magnet technology for future hadron colliders. Moreover, magnet power supplies and pulsed magnets and power supplies therefor were developed to suit the respective purposes of J-PARC, the electron-positron injector, SuperKEKB, the Photon Factory (PF)/Photon Factory Advanced Ring (PF-AR), the ATF, and other relevant facilities. Most of these apparatuses are operated in conditions close to the limit of ultimate performance. Moreover, they are equipped with various contrivances necessary to withstand actual long-term operation. Recent examples of such contrivances include the high repetition power supply equipped with the large-capacity condenser bank developed for the beam intensity upgrade of the J-PARC Main Ring (MR), the pulsed multipole-magnet system for beam injection at the PF and PF-AR, and the pulsed magnet power supply that allows simultaneous top-up injection into four rings, each different in beam energy. Furthermore, as can be seen in SuperKEKB, KEK also has an excellent track record in precision surveying and alignments for large-scale accelerator facilities. The design of advanced magnets will continue and development research contributory to comprehensive system enhancements, including high-precision power supplies, high-precision alignments, and superior rad-hard performance will be pursued, as will the work to improving power-saving performance.

For beam sources (e.g., electron, positron, proton, and negative hydrogen ion), which are critical factors that determine the beam performance for all projects, including J-PARC, SuperKEKB, and the ILC, KEK will pursue both its in-house development efforts and collaborations with institutions within and outside of Japan as well as with colleagues from other fields. Moreover, the development of laser and other related technologies will be actively promoted.

Accelerator vacuum systems are exposed to harsh environments with electromagnetic fields, heat, discharges, beam losses, electron clouds, and other negative factors that result from the passage of high-intensity beams. KEK has accumulated experience in the development, design, and operation of various vacuum system components at the high-current storage ring KEKB/SuperKEKB and of a large-scale ceramic beam pipe system at J-PARC. KEK will strive to advance the development of components for use in extreme high vacuum/ultra-high vacuum systems in next-stage particle accelerators, while acquiring and absorbing a deeper understanding of related areas of surface physics and material science.

KEK has been accumulating a large amount of diverse experience and expertise on high-precisions, high-speed beam diagnostics devices. In this field, however, new methods and techniques emerge one after another at a remarkable rate. While paying constant attention to their emergence and adopting them as appropriate and necessary, cutting-edge diagnostic techniques will also be pioneered. The integrated accelerator control based on such diagnostic techniques and EPICS has made KEK a global leader in versatility and scalability. Efforts to advance accelerator control-related technology developments, including machine learning, and the pursuit of their application and expansion to measuring instruments and other peripherals will continue.

Regarding refrigerator systems, development research, built on past achievements, including the practical utilization of 2K refrigerators with saturated superfluid helium will continue. Further performance improvement in beam delivery systems, personnel and machine protection systems, collimator systems for high-intensity beams, and beam targets/beam dumps will be pursued.

Also, in accelerator theory and beam dynamics, KEK has made a number of ground-breaking contributions. Efforts to develop and spread advanced methodologies for accelerator design and computer codes will continue. For state-of-the-art accelerators, a scheme is necessary that allows new ideas to be tested rapidly through the tightly meshed combination of beam diagnostics and control technology with accelerator design and theory to extract extreme performance. The world's current highest levels of beam performance marked by KEK's accelerators, including J-PARC and SuperKEKB, are the results of pursuit from both simulations and systematic beam studies. Constant, long-term efforts are often required to improve the beam performance of these accelerators. KEK plans to further enhance the methods for that purpose ahead of the rest of the world.

Seed research projects that have the potential to lead to future accelerators with significantly higher performance than that of conventional ones will also be steadily promoted with a long-term vision. These research projects will cover high-gradient acceleration using normal-conducting RF technology, large-current high-gradient acceleration using superconducting RF technology, new acceleration technologies using laser-plasma, high-intensity muon acceleration, and emerging research on beam utilization technologies.

Regarding radiation protection, techniques for measuring and simulating the radiation and radioactivity resulting from accelerator operation will be improved and the research and development of mixed radiation field measurement and measures for reducing the radioactivation of air, water, and accelerator structural elements will be pursued; obtained results will be incorporated into the safety system design of future accelerators. Besides analysis for environmental protection, chemical analysis of cooling water resulting from accelerator operation and samples produced during the manufacture and development of accelerator equipment will be performed and improved.

Technologies for performing data analysis on a vast scale and operate the distributed computing infrastructure, a GRID Center, to share data and computing resources worldwide for projects such as the Belle II experiment will be researched and developed. New technologies to efficiently utilize networks, storage systems, and high-performance computing systems that will serve as future infrastructure for information processing systems will also be sought. Moreover, to meet the needs of the new era while preparing for increasingly advanced information security threats, technologies that contribute to the maintenance and improvement of information security at KEK will be supported with an attentive eye on technological trends.

KEK will contribute to accelerator equipment and physical experiments using cryogenic and superconducting technologies, supply large quantities of liquid helium, and develop advanced superconducting and cryogenic technologies for accelerators, such as next-generation superconducting electromagnet technology.

KEK designs and manufactures experimental equipment and devices using high expertise in mechanical engineering and advance technologies in mechanical engineering fields such as design, fabrication, measurement, robotics, mechatronics, and materials. In particular, KEK will contribute to the automation and remoteness of user experiments by applying these technologies. Moreover, the mass production technologies of superconducting cavities at the Cavity Fabrication Facility (CFF) will be developed and demonstrated.

KEK will always keep an eye on new concepts and technologies, including AI and quantum information technologies, and actively incorporate them into particle accelerators and their support infrastructure and develop and feed the resulting technologies back to society.

2.4 Development of Measuring Instruments at KEK

Accelerator technology is a technology that brings new "light" to the world of science, and detector technology is a keen "eye" for this new "light". This "eye" is an indispensable foundation for the various fields of basic science, which is the mission of KEK, ranging from the exploration of the microscopic world of elementary particles and nuclei to molecular imaging using synchrotron radiation, neutrons, and muons.

KEK has established the Detector Technology Project Office and has been promoting various instrumentation-related technologies across the organization in order to be at the forefront of these efforts. In the past few years, it has focused on the development of ultrahigh resolution, ultrafast speed, and high-performance pixel sensors for synchrotron radiation, X-rays from space, measurement of decay points of elementary particles, accelerator monitors, and dark-matter searches. The results of this research and development have been highly evaluated internationally as advanced technologies and systems originating in Japan and KEK and have led to the development of applications in industry as well as in basic science.

In order to continue to develop detector technologies, a detector development platform was launched in 2019. This platform will promote the exchange of researchers in a wide range of fields such as particle and nuclear physics, astronomy, condensed matter physics, engineering, and medicine, and create new research themes. Beam test is an essential part of instrument development, and the operation of the test beamline is an important role that the community expects from KEK, which possesses a large accelerator. In cooperation with the Photon Factory, construction of the electron test beamline at the PF-AR began in 2020, and it will be operational in 2022. For the future, the construction of a hadron test beamline at J-PARC is also planned. By utilizing these test beamlines and large facilities, KEK, as a center of excellence for instrument development, will promote international collaboration, both domestically and internationally, especially with neighboring Asian countries. In addition, the maintenance, improvement, and archiving of detector technologies within the framework of Open-It has been steadily progressing, and KEK will continue to play an important role in passing on its technologies.

In recent years, society has expected various applications of the results of research and development in basic science, such as next-generation electron microscopes, high-performance visualization devices using X-rays and neutrons, and the development of advanced medical and diagnostic devices using particle beams and other technologies. Such applied research is one of the important missions for future activities. Major accelerator and experimental research institutes around the world share the same emphasis on diversification and multipurpose research and spin-offs, and KEK will strategically develop the same kind of research.

2.5 KEK as a Center for International Cooperation, Human Resource Development, and Social Contribution

International cooperation in the field of accelerator science is becoming more and more important as large accelerator projects become larger and longer in duration, and as the technology required for them becomes more advanced. To this end, KEK will take on the role of an international center for accelerator science research.

The growth of accelerator projects in terms of their size and applications indicates an acute need for aggressive human resource development in the field of accelerator science. KEK, as a research institute with state-of-the-art accelerators, will serve as a center of human resource development for accelerator science, it is actively engaged in graduate school education at the Graduate University for Advanced Studies (SOKENDAI) and others.

KEK has been carrying out various activities to promote international cooperation and to develop human resources at home and abroad, such as the Japan-US cooperation in high energy physics for more than 40 years, cooperation programs with laboratories and institutes in France and Canada, joint workshops with universities and research institutes in the Asian region, and the promotion of multinational research and development in accelerator research. KEK is carrying out various programs such as the organization and support of various international schools, the promotion of gender equality in accelerator science in cooperation with overseas research institutions, and training courses and practical training for undergraduate and graduate students, young researchers and engineers in Japan and abroad in cooperation with university researchers. In addition, KEK supports graduate students and young researchers in materials and life sciences to improve their skills, taking advantage of the cooperation with research institutions in the Tsukuba, Japan, area. These efforts are important for cultivating new joint research projects and fostering young researchers, and will be actively promoted.

KEK has been accepting many users from abroad through international collaboration experiments and other opportunities, and is expected to play an important role as a research center for researchers around the world, not only for users from Japanese universities. As the internationalization of KEK is expected to progress further in the future, it will improve necessary user support by listening to the opinions of overseas researchers.

Although the main purpose of KEK is to promote basic science research, the technology and knowledge developed for this purpose can be used for research in a broader range of application fields. KEK will promote academia-industry cooperation, strengthen cooperation with universities and research institutions in the region, and play a role as a bridge between academia and society by developing technologies for application.

In promoting these efforts, KEK will appoint URAs and other specialists and utilize collaborations with other Inter-University Research Institute Corporations and the Graduate University for Advanced Studies. It will strive to contribute to the strengthening of the university's functions through systematic cooperation with universities.

The world is being transformed by the corona pandemic. While international cooperation and collaboration in science and technology is becoming increasingly important, conventional forms of international exchange cannot be sustained as they are; KEK will develop and implement new research methods by combining digital technology and on-site research, and will contribute to the development of international research cooperation both during and after the corona pandemic.

Through these efforts, KEK will contribute to the "2030 Agenda for Sustainable Development" (SDGs).

3. Research Strategy for FY2022-FY2027

3.1 J-PARC

J-PARC is a multi-purpose research facility based on the high intensity proton beam and covers a wide range of research fields from the origin and structure of matter to the origin of life. J-PARC is a joint project of KEK and the Japan Atomic Energy Agency (JAEA), which has been conducting its researches in all the experimental facilities (neutrino, hadron, and materials/life science facilities) at J-PARC. The research is supported by accelerator science, superconducting technology, radiation science, and computational science. Research that combines the expertise of KEK and JAEA, such as the development of elemental technologies to withstand activation, are also underway. In this roadmap period, KEK continues to aim at producing high-impact research results together with the community by taking advantage of the high-intensity proton beam. In the field of elementary particles and nuclei, KEK will conduct a comprehensive investigation of the generation structure in the standard model together with SuperKEKB and pursue the origin of matter in the universe by improving our understanding of strong interactions. In materials and life sciences, beam intensity, resolution, and sample environment for neutron and muon experiments will be pursued to the utmost limit, and the facility will constitute a combined quantum-beam platform together with synchrotron radiation and slow positron facilities. In addition to the normal user program, collaborations with domestic and international communities, including industry, will be strengthened by utilizing the branches of universities and industries set up in Tokai and operating the beamlines in the MLF jointly to maximize the scientific results. In order to support these studies, the accelerator will be upgraded as soon as possible to achieve the design performance described below.

J-PARC Neutrino Experimental Facility

KEK will promote the upgrade of the T2K Experiment and the construction of the Hyper-Kamiokande project to discover and measure leptonic CP violation.

The T2K experiment discovered electron neutrino appearance and is making significant strides in detecting signs of leptonic CP-symmetry violation through the measurement of difference between electron neutrino appearance and anti-electron neutrino appearance. The J-PARC MR is expected to achieve the original design intensity of 750 kW and even higher beam powers by increasing the repetition rate in 2021. In the meantime, the T2K experiment will make major upgrades to the near neutrino detector. KEK will continue to increase the beam power and provide neutrino beam to T2K, and will improve systematic errors with the upgraded new near detector to continue the search for leptonic CP violation.

Construction of the Hyper-Kamiokande project, hosted by the Tokyo University Institute for Cosmic Ray Research and KEK, started in 2020. Besides cosmic neutrino observation and the search for nucleon decay, a long-baseline neutrino oscillation experiment using the neutrino beam from J-PARC is one of the main objectives of the project. The experiment is planned to start operation in 2027. KEK is in charge of realizing the high-intensity neutrino beam and the upgrade of the near neutrino detector complex.

To realize a high-intensity neutrino beam, KEK plans to upgrade the beam facility step-by-step and will accumulate experience in providing a stable beam to T2K. KEK aims to realize a 1.3 MW neutrino beam by the time the Hyper-Kamiokande experiment starts. Regarding improvements to the near detector complex, KEK will upgrade the existing near detector and will construct a facility for a new water Cerenkov detector. It will also promote measurements of hadron production from proton-nucleus interactions to improve the precision of the neutrino beam flux prediction.

Many of the technological challenges to realizing the above-mentioned goals are common between KEK and the proton accelerator facilities at Fermi National Accelerator Laboratory (FNAL) in the United States, CERN, and other institutions. KEK will continue international cooperation for these technological developments.

Experiments to measure neutrino-nucleus interactions, as well as detector development for those experiments, are underway using the J-PARC neutrino beam; these will improve the accuracy of the long-baseline neutrino experiments. Advancement of the sterile neutrino search experiment at J-PARC is also expected. KEK will cooperate with universities and laboratories in Japan and abroad and promote basic development for innovative beams, such as multi-megawatt class neutrino beams, and high-performance neutrino detectors, such as liquid argon tracking detectors, from a long-term perspective.

Hadron Experimental Facility

The Hadron Experimental Facility has been operated for experiments at beam intensities of up to 51 kW, and the rare-decay experiment of neutral K mesons (KOTO) at the KL beamline has already attained the best sensitivity in the world. In the study of hadron many-body systems containing strange quarks, at the K1.8 and K1.8BR beamlines, a deeper understanding of the interactions among hadrons has been developed through pioneering research of hyper nuclei with two strange quarks (S=-2), the discovery of a bound state of a K^--meson and two protons, and the successful completion of an experiment for Σ hyperon scatterings. With the upgrade of the MR accelerator and the operation of the secondary-particle production target that accommodates the 95 kW beam, precise and systematic spectroscopic studies of S=-2 hyper nuclei will be carried out and further breaking of its own world record by the KOTO experiment is expected within a few years from 2022. By developing and installing a new production target, experiments will be conducted more efficiently with a beam intensity of over 100 kW. At the new primary proton beamline (B-line), which started operation in 2020, the study of changes in the meson-mass spectrum in nuclear matter is making progress. In 2023, at the new proton beamline (C-line), the first stage of the COMET experiment to search for the phenomenon of muon-electron conversion will begin.

Based on the achievements at the present facilities, with an ambition for drastic advances in the research, KEK aims to start an extension of the Hadron Experimental Facility for experiments with multiple production targets and new beamlines. In particular, in order to elucidate the baryon many-body force, which is more important for understanding dense nuclear matter inside neutron stars, it is necessary to measure the energy levels of S = -1 Λ hyper nuclei with an accuracy of several tens of keV (more than ten times better than has been achieved to date). A new high-intensity and high-resolution π meson beamline utilizing the technique of momentum dispersion matching is required to realize these measurements. The sensitivity of the KOTO experiment would be improved by two orders of magnitude to catch the deviation from the branching ratio of 3×10^{-11} predicted by the Standard Model, by constructing a new neutral K-meson beamline with small-angle extraction. By extending the hall and installing multiple targets, the number of beamlines can be increased and, together with the experiments using existing beamlines, high-precision and richly varied research can be developed.

Also, the COMET experiment would reach a sensitivity beyond 10^{-14} (more than 100 times better than the current upper limit) in the first phase and, along with the upgrading of the detectors and the muon-capture system in parallel, aims to reach the ultimate goal of a sensitivity beyond 10^{-16} early.

Consequently, the Hadron Experimental Facility will enable us to meet the expectations of researchers around the world as a world-leading center for nuclear, hadron, and particle physics. Consideration will also be given to the future potential of the facility, such as experiments with heavy ion beams, while paying attention to global research trends.

Materials and Life Science Experimental Facility

In close partnership with the JAEA and in cooperation with the registered institution for the Act on the Promotion of Public Utilization of the Specific Advanced Large Research Facilities or relevant agencies, including the Ibaraki prefectural government, KEK aims to promote the rapid development of materials and life science research and industrial applications of the J-PARC pulsed neutrons and muons, which have the highest peak intensity in the world. It will develop fundamental technologies, such as a sample environment and analysis software to further improve the experimental equipment, and promote a wide range of research using various experimental instruments at MLF. This will allow KEK to maximize research results by establishing a rational safety management system and enriching the usage system from the viewpoint of users including industry.

Through these studies, KEK will expand the facility user community and research frontiers, as well as strengthen the linkage with the Photon Factory and Slow Positron Facility. Through these developments, neutron and muon science will become a part of the IMSS multi-quantum beam platform whereby the platform will become an international research hub. In cooperation with the community, it will focus on fostering human resources who will be responsible for these activities and research results in the future.

In the field of neutron science, KEK will make a breakthrough in materials and life science research using the world's best J-PARC pulsed neutrons, and its current neutron instruments have been designed for the highest resolution or highest intensity or uniqueness of sample environment. KEK will achieve the expected performance of the instruments by upgrading the detectors and will further improve them by preparing special sample environments. In cooperation with JAEA, it will promote a wide range of research using various neutron instruments at the Materials and Life Science Experimental Facility.

To promote the grand challenge research in materials and life sciences, KEK will develop basic technologies for upgrading neutron instruments by combining the technologies of KEK and other universities and institutions. For example, a rotating elliptical neutron mirror, developed by applying precise metal processing techniques, and a focusing device with a magnetic field gradient will be developed to produce a highly brilliant and microscopic beam. This will enable the measurement of dynamic structures near surfaces and interfaces, and local structures of novel materials such as high-performance batteries. Inelastic neutron scattering by pulsed neutrons and polarized neutrons will allow the precise measurements of various excited states and contribute to the elucidation of the origin of cross-correlation properties. For this reason, the first step in the construction of a polarized neutron analysis system to determine the magnetic structure and its dynamics in detail by spin-polarization analysis is to make inelastic scattering experiments with polarized neutrons up to 40 meV available to users as soon as possible, and to develop a polarization and polarization analysis system for neutrons with energies up to 100 meV. On the other hand, KEK will develop a neutron spin-echo spectrometer to precisely measure the energy transfer by using polarized neutrons with an extended maximum Fourier time of 0.1 microseconds in order to elucidate the function of multi-component soft matter. In addition to the above, research on the basic physics of neutrons, such as the feV science by cold neutron interferometry, will be carried out.

In muon science, cooperative experiments at the decay muon line (D-line) and the slow muon line (S-line, S1 area) are progressing smoothly, and at the ultra-slow muon line (U-line) the development of a nanometer μSR method and a transmission muon microscope are underway. With these instruments, KEK will carry out extremely challenging research using ultra-low energy muons and the μSR technique. Furthermore, it will promote a wide range of interdisciplinary applied research from materials science to archaeology and cultural heritage science by negative muon characteristics X-ray analysis.

In addition, KEK will develop basic physics research, such as the high-precision muonium atom spectroscopy exploiting the high intensity at J-PARC and the precision experiment of the muon anomalous magnetic and electric dipole moments (g-2/EDM), by upgrading the H-line core facility for basic physics and transmission microscopy. Further, it will also develop a transmission muon microscope that utilizes muons as a matter wave, and strongly promote extremely challenging research.

The MLF second target station and other facilities will be developed together with the Japanese Society for Neutron Science and the Society of Muon and Meson Science of Japan to achieve 10 times brighter neutrons and 50-100 times stronger muon intensity.

Accelerator upgrades

The J-PARC accelerators (Linac, 3 GeV Synchrotron (RCS), and Main Ring Synchrotron

(MR)) are delivering high-intensity beams at the world's highest level to each of the three experimental facilities. The top priority is to keep increasing their beam intensities while continuing stable beam operation.

RCS has already successfully delivered a beam with a design intensity of 1 MW to the Materials and Life Science Experimental Facility. The next goal is to develop a neutron production target capable of withstanding high intensity proton beam and to start the RCS operation with a 1 MW beam power. In addition, beam studies will be promoted at the Linac and the RCS along with research and development of accelerator components to achieve the 1.5 MW beam power, which is expected to be necessary when the Second Target Station at the Materials and Life Science Experimental Facility comes into operation.

On the other hand, the goals for the MR during the current Roadmap period are to deliver a beam exceeding the 750 kW design intensity to the T2K Experiment by fast extraction (FX) and to establish a 1.3 MW beam operation toward the start of a long-baseline neutrino oscillation experiment due for 2027 at the Hyper-Kamiokande and to deliver a 100 kW stable beam to the Hadron Experimental Facility by slow extraction (SX). Upgrades for achieving these goals will be implemented, including the following: introduction of new main magnet power supplies for a high repetition rate with high stability, upgrade of the RF system, including the addition of a second-harmonic cavity, and upgrade of the injection and extraction devices. Moreover, to achieve a beam intensity of over 100 kW by SX, beam studies and development research will be advanced toward a high-efficiency beam extraction that exceeds even the world's highest 99.5 percent extraction efficiency already achieved.

In parallel, a large-scale upgrade plan for the J-PARC accelerators and new accelerator construction plans will be considered for the future of neutrino experiments and particle and nuclear physics experiments at the Hadron Experimental Facility. Regarding neutrino experiments, to realize a multi-megawatt class beam, design and development research will be advanced for a booster synchrotron to be newly installed downstream of the RCS for an MR injection energy upgrade to 8 GeV as well as a superconducting Linac-based high-intensity proton driver with a view to deployment at the Tsukuba campus. Regarding particle and nuclear physics experiments at the Hadron Experimental Facility, besides development research for beam intensity upgrades, consideration will be given to a superconducting stretcher ring for a significantly increased beam time.

3.2 SuperKEKB/Belle II

The KEK Super B–Factory project will be promoted and the fully instrumented Belle II detector will operate and continue physics data collection while the performance of the

SuperKEKB accelerator is improved. The Belle II experiment aims to make new physics discoveries at a high-energy scale through, for example, CP violation and lepton flavor violation, and by measuring the decay processes of B mesons, D mesons, and τ leptons with high precision. By clarifying the presence or absence of a number of new phenomena, including the current lepton flavor universality violation anomaly, important information for determining the new physical laws governing high energy scales will be provided. Dark matter will also be searched for at a lower energy scale and the mechanism of hadron formation will be studied, which will lead to advances in particle physics, hadron physics, and astrophysics and their associated interdisciplinary fields.

By improving the stability and preserving the emittance of the beams through modifications of the injector, enlarging the aperture at the interaction point, improving the radiation tolerance and performance of the detector, and reinforcing the RF (Radio-Frequency) system, it will be possible to increase the beam currents and further reduce the beta function at the interaction point. Most of these modifications will be made around 2026, leading to a significant improvement in luminosity thereafter. With a factor of several dozen times higher instantaneous luminosity than the current world record luminosity of 2.40×10^{34} cm^{-2} s^{-1} achieved in 2020, and 8 months of operation per year, by around 2031, 50 ab^{-1} of data will be accumulated and provide the world's highest sensitivities for searches for new phenomena ahead of others. In particular, a major strength of the research program will be its originality, including inclusive analyses and measurements of modes whose final states contain multiple neutrinos or invisible particles.

If reliable evidence of new physics discoveries is observed in the data up to 50 ab^{-1}, further luminosity upgrades and continued operation will be required to elucidate the details. Other proposals for future research, such as measurements using the Belle II detector and polarized electrons requiring a modest upgrade to SuperKEKB, have been made. R&D will continue to examine the technical feasibility of such projects while confirming their physics impact.

As the world's only operational electron-positron B-factory collider, the Belle II experiment has attracted increasing attention and has grown into a collaborative international experiment that consists of more than 1,000 researchers from 26 countries and regions. Belle II is the largest collaborative international project hosted in Japan, and KEK will serve as a research center for researchers from all over the world as well as for the Japanese university community.

3.3 LHC/ATLAS

The most important task of the LHC is to discover new physics phenomena beyond the Standard Model. For this purpose, it is important to search for new physics based on various ideas with an open mind, and in the LHC experiment, the world's highest energy of 13 TeV has been used to search for new physics in the TeV region. At the same time, signs of new physics phenomena are being searched for with precise measurements of the properties of known elementary particles such as Higgs boson and top quarks, taking advantage of the LHC, which can produce heavy particles.

From 2022 to 2024, the third phase of operation will double the amount of collected data and further advance the frontiers of new physics exploration, and KEK will send its researchers on extended stays at CERN to carry out the international ATLAS experiment. Based on task sharing in the domestic group, KEK will play a central role in the maintenance and operation of the detector by coordinating domestic researchers while the International Center for Elementary Particle Physics at the University of Tokyo will play a leading role in computing, leading to improvement in the quality and quantity of data and producing physics results.

As the increase of the integrated luminosity at the proton-proton collision experiment allows the exploration of higher energy regimes, exploring the energy scale of new physics through enhanced luminosity is important in determining the direction of high-energy physics in the future. For this reason, CERN is carrying out a High Luminosity LHC project (HL-LHC) to increase the luminosity by an order of magnitude compared to the LHC, in which about 1 billion collisions per second occurs, through international cooperation not only in Europe, but also in the U.S., China, and other countries from all over the world. The HL-LHC will dramatically increase the limit of the search for new physics phenomena with approximately 4,000 fb^{-1} of proton-proton collision events. In Higgs boson measurement, for example, the accuracy of the measurement of the coupling constants will be improved several times, and verification of self-coupling will come into perspective. Japan was the first country outside of CERN member states to decide to participate in the LHC, and its diverse activities in the construction of the LHC accelerator and the ATLAS experiment have contributed greatly to the discovery of the Higgs boson and other physics results. In the upgrade for HL-LHC, KEK will also play an indispensable role for the success of the project together with Japanese researchers.

The accelerator and the detector will be upgraded immediately after the end of the third phase of operation, and the HL-LHC will be restarted in the second half of the 2020's. Since the number of particles produced by the HL-LHC is dramatically increased, for example, the innermost layer of the detector is exposed to radiation of more than 1×10^{16} cm^{-2}・1 $MeVn_{eq.}$, KEK has promoted detector development incorporating state-of-the-art technologies.

Having spent nearly ten years in technology development, KEK has come close to overcoming the technical challenges and will shift to the preparation period for the mass-production and construction of the actual detector.

For the accelerator, the various magnets installed near the collision point will be replaced to achieve higher luminosity. KEK will replace the beam separation magnets conventionally implemented by normal conduction with superconducting magnets. As regards the tracking detector and the muon trigger, the manufacturing and construction of the actual hardware will take place after the completion of the technology development for achieving a superiority of about 10-times the existing detector in resolution, speed, and radiation hardness. KEK will lead these activities as the domestic center of excellence.

3.4 ILC

High-energy physics has undergone dramatic advances driven by two major tools: hadron and lepton colliders. Based on the discovery of the Higgs boson at the LHC, the ILC will initially operate as a Higgs factory with a center-of-mass energy of 250 GeV. Taking advantage of various virtues of a lepton collider, the ILC will perform clear and accurate measurements of Higgs bosons and high-sensitivity searches for new particles of types difficult to discover at the LHC. Based on the results achieved at the initial stage of the ILC or the future discoveries expected of the LHC, the ILC will investigate in further detail the identified new particles and new phenomena. This is naturally enabled by its energy extendibility. Through these activities, the ILC will provide a deeper understanding of the mechanism of electroweak symmetry breaking and advance the elucidation of new physical laws behind it to make particle physics jump to the next level.

The key technologies of the ILC accelerator are nanometer-size beam control and superconducting acceleration. KEK has almost achieved the target beam size at the ATF and is promoting the research and development of nanometer-size beam focusing technology by pursuing further reliability and stability. Superconducting accelerator development and high-performance cavity fabrication technology development are in progress at the Superconducting Linac Test Facility (STF) and the CFF, respectively. Moreover, additional research and development are underway in Japan, including for the cost reduction of superconducting accelerators, through partnerships with counterparts in the United States and Europe. While steadily continuing the research and development of these key technologies, KEK will also research and develop other systems of the ILC accelerator, including the positron source and beam dumps, and develop the overall design of the accelerator facility. Moreover, KEK is required to strengthen its function as the domestic base for Japanese scientists, who have been essential players in physics studies and detector development for the ILC.

The intention is to realize the ILC through international cooperation among particle physicists and accelerator scientists worldwide. Since 2005, the research and development for the ILC and its design have been promoted by an international design team set up under the International Committee for Future Accelerators (ICFA). A technical design report on the ILC was published in 2013. In 2012, the Japanese high-energy physicist community proposed that Japan host the ILC. In July 2017, based on results of the LHC Run 2, the Japan Association of High Energy Physicists made another proposal for the early construction of the ILC as a Higgs factory with a center-of-mass energy of 250 GeV. This proposal received the endorsement of the ICFA. It is now the worldwide consensus that an electron-positron Higgs factory is a top-priority project for the next-generation collider.

Based on the ICFA′s proposal in February 2020, an International Development Team (IDT) was set up in August 2020 with KEK as its host. In accordance with the October 2019 KEK International Working Group Report, the IDT will develop an organizational design for the ILC Pre-Lab, an international preparatory body, toward timely realization of the ILC. The pre-existing international cooperation framework will be taken over to advance the research and development of the accelerator and the physics/detector and to develop international partnerships for engineering design. Based on international agreements, the Pre-Lab will promptly start its operation and complete the necessary preparation to start the construction of the ILC in about four years. Then, the ILC will undergo an approximately ten-year-long period of construction under an ILC Laboratory to be established by an intergovernmental agreement. If smooth progress is achieved, the ILC will become operational around the mid-2030s. For this purpose, KEK will play a major role in the ILC project in collaboration with the international community.

3.5 Photon Factory

The Photon Factory (PF) was established as Japan's first dedicated facility to enable the use of synchrotron radiation with a wide range of energies in the X-ray region, leading to the dawn of synchrotron radiation science and producing outstanding research results for 40 years. During this period, the situation surrounding PF has changed dramatically with the construction of many new synchrotron radiation facilities both in Japan and abroad, as well as the increasing sophistication and versatility of its light sources. In light of these circumstances, the PF has returned to its mission as a large-scale academic synchrotron radiation facility, and aims to bring about a revolution in synchrotron radiation science and lead it to the next level of success, viewing the present as the second dawn of its existence. The mission of the PF is to (1) produce new technologies and young researchers who will lead the world's synchrotron radiation science through further research and development and (2) promote various research related to materials and life as an advanced platform facility. In order to accomplish this mission, it is important to have a high degree of freedom in the use of light sources, beamlines, and their operations. This means a highly flexible light source that can produce synchrotron radiation for a specific purpose, a set of beamlines that can be used for that purpose, and management of the facility that encourages the testing and realization of researchers' ideas. The PF is still a highly flexible facility that allows for a wide variety of research, but this will be further strengthened in the future.

As of April 1, 2019, the PF was reorganized to make it more suitable for the accomplishment of its mission. The new structure will allow the promotion of synchrotron radiation science by taking advantage of the features of the two light sources in operation, and to further advance them by realizing short-term future plans. In addition, KEK will build a system to promote long-term future plans and strengthen ties with related facilities and communities to construct future light sources with much greater flexibility by the early 2030s, 50 years after the start of operation of the PF.

Light source accelerator

The upgrading of the PF ring will be carried out in a three-year plan. The basic performance of the PF ring, such as average and peak brilliance, will be improved, while the degree of freedom of operation parameters and beam stability will be improved to enable more diverse research. In addition, the performance of the world's only vertical wiggler will be improved.

Toward the realization of the long-term plan, KEK will advance the conceptual design of the hybrid ring and other light sources that can dramatically increase the degree of freedom. The hybrid ring is a proposal of a variable light source which can coexist with the superconducting injector and the third-generation storage mode. The research and development of related accelerator technologies will also be promoted.

Experimental facilities

Cutting-edge research projects with a group of unique beamlines will be developed by making the most of the increased performance and flexibility afforded by the advancement of accelerators. In the short term, the upgrade of about five beamlines, including the construction of a dedicated R&D beamline and a medical imaging beamline, is planned.

The construction of these beamlines will enable the sustainable development of synchrotron radiation facilities in Japan and around the world by promoting research and development of

SR-related technologies. It will also serve as the only beamline in Japan for feasibility testing of new instruments to be developed by researchers, thus contributing to the creation of new research fields. The wide field of view and high resolution X-ray interferometer using the vertical wiggler mentioned above still has the world's highest density resolution (density difference detection limit), and by further improving the performance of the beamline, a medical imaging beamline that enables the visualization of capillaries without contrast media will be developed. In addition, other beamlines, such as X-ray microscopy with variable magnification (>10x) and time-resolved diffraction imaging using coherent soft X-rays will be developed. In addition, the group will provide full support for the development of detector development test beamlines, which are being led by the detector group in IPNS.

As for the long-term plan, new developments in femtosecond dynamics research using the single-pass mode of the hybrid ring and two-mode simultaneous use of single-pass and storage will be considered, as well as new developments in synchrotron radiation science.

3.6 Promotion of Other Important Projects

3.6.1 Medical and industrial applications of accelerator technologies

For the application and deployment of the accelerator technologies developed so far by KEK for industrial, medical, and other purposes, the Center for Applied Superconducting Accelerator (CASA) was established in 2019. KEK realized beam acceleration using superconducting radio frequency (SRF) technology ahead of other institutions in the era of the TRISTAN accelerator and serves as an R&D hub for SRF accelerators, such as the ILC. SRF accelerators can accelerate high-intensity beams with high power efficiency, and their application is underway worldwide in medicine, info-communications, infrastructure, energy, and the environment. KEK has also promoted applied research for such purposes as the production of medical radioisotope (Mo-99), infrastructure life extension through asphalt modification, and EUV-FEL exposure light sources for next-generation semiconductors. For their practical utilization, it will continue to promote research and development by exploiting the large-current superconducting RF test accelerator (cERL) for the applied research of superconducting accelerators and the industry-academia collaboration facility installed with superconducting cavity development equipment (COI building). A low-loss accelerating cavity using superconducting film will enable accelerator operation with a small refrigerator, thereby leading to a breakthrough in the compact accelerator. KEK will work on developing accelerator elements, including acceleration cavities, to suit the needs of accelerators.

The CASA aims at the applied use of various accelerators, including normal-conducting accelerators, and will pursue research and development for improved performance of boron neutron capture therapy (BNCT) using linear accelerators and promote the applied use of such advanced accelerators as induction synchrotrons (digital accelerators).

For the promotion of accelerator application through industry-academia cooperation, the Applied Superconducting Accelerator Consortium has been established. This consortium plays a central role in cultivating new needs for industrial and medical applications and deploys KEK's accelerator technologies to contribute to society.

3.6.2 Slow Positron Facility (SPF)

The Slow Positron Facility (SPF) is the only facility in the world that is currently operating with total-reflection high-energy positron diffraction (TRHEPD) and low-energy positron diffraction (LEPD). Positron diffraction is an ideal technique to determine the atomic arrangement of a few topmost layers of a materials' surface in a more sensitive and precise manner than any other technique and has attracted worldwide interest. TRHEPD has recently been installed in the neutron-induced positron source munich (NEPOMUC), a slow-positron beam facility using neutrons and γ-rays from a research reactor in Germany, in cooperation with SPF.

SPF achieved remarkable improvements in performance with the increased beam intensity in 2010 and the subsequent development of innovative equipment. Further improvements in beam intensity and brightness are desired to realize shorter measurement times and wider applications. This is crucial for SPF to continue to lead the world in meeting the widely ranging needs of research and development for functional surfaces. The SPF is working on increasing the primary electron beam power to increase the positron beam intensity and improving the slow positron beam transport technique to achieve higher brightness. The development of a next-generation positron source to increase the beam intensity by orders of magnitude will also be attempted. The SPF is hoped to become a world center for materials research using the world's highest-intensity slow positron beam.

3.6.3 KEK Isotope Separation System (KISS)

KEK has established the Wako Center for Nuclear Science in collaboration with RIKEN, and operates its own experimental facility, KISS, to provide low-energy, neutron-rich nuclear beams for user experiments that cannot be provided by similar facilities in the world. The unique instrumentation used in KISS has contributed to the study of elemental synthesis processes in space. By utilizing the multiple reflection time-of-flight mass spectrometer (MRTOF), which has been developed for the next generation instrument KISS-II with dramatically higher sensitivity and efficiency, and the gas-cell instrument using radio frequency ion transport, KEK aims to elucidate the origin of uranium and to provide the first unambiguous identification of superheavy elements beyond nihonium.

3.6.4 Collaboration with other organizations and fields

KEK will promote the following three projects in cooperation and collaboration with other organizations and fields.

TUCAN

KEK developed an Ultra-cold neutron (UCN) source that combines a spallation neutron source with a superfluid helium converter and successfully produced UCNs. Based on this success, an international collaboration named TUCAN was organized aiming to search for the neutron electric dipole moment (EDM). TUCAN has constructed a new UCN source on a proton beamline at TRIUMF in Canada in order to achieve more than 100 times higher UCN density than the present source. The new source enables the search for the neutron EDM at a precision of 10^{-27} ecm, which is one order higher than the current sensitivity, by three years of data acquisition. The experiment is scheduled to start in 2023. KEK is in charge of the development of a high-cooling power helium cryostat, which is a key element.

LiteBIRD

The LiteBIRD satellite was proposed by the KEK CMB group and selected by the Japan Aerospace Exploration Agency (JAXA) for the second strategic L-class space science mission, scheduled to be launched in the late 2020s. The main purpose of this mission is to precisely observe the polarization of the CMB across the entire sky and to test representative cosmic inflation models, which will determine the future of cosmology. The observations are expected to pave the way for testing quantum gravity theories including superstring theory, and also provide many achievements in cosmology, particle physics, and astronomy. As a spin-off of accelerator technology, KEK has conducted observations of the CMB polarization using a telescope installed at Atacama, Chile, and has succeeded in producing results, including the first evidence for gravitational lensing based purely on CMB polarization. KEK's expertise in CMB observations, including cryogenic microwave measurement techniques, is needed for the success of the LiteBIRD project.

KAGRA

The Large-Scale Cryogenic Gravitational Wave Telescope (KAGRA) is a project hosted by the Institute for Cosmic Ray Research at the University of Tokyo in collaboration with KEK and the National Astronomical Observatory of Japan. This project went into construction in

2010 in Kamioka-Cho, Hida City, Gifu Prefecture, and started observation in 2020. Its main scientific objective is to observe such phenomena as compact object coalescences and supernova explosions through the international gravitational-wave observation network formed with the LIGO in the United States and the Virgo in Europe, and to develop gravitational-wave physics and astronomy. KEK has played essential roles in such fields as cutting-edge technologies in accelerator covering vacuum, cryogenics, control, and survey, the know-how of large-scale facility construction and operation, and theoretical research. KAGRA will continually evolve through approximately three-year cycles of observation and upgrading. KEK plans to contribute to the advancement of gravitational wave astronomy through the fields listed above.

4. Summary

The "KEK Roadmap 2021" has been developed as a major guideline for KEK's research for the six years starting from FY2022. The Roadmap includes ongoing projects, namely J-PARC, SuperKEKB/Belle II, LHC/ATLAS, and the Photon Factory, and their future development, and efforts to realize the ILC as an international project. Other important medium-scale projects include the medical and industrial use of accelerator technology, the Slow Positron Facility, and KISS at the Wako Nuclear Science Center, as well as TUCAN, LiteBIRD, and KAGRA in collaboration with other organizations and fields.

These research projects will be carried out in collaboration with other institutes and research centers in Japan and abroad, and KEK will be able to play a leading role in accelerator science and make significant contributions to academia and society.

Members of the Research Steering Committee, High Energy Accelerator Research Organization (KEK)

Shin-ichi Adachi, Kenta Amamiya, Shinichi Itoh, Yutaka Ushiroda, Kouki Uchimaru, Shoji Uno, Yasuhiro Okada (Chair), Toru Ogitsu, Yukihide Kamiya, Nobuhiro Kosugi, Tadashi Koseki, Takashi Kobayashi, Yukinori Kobayashi, Takeshi Komatsubara, Masani Gomita, Naohito Saito, Shinichi Sasaki, Shinya Sawada, Koichiro Shimomura, Hideki Seto, Toshiya Senda, Makiko Takahashi, Katsuo Tokushuku, Makoto Tobiyama, Shoji Hashimoto, Kazunori Hanagaki, Junji Haba, Nobumasa Funamori, Atsushi Manabe, Shinichiro Michizono, Satoshi Mihara, Seiya Yamaguchi, and Michiharu Wada