Survey and Analysis of the Technical Feasibility of the International Linear Collider (ILC) Project and Technical Issues Posed by Construction of the ILC Accelerator

Summary

-Draft of English Version-

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Introduction

In May 2013, the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) tasked the Science Council of Japan (SCJ) with investigating the feasibility of the International Linear Collider (ILC) project proposed by researchers in high energy physics. In its response, submitted to MEXT at the end of September 2013, the SCJ observed, “There are risks and uncertainties concerning key elements, making it premature at this point to approve full-scale implementation of the project.”

In light of this response, MEXT has been conducting studies to help determine whether to proceed with the project. As part of this process, in FY2014 it commissioned a survey and analysis of the technological and economic spin-offs and future plans and projects around the world in the fields of particle and nuclear physics. In FY2015, another survey and analysis was made of the technical feasibility of construction of the ILC, the technical issues that will need to be surmounted in order to mass-produce the components required by the ILC accelerator, and efforts to reduce the cost of its construction.

Technical feasibility was investigated by studying and analyzing the levels of achievement and problems associated with developing the element technologies used to construct the accelerator for the ILC, taking into account how success or failure in developing each of these technologies would affect the targeted performance of the ILC project. Risk was then evaluated given current progress on development. The technical issues related to construction of the ILC accelerator were investigated by examining the technical obstacles to transitioning from prototype construction to the mass production of ILC-related materials, as these materials will have to be produced on an unprecedented scale. We also assessed the efforts being made to reduce the cost of construction of accelerators while studying the feasibility of enhancing efficiency by introducing new technologies that were not considered in the Technical Design Report (TDR) for the ILC.

A body called the Investigative Committee on the Technological Feasibility of the ILC was set up to assist implementation of this survey and analysis. This committee was composed of experts with extensive knowledge and experience of the utilization of accelerator technology in a range of fields. They have reviewed the survey and analysis findings and commented on the reports produced based on them. We deeply appreciate the vigorous discussion and valuable comments made by all the members of the committee, including the chairperson, Dr. Noritaka Kumagai. We are also very grateful to the accelerator experts who assisted us with our interview surveys and accompanied us on our survey visits to Europe and the United States.

Members of the Investigative Committee on the Technological Feasibility of the ILC

(in alphabetical order)

Member	Shuichi AIZAWA	Corporate Officer, Device Division, Nihon Koshuha Co., Ltd.
Member	Kazuo HASEGAWA	Accelerator Division Head, J-PARC Center, Japan Atomic Energy Agency (JAEA)
Member	Shinya ISHII	Project Manager, ICT Solution Center, ICT Solution Headquarters, Mitsubishi Heavy Industries, Ltd.
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Member	Kiyotomo KAWAGOE	Director, Research Center for Advanced Particle Physics, Kyushu University
Chairperson	Noritaka KUMAGAI	Research Advisor, Japan Synchrotron Radiation Research Institute (JASRI)
Member	Yukio KUMATA	Vice President, Corporate Technology Management Group, Sumitomo Heavy Industries, Ltd.
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Member	Hideyuki TAKATSU	Specially Appointed Counselor of the Fusion Research and Development Directorates, Japan Atomic Energy Agency (JAEA)
Member	Hitoshi TANAKA	XFEL Research and Development Division Director, RIKEN SPring-8 Center

Experts who accompanied the interview teams (in alphabetical order)

Expert	Takaaki FURUYA	Professor, Support Center for Accelerator Science and Technology, High Energy Accelerator Research Organization (KEK)
Expert	Shinichiro MICHIZONO	Professor, Accelerator Laboratory, High Energy Accelerator Research Organization (KEK)

Interview acknowledgements

For this survey, we visited a number of research institutes and private-sector firms around the world to conduct interviews, and we would like to thank everyone who took part for their valuable contributions to this report. The organizations visited are listed below.

Research Institutes (in alphabetical order)

Country	Name of Organization
France	CEA-IRFU (Institute of Research into the Fundamental Laws of the Universe)
	CNRS-LAL (Laboratoire de l'Accélérateur Linéaire)
Germany	DESY (Deutsches Elektronen-Synchrotron)
Italy	INFN-LASA (The Istituto Nazionale di Fisica Nucleare – Laboratorio Acceleratori e Superconductitivita Applicat)
	INFN－LNF (Laboratori Nazionali di Frascati)
Japan	KEK (High Energy Accelerator Research Organization)
	RIKEN SPring-8 Center
Switzerland	CERN (European Organization for Nuclear Research)
UK	STFC (Science and Technology Facilities Council) Daresbury Laboratory
US	FNAL (Fermi National Accelerator Laboratory (Fermilab))
	Jefferson Lab (Thomas Jefferson National Accelerator Facility (JLab))
	SLAC National Accelerator Laboratory (SLAC)

Companies (in alphabetical order)

Country	Company Name
France	Air Liquide
	Alsyom
	Aperam
	Thales Electron Devices
Germany	Babcock Noell GmbH
	RI Research Instruments GmbH
Italy	Ettore Zanon S.p.A.
Japan	GeoSystem Institute
	Mitsubishi Heavy Industries, Ltd.
	Nihon Koshuha Co., Ltd.
	Obayashi Corporation and Shimizu Corporation
	Toshiba Electron Tubes & Devices Co., Ltd.
US	Advanced Energy Systems (AES)
	C. F. Roark Welding & Engineering Co., Inc. (ROARK)
	Communications & Power Industries (CPI), LLC

Survey goals and methods

1. Survey goals

1.1 Survey on technical feasibility of construction of the ILC

Technical feasibility was investigated by analyzing the achievement level and problems associated with the development of the various technological elements used to construct the accelerator for the ILC. In the process we considered how the success or failure of development of each technology would affect the targeted performance of the ILC project, and evaluated risk based on the current state of development.

1.2 Analysis of technical issues related to construction of the ILC accelerator

The technical issues related to construction of the accelerator were studied by examining the technical obstacles to transitioning from prototype construction to the mass production of ILC-related materials, as these materials will have to be produced on an unprecedented scale.

1.3 Analysis of efforts to reduce cost of construction of the ILC accelerator

The efforts being made to reduce the cost of construction of the ILC accelerator were examined by studying the possibility of achieving higher efficiency while reducing costs by introducing new technologies that were not considered in the TDR for the ILC.

2. Survey methods

2.1 Survey on technical feasibility of construction of the ILC

An interview survey was conducted concerning the feasibility of achieving the performances targeted for the ILC with the specifications described in the TDR (which comprises the design documents so far prepared by researchers involved with promoting the ILC project) and the current state of technical study on implementation of the project. Information was also compiled from various sources, including the TDR and information obtained from visits to research institutes and companies in Japan and other countries that have a vested interest in the ILC.

Interviews were conducted by a team accompanied by at least one outside expert in accelerator research on each occasion, and visits were made to at least two research institutes and two companies in each of the following countries where accelerators are widely built and used: Japan, the US, Germany, France, and Italy.

Survey items

(1) Components

(2) System design
(3) Management
(4) Infrastructure

2.2 Analysis of technical issues related to construction of the ILC accelerator

As the ILC will require precise assembly in a limited time as well as the production of large-scale components, an on-the-spot survey was made of companies in Japan and overseas to verify whether the construction schedule for mass-produced items could be met given each company's manufacturing capacity. The survey team was accompanied on each of its visits by at least one outside expert in accelerator research.

Based on the results of the survey described in 1) above, an analysis was made of the issues that must be resolved by each type of manufacturer (component manufacturers, research institutes involved with the manufacturing of components, etc.) if the ILC is to be built (including the manufacturing of the component parts). At least two research institutes and two companies were visited in each of five countries (including Japan, the US, Germany, France, and Italy) where accelerators are widely built and used.

Survey items
(1) Sites evaluated (infrastructure only)
(2) Methods of solving problems
(3) Duration and cost of solutions

2.3 Analysis of efforts to reduce cost of construction of the ILC accelerator

To determine the feasibility of replacing currently planned ILC parts with higher performing and more compact parts as well as to assess progress on research and development, visits were made to research institutes and companies in Japan and several other countries around the world. Efforts were made to determine their current technological levels, the estimated times until technologies become practical to use and obstacles to their use, and potential production capacities. Interviews were then conducted to follow up on specific high-performance components that are nearing the practical use stage.

Interviews were conducted by a team accompanied by at least one outside expert in accelerator research on each occasion, and visits were made to at least two research institutes and two companies in each of the following countries where accelerators are widely built and used: Japan, the US, Germany, France, and Italy.

Survey Results

Contents

1. Technical feasibility of construction of the ILC……..……7
2. Technical issues related to construction of the ILC accelerator…….……..13
3. Efforts to reduce cost of construction of the ILC accelerator……..16

1. Technical feasibility of construction of the ILC

The findings of the interview survey of research institutes and related companies in Europe, the US, and Japan concerning the technical feasibility of the key component technologies (including products) that will constitute the ILC are summarized below. (See also the summary in the attached Table 2).

1.1 Superconducting RF accelerator and cryogenics technologies

TESLA-type superconducting RF accelerator cavities have already been developed and fabricated for the European X-Ray Free-Electron Laser (E-XFEL), which is considered a prototype for the ILC, and their current performance (average accelerating gradient) almost meets ILC requirements. Efforts should now shift to achieving required performance in a less costly and more efficient manner. Performance should be enhanced by improving the cavity production process (including the implementation of electropolishing at the final stage), as well as by developing electron beam welding methods, devices for mass processing (including four-cavity simultaneous electron beam welding), and low-cost and efficient techniques for the cavity surface treatment (such as alkaline electropolishing and vertical electropolishing machines). Facilities and work in clean rooms also need to be improved in order to generate further performance enhancements.

Like the accelerator cavities, the cryomodules developed and fabricated for E-XFEL are considered prototypes for the ILC. However, their performance (average accelerating gradient) is insufficient for the ILC (less than 90% of the target), and the factors that cause the gradient performance degradation after module assembly and connection with accelerator cavities will need to be identified and then appropriately addressed if required performance is to be achieved. Performance when multiple cryomodules are connected also remains to be demonstrated.

The superconducting magnet technology for the ILC, on the other hand, is largely already in place as a result of work at the European Organization for Nuclear Research (CERN) in Switzerland using the Large Hadron Collider (LHC).

Regarding cryogenic plants, the one used for the LHC at CERN is considered a prototype for the ILC in terms of its scale and technology, and the element technology constituting such plants is already in place. In the future, the locational characteristics of the ILC may present some minor issues that will have to be addressed, including the maintenance and improvement of the cooling efficiency of long-distance cryogenic transport lines as well as the minimization of helium loss.

1.2 Radiofrequency power technology

Although three types of modulators are now being developed as prototypes for the ILC—namely, (1) the SLAC-P2 Marx Modulator, (2) the DTI Marx Modulator, and (3) the KEK chopper-type Marx Modulator—research on type (1) has been suspended and no type (2) devices are currently operational. At the time of the survey, only the type (3) chopper-type Marx Modulator was undergoing demonstration testing by the High Energy Accelerator Research Organization (KEK) in Japan. Research should therefore focus on the development and demonstration of a single prototype of Marx modulator by consolidating development structures and technologies. Additionally, high-speed, large-current, high-voltage and low-loss semiconductor switches (including semiconductor elements) as well as pulse-generating hardware and pulse-controlling software should be developed.

The prototype klystrons for the ILC are the 1.3 GHz 10 MW multi-beam klystrons (MBKs) manufactured for E-XFEL by Japanese, American, and European companies. As the specifications of these MBKs differ slightly from the requirements for the ILC, their mechanical design will need to be modified slightly. As no drastic design changes appear necessary, however, existing MBK products (technology) should meet the performance requirements of the ILC.

The prototype couplers for the ILC are those manufactured for E-XFEL by Japanese, American, and European companies. These couplers already meet the performance standard required for the ILC, and no critical issues in technology were observed during the study.

With regard to the local RF power distribution system (LPDS), the technology for waveguides and waveguide components for the ILC has been established. However, it was noted that work is still required in order to, among other things, determine the optimal method for mounting the LPDS onto the cryomodule and refine the design of cryomodule integration with the LPDS. The waveguide and some of its components also need some improvement.

1.3 Beam technology

The polarized electron source consists of the following three components: a photocathode, an electron gun, and a laser system. Superlattice cathodes (made from a combination of gallium arsenide and gallium arsenide phosphide) should be used as the photocathodes for the ILC. Although the target value has been achieved in demonstration tests, it would be useful to be able to manufacture high-polarized cathodes with a higher quantum efficiency. The technology for the ILC electron gun is well established, but it is likely that higher-voltage electron guns will be needed in the future to improve the performance of the electron beam (i.e., technology will be needed to reduce

beam spreading and loss in beam transport). The ILC needs a laser system with a multi-bunch time structure, and the laser system OPCPA developed by Deutsches Elektronen-Synchrotron (DESY) of Germany will be of use to the ILC. However, several issues were noted, including the need to develop a demonstration machine on which pulse length and repetition rate are adjusted for the ILC electron source.

The ILC is expected to use a positron source composed of a helical undulator and water-cooled targets. A superconducting helical undulator module has been developed as a prototype for the ILC by the Science and Technology Facilities Council (STFC) in the United Kingdom. However, not all the ILC target values (such as for the accuracy of the magnetic field) have been achieved, and a beam test has yet to be conducted. Beam tests on the equipment for the helical undulator will therefore be necessary in the future.

On the other hand, two target-cooling methods that do not depend on water-cooling—namely, (1) a sliding contact cooling method and (2) a radiation cooling method— are currently being developed because a water-cooling method has not yet been successfully demonstrated. Major hurdles remain, however, as suggested by the fact that the contact parts for type (1) are still under development and that type (2) is still in the design optimization stage. It consequently remains necessary to establish target cooling technology, develop a prototype, and conduct beam tests to guarantee performance, as well as to develop the technology for the remote replacement of consumable parts.

An electron-driven system for the positron source (backup) is being developed by KEK as a backup method for the helical undulator system mentioned above. Although the element technology for this method has already been demonstrated and is considered standard technology, several technical issues remain regarding the target. A target prototype has to be developed and demonstrated, and there is a particular need for development of a model for the rotating shaft seals (including tests of the radiation resistance of rotating body seals and verification of degradation of the seal materials). Moreover, as polarized positrons cannot be obtained with an electron-driven system, some modifications will have to be made to the ILC physic experiment plan.

As for the damping ring (DR), many third-generation light sources exist. Because these sources are equipped with the same kind of rings as will be used for the ILC (e.g., Diamond, ASLS, ESRF, SLS, and SSRF), the basic element technology has been established. Additionally, several of the existing electron-positron colliders and synchrotron light sources have achieved performances equivalent to the beam performances required for the ILC DRs (in terms of ultra-low emittance, bunch number, and bunch distance). However, several future issues were noted, including the need for further

research and development work in order to simultaneously demonstrate important components of the ILC DRs beam injection and extraction system (e.g., pulse rise time and fall time, pulse repetition rate, and kick amplitude and amplitude stability), evaluation of the long-term operational stability and reliability of fast kickers, and reduction of the instability of the electron clouds in the vacuum system.

Regarding beam control, there are not presently any DR circulating beam fast feedback systems that might be regarded as prototypes for the ILC, and feedback system performance under DR parameters has yet to be verified. However, some of the required technology is available in the form of the systems used for DAΦNE at the Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Frascati (INFN-LNF) in Italy, and SuperKEKB at KEK. Development of a prototype fast feedback system following the ILC DRs parameters has been therefore identified as a future challenge.

As for the fast feedback system at the interaction point, a prototype multi-bunch beam monitoring and control systems developed by the John Adams Institute (JAI) in the UK has been installed on the beam line for ATF2 at KEK, and it has already been proven capable of producing the performance required for the ILC. In the future, research will need to be conducted on the transverse measurement technology for the beam diagnostic systems used for the ILC.

A prototype for a beam dump that meets ILC specifications has yet to be developed and performance required for the ILC has not been demonstrated. (The only relevant activity to date in this area has been on the design and simulation work performed on the basis of the 2.2-MW dump developed at the SLAC National Accelerator Laboratory.) Future priorities should be to investigate strategies for preventing and containing accidents in the event that a beam dump window is accidentally destroyed due to the concentration of the bunch on one point of the window, verify the resistance of the window materials to corrosion caused by cooling water in a highly radioactive environment, and develop technologies for safely managing the radioactive substances (such as tritium) produced by the dumped beam.

As for the crab cavity system, a prototype of the superconducting nine-cell crab cavity that is expected to be used for the ILC has not yet been developed (only experiments with a one-cell cavity have been carried out), and the performance required for the ILC has yet to be demonstrated. The high-order mode (HOM) coupler indispensable to the crab cavity system has also not yet produced the required performance. Future work is therefore required to create a superconducting 9-cell crab cavity prototype (equipped with coupler), design a cryomodule/cryostat, manufacture and test the prototype, and redesign, manufacture, and demonstrate the HOM coupler.

1.4 Infrastructure engineering technology

The tunnels and underground caverns at the ILC are expected to be built using the New Austrian Tunneling Method (NATM) (Fig. 4). NATM is considered efficient because it can be flexibly adapted to suit different geological features. However, construction of these tunnels and caverns was observed to pose the following issues.

Regarding construction management, it was observed that in-house engineers, including CM (construction management) experts, will be required to establish construction-related rules (such as rules on risk management between the client and contractors). In addition, information technology-based construction will have to be introduced to allow work to be flexibly modified in order to cope with unexpected situations, prevent environmental assessments from becoming protracted due to the wide range of likely environmental impacts, and address the issue of time overlaps between engineering work and accelerator installation work. Moreover, some experts also commented that the four-year preparatory period for ILC construction is too short.

Regarding water inflow management, it is estimated that almost no water will flow up inside the tunnels as spring water will be directly discharged outside the tunnels via a drain or ditch installed in the back of the covering sheet or the batholith. Although water will flow into the tunnels during excavation, it can be dealt with by implementing measures to drain the water inside the tunnels to the outside (such as by installing water storage pits and pumps). Taking all these factors into consideration, it is likely that groundwater (water inflow) in the tunnels will be completely manageable, although predicting the volume of groundwater may be difficult.

The likelihood of a large amount of water inflow during excavation is expected to be significant in the Kitakami area, where it is proposed the ILC be built, and treatment of water inflow during construction is considered an important issue. More specifically, it is vital to plan drainage boring holes to reduce groundwater as well as efficient and economical drainage/pump-up facilities.

In terms of managed drainage, it will be impossible to prevent small inflows of water from, for example, cracks in the secondary lining concrete even if sufficient waterproof measures are taken in the tunnels of the ILC. Management of water in tunnels is therefore crucial. It is currently difficult to accurately calculate the volume of water that will have to be managed in ILC tunnels. If a significant amount of water flows into tunnels after construction, it will be necessary to install lateral grooves, water conveyance pipes, and water storage tanks to collect and treat water with monitoring controls. On the other hand, if the volume of water inflow is so small that only drops are observed, this situation can likely be dealt with by installing roofs and water drop plates in the tunnels or by letting

water evaporate naturally.

Regarding the effects of radiation when the ILC is in operation, the spring water on the back side of the secondary lining concrete is not likely to be radioactive if the lining concrete is least 30 cm thick. However, some experts observed that the thickness of the concrete should be reconsidered in order to provide sufficient thickness to prevent radioactivation of water outside the waterproof sheet so that it can be treated as clean water.

As for temperature and humidity management, the target temperature inside tunnels at the ILC will be around 25°C and around 40–60% humidity (according to KEK). Although it will be possible to manage temperature and humidity inside the tunnels by means of control facilities, including ordinary air-conditioning, it was suggested that temperature estimates (based on calorimetric values inside the tunnels) should be calculated.

To prevent accidents, underground structures and aboveground buildings typically employ completely different approaches to treating smoke, and it was observed that disaster prevention plans will need to be developed taking these differences into account. More concretely, measures to prevent submersion in the case that tunnel power supply is lost, control and exhaust smoke, supply fresh air in case of a fire, and deal with helium leaks need to be developed.

Regarding anti-earthquake design, the standard specifications for tunnels issued by the Japan Society of Civil Engineers state that “it is not as a rule necessary to consider the impact of earthquakes on underground facilities built in solid ground.” However, as the ILC is projected to be a state-of-the-art international experimental facility that will use long tunnels and large underground caverns, it was noted that maximal consideration will need to be given to ensuring safety and earthquake resistance. Concrete issues include the adequate setting of input seismic motions, the selection of the analysis evaluation method, and the appropriate setting of evaluation criteria. Moreover, the impacts on the access tunnel entrance, fault crushing belt, and areas of abrupt geological change must be evaluated.

2. Technical issues related to construction of the ILC accelerator

Summarized below are the results of interviews with research institutes and related companies in Europe, the US, and Japan on the possibility of and technical obstacles to the mass production of the main equipment and components required for the ILC accelerator. (See the summary in the attached Tables 2 and 3.)

The main devices and components whose mass production was investigated were superconducting RF accelerator cavities, cryomodules, klystrons, and couplers. Table 1 shows rough modeling assumptions of the volumes of mass-produced components that will be required for the ILC based on information provided by KEK.

Table 1 Volumes of mass-produced components required for the ILC (production period: six years)

(number of units)

	Production volume required for entire ILC		Annual production volume required (production period: six years)		
	Total	Per region (JP, US, EU)	Total	Per region (JP, US, EU)	Per company for each region*
Accelerator cavities	18,000	6,000	3,000	1,000	500
Cryomodules	1,855	618	309	103	52
Couplers	16,000	5,333	2,667	889	444
Klystrons	440	147	73	24	12

*Assuming components are produced by two companies in each region.

Source: Modeling assumptions based on information provided by KEK about the production volumes required for the ILC.

2.1 Superconducting acceleration technology

2.1.1 Superconducting RF accelerator cavities

The following is a summary of the feasibility of mass production of superconducting RF accelerator cavities by the principal manufacturers. The European manufacturer Zanon responded that it can produce 400 cavities per year by doubling its manufacturing capacity (by increasing its facilities and labor by around 60%). RI Research Instruments indicated that annual production of 500 cavities is attainable if it increases cavity production capacity by inputting more labor (by operating three shifts a day, seven days a week) and expanding its production facilities by 20%.

The American manufacturer ROAK specified that it will be able to meet demand by speeding up production by four to five times from the current level and obtaining capacity investment from the US government and research institutes in the US . Mitsubishi Heavy Industries of Japan stated that it

can produce 500 cavities annually by expanding its electron beam welding (EBW) capacity and introducing four-cavity simultaneous EBW technology.

Some manufacturing-related issues remain to be addressed if cavities are to be successfully mass-produced for the ILC. In particular, action is required to reduce cavity manufacturing time (such as by reducing the number of parts, changing the materials used, improving the electron beam welding process, and adopting the use of laser welding or TIG welding), partially automate manufacturing lines (by automating visual and frequency inspections, developing automation software, and so on), upgrade and upsize manufacturing facilities, introduce shift work (by, for example, adopting a three-shift system), practice better quality control of mass-produced parts and processes (by, for example, introducing EDMS), and comply with the provisions of the High Pressure Gas Safety Act in Japan (such as the need for all cavities to be inspected).

2.1.2 Cryomodules

The issues in terms of mass production of cryomodules include the standardization and sharing of module mounting methods, improvement of cleanliness inside clean rooms (jigs and exhaust systems, etc.) and on cryomodule parts (electropolishing of small parts such as bolts, etc.), and development of special shipping frames that are resistant to shock and vibrations during long-distance transport (by sea or air) to Japan.

2.2 Radiofrequency power technology

2.2.1 Klystron

The findings regarding the possibility of mass production of klystrons by the principal manufacturers are summarized below. Thales of Europe indicated that it is capable of producing 15 multi-beam klystrons (MBKs) per year for the ILC (it currently produces 12 per year). CPI of the US responded that it will be able to manufacture three to five MBKs per month (it currently produces one every three months). In Japan, Toshiba Electron Tubes & Devices responded that while it is potentially capable of mass-producing MBKs, it will need to expand its facilities based on the assumption that it will also be able to take orders for other projects if production exceeds 20 per year.

The issues regarding mass production of klystrons include reducing the time consumed by quality control (currently a bottleneck), installing additional vacuum pumping and baking and test devices (test stands exclusively for MBK), enlarging manufacturing spaces, performing aging and testing simultaneously by using external laboratories, and improving the efficiency of MBK adjustment work (adjustment of operating parameters).

2.2.2 Couplers

On the feasibility of mass production of couplers, Thales stated that it will be able to double its production speed (to 1,000 units annually) without any new capacity investment. CPI reported that it will be able to produce around 1,200 units annually by using existing production facilities and adopting a two-shift system. Toshiba Electron Tubes & Devices indicated that it will be able to manufacture 890 couplers per year, which is the required volume in Japan, by upgrading its plant facilities (such as by adding high-level clean rooms).

As for the issues regarding mass production of couplers, the following areas for action were identified: reinforcement and improvement of facilities (including high-level clean rooms and EBW and vacuum brazing facilities), establishment of high-quality copper plating technology, increase of manpower such as workers skilled in EBW, proper supervision, maintenance, and repair of large numbers of couplers, and establishment of a system for conditioning large numbers of couplers.

3. Efforts to reduce cost of construction of the ILC accelerator

Interviews were conducted with research institutes and related companies in Europe, the US, and Japan concerning the potential cost reductions and current progress in terms of replacing key equipment and components required for the ILC accelerator with more compact and better performing equivalents, and the findings are summarized below. (Limited information was available on these subjects.)

3.1 Reduction of cost of cavity production by directly cutting niobium sheets from ingots

Directly slicing niobium sheets from ingots is less costly than the existing method of using rolled sheets, and the technology for doing so is now being developed and evaluated. Currently, 10% of the cost of the ILC cryomodules is attributed to the niobium required to manufacture the 18,000 cavities. Thus while the precise impact is still being calculated, reducing niobium costs in this way should make a very significant contribution to reducing the cost of the project.

3.2 Reduction of cost by manufacturing integrally molded superconducting RF accelerator cavities

DESY has been successful in producing niobium tubes using so-called flow-forming technology and in fabricating three-cell cavities using hydro-forming technology. It has manufactured a nine-cell cavity assembled by connecting these three three-cell cavities using electron-beam welding technology. To date, three nine-cell cavities have been manufactured, and these have achieved accelerating gradients of 27 MV/m to 35 MV/m. However, no nine-cell cavities have yet been directly fabricated by a single hydro-forming process. Moreover, Mitsubishi Heavy Industries has manufactured two-cell cavities using niobium tubes made by deep drawing to create one cavity by spin processing and performing electron beam welding from both sides of the half cell. Assisted by the Thomas Jefferson National Accelerator Facility (JLab) in the US, Mitsubishi Heavy Industries has performed surface treatment and accelerating gradient evaluations, and has achieved an accelerating gradient of 32.4 MV/m. However, neither company has yet to assess precisely how much cheaper these cavities are to make compared to conventionally fabricated ones.

Table 2 Progress, issues, and feasibility of development and mass production of key ILC technologies and products (summary)

Summary of all survey results (superconducting RF accelerator technology and cryogenics technology)

Key technologies/products		Quantity required for ILC	Specifications and requirements for ILC	Research/ testing/ manufacturing entity	Progress ■Prototype status ● Progress on required performance for ILC	Issues ■Technical ●Manufacturing-related (mass production)	Feasibility of development and mass production	
							Outlook	Entities involved
Superconducting RF accelerator technology	Superconducting RF accelerator cavities	18,000	■Accelerating gradient (for 500-GeV operation) ・During manufacturing: 35 MV/m (90%) ・During operation: 31.5 MV/m	*Europe* DESY, INFN, RI, Zanon	■Prototype(s) ・TESLA-type cavities for E-XFEL ●Required performance almost achieved ・Overall average performance of 30 MV/m achieved (after re-treatment) ・Estimated value: 34 MV/m (94%) (with three re-treatments)	■Technical issues ・Improvement of clean rooms (better facilities and performance, well-trained operators and drills) ・Improvement of manufacturing processes (re-treatment by electropolishing and HPR in the final process) ・Increase in number of re-treatments (more processes where performed three times) ●Manufacturing-related issues ・Partial automation of production line (development of automation software) ・Upgrading and upsizing of production facilities ・Introduction of shift work on production lines (three shifts) ・Enhancement of quality control of mass-produced parts and processes (introduction of EDMS) ・Compliance with High Pressure Gas Safety Act in Japan (all cavities should be inspected) ・Employment of adequate packing system to address issues with long distance shipping	◎	■Development and testing ・DESY ●Manufacturing (mass production) ・RI (Germany), Zanon (Italy) Capability of mass production by companies to meet ILC requirements ・Zanon: Able to manufacture 400 units annually by doubling cavity production capacity (by expanding facilities and labor by around 60%) ・RI: Annual production of 500 units attainable by increasing manpower (three shifts, seven days a week) and expanding facilities by 20%
				US JLab, FNAL, AES, ROARK	■Prototype(s) ・TESLA-type cavities for CEBAF ・Prototype cavities for ILC R&D and LCLS-II (same design as for ILC) ●Required performance almost achieved ・Performance of 35 MV/m ± 20% achieved with 80 C-100 type units in vertical test	■Technical issues ・Consideration of shapes, materials, and processing required to achieve high-efficiency high-gradient (HEHG) SRF ・Research on final processing step to reduce medium field Q-slope and field emissions ●Manufacturing-related issues ・Need for four- to five-fold increase in current speed of manufacturing (e.g., by improving electron beam welding process) ・Unlikely that private capital will be sufficient due to limited life of production facilities and difficulty of converting to other uses	○	■Development and testing ・JLab, FNAL ●Manufacturing (mass production) ・AES, ROARK, Niowave PAVAC Industries Capability of mass production by companies to meet ILC requirements ・AES: Unlikely to be able to invest sufficiently in ILC manufacturing capacity in the seven-year period for ILC construction ・ROAK: Able to increase production four- or five-fold if government and research institutes contribute to capacity investment

				Japan KEK, Mitsubishi Heavy Industries	■Prototype(s) ・34 STF cavities already manufactured for ILC (Tesla-type superconducting RF accelerator cavities) by Mitsubishi Heavy Industries ●Required performance almost achieved ・Average accelerating gradient of 35.2 MV/m achieved for cavities manufactured by the standard procedure (average for cavities Nos. 12-26) ・While the performances of the first four units manufactured by four-cavity simultaneous electron beam welding (Nos. 27–30) vary widely, it is likely that performance of 35 MV/m will be achieved due to the accumulation of experience.	■Technical issues ・ Improvement of stability of four-cavity simultaneous electron beam welding (EBW) facilities ・Development of low-cost and highly-efficient cavity surface treatment methods (pulse current electropolishing, alkaline electropolishing, vertical-type electropolishing devices, etc.) ・Development of inner surface inspection devices for cavities (cavity surface temperature distribution measuring devices, radiation measuring devices, etc.) ・Development of low-cost and highly-efficient vertical measurement devices for cavities ●Manufacturing-related issues ・Reduction of cavity manufacturing time (fewer parts, changes in materials, conversion to laser welding or TIG welding, etc.) ・Optimization of surface treatment procedure and devices for ILC ・Automation of surface and frequency tests (pre-tuning) ・Adoption of shift work arrangements ・Confirmation that validity of certification for cavities under the High Pressure Gas Safety Act is of a sufficient duration to cover the completion inspection of cryomodules	◎	■Development and testing ・KEK ●Manufacturing (mass production) ・Mitsubishi Heavy Industries, Hitachi, Toshiba, etc. Capability of mass production by companies to meet ILC requirements ・Mitsubishi Heavy Industries: Annual production of 500 cavities possible with additional installation of EBW devices and introduction of four-cavity simultaneous EBW technology
	Cryomodules	1,855	■Accelerating gradient ・During operation: 31.5 MV/m	*Europe* DESY/INFN, CEA-IRFU, ALSYOM	■Prototype(s) ・Cryomodules for E-XFEL (improved version of type III module for FLASH) ●Required performance not achieved ・Average 27.2 MV/m = 86% of the goal set for ILC (average value of 60 modules for E-XFEL (measured at DESY)) ・Average ~29 MV/m (latest values starting from the 60th module (measured at DESY))	■Technical issues ・Identification of cause and solution of problem of cavity degradation → modules (~6%) (difficult to directly determine cause by disassembling modules) ・Demonstration of performance by combining several cryomodules ●Manufacturing-related issues ・Standardization of module mounting method (sharing) ・Improvement of parts management, quality and manufacturing control, etc. ・Addressing of issues posed by long-distance shipment (sea or air) to Japan (by developing special shipping frames that are resistant to shock and vibrations, making adjustments to standard 40-foot containers, etc.)	○	■Development and testing ・DESY, CEA-IRFU ●Manufacturing (mass production) ・Zanon (Italy): Cold mass ・ALSYOM (France): Assembly at CEA site
				US JLab, FNAL	■Prototype(s) ・Performance test finished for the ILC R&D prototype ・Cryomodule for 1.3 GHz nine-cell cavity manufactured as part of LCLS-II project ●Required performance achieved ・Average performance of 32.2 MV/m achieved during test conducted with one eight-cavity equipped module owned by FNAL (demonstration module for LCLS will be produced by September 2018)	■Technical issues ・Implementation of tests with ILC cryomodules and in tunnel to identify issues ・Performance of measurements to prevent contamination by dust during connection of beam line (demonstration with mobile high-performance clean room) ●Manufacturing-related issues ・Allocation of all lines and manpower to ILC to enable production in seven years	○	■Development and testing ・JLab, FNAL ●Manufacturing (mass production) ・JLab, FNAL, and partner companies
				Japan KEK, Mitsubishi Heavy Industries, Hitachi	■Prototype(s) ・Cryomodules already manufactured for the ILC S1-Global experiment at KEK-STF ●Required performance still to be achieved ・Performances of cryomodules already tested at KEK	■Technical issues ・Currently no issues with manufacturing technology for single modules ・Verification that performance is sustained when several modules are connected ●Manufacturing-related issues ・Improvement of cleanliness in clean rooms (jigs, exhaust systems, etc.) ・Improvement of cleanliness of cryomodule parts (by electropolishing of small parts, including bolts) ・Determination of optimal assembly sites in Japan (including consideration of whether assembly should occur at existing plants	○	■Development and testing ・KEK ●Manufacturing (mass production) ・Mitsubishi Heavy Industries, Hitachi

						or at ILC site)		
	Superconducting magnets			Toshiba (Japan) Babcock Noell (Germany), etc.	■Prototype(s) ・Superconducting magnets for final focus already developed (US) ・Superconducting quadrupole magnets for ILC main linac already developed (US-Japan cooperation) ●Required performance achieved	■Technical issues ・Superconducting magnet technology already established ・Examination of effects of magnet support structure and weak vibration from refrigerant on accuracy of magnetic field ●Manufacturing-related issues ・Quality control, etc.	◎	●Manufacturing (mass production) ・Toshiba (Japan), Babcock Noell (Germany), etc.
	Cryogenic plants	10 plants	■Underground units (refrigerators): 2K ■On surface units: 4.5 K ■Required power: 50–60 MW	CERN Air Liquide	■Prototype(s) ・LHC cryogenic plant (same scale and technology, 55 MW) ・Plant component technologies already established ●Required performance achieved	■Technical issues ・Improvement of cooling efficiency and maintenance of long-distance cryogenic transfer lines ・Reduction of helium loss ●Manufacturing-related issues N/A	◎	●Manufacturing (mass production) ・Air Liquide (France), Linde (Germany, Switzerland)

Summary of all survey results (radiofrequency technology)

Key technologies/products		Quantity required for ILC	Specifications and requirements for ILC	Research/testing / manufacturing entity	Progress ■Prototype status ● Progress on required performance for ILC	Issues ■Technical ●Manufacturing-related (mass production)	Feasibility of development and mass production	
							Outlook	Entities involved
Radiofrequency power technology	Modulators (Marx generators)	440	■Output voltage: 120 kV ■Output current: 140 A ■Pulse width (flat- top): 1.65 ms ■Pulse repetition frequency: 5 Hz ■Basic requirements: compact, low-cost, high operation rate, easy maintenance	SLAC KEK	■Prototypes under development ・The following three types exist for Marx modulators: (1) SLAC-P2 (2) KEK chopper-type (3) DTI ●Required performance not achieved ・Research suspended for type (1), and type (3) does not function due to failure ・Two of type (2) have been made (4 cells/unit) and are undergoing demonstration testing at KEK. 20 units (80 cells) are to be manufactured in 2016 to check their performance as power sources and test their long-term continuous operation.	■Technical issues ・Ending of distributed development (of three types) and development/demonstration of ILC prototypes through consolidation of structures and technologies ・Development of high-speed, high-current, high-voltage, and low-loss semiconductor switches (including development of semiconductor elements) ・Development of pulse-generating hardware and pulse-controlling software ・Demonstration of durability and stability through long-time continuous operation ●Manufacturing-related issues ・Development of modulators in cooperation with private companies, technology, and information sharing ・Establishment of supply structure by several vendors	△	■Development and testing ・KEK and Pulsed Power Japan Laboratory Ltd. (PPJ) (Japan) ・SLAC ●Manufacturing (mass production) ・DTI (US) ・PPJ (Japan)
	Klystrons	440	■Frequency: 1.3 GHz ■Peak power output: 10 MW ■Average power output: 150 kW ■Efficiency: 65% ■RF pulse width: 1.65 ms ■Cathode voltage: >120 kV ■Cathode current: <140 A	*Europe* Thales	■Prototype(s) ・10 MW multi-beam klystron (TH1802) made by Thales ・23 units already delivered to E-XFEL ・Can be adapted to ILC with current technology ●Required performance achieved	■Technical issues ・Continue research and development of long-life cathodes ●Manufacturing-related issues	◎	●Manufacturing (mass production) ・Thales (France) Capability of mass production by companies to meet ILC requirements ・Thales: Said that annual production of 15 MBK units for ILC should be possible (currently 12 units annually)
				US CPI	■Prototype(s) ・1.3 GHz 10 MW multi-beam klystron (VKL-8301A/B) made by CPI ・CPI has already produced ~300 units required for SLC and repaired devices that have operated for 4,000 hours (~7 years) ・Can be adapted to ILC with existing technology ●Required performance achieved	■Technical issues ・N/A (ILC TDR specifications satisfied) ●Manufacturing-related issues ・Reduction of time for quality control (bottleneck)	◎	●Manufacturing (mass production) ・CPI (US) Capability of mass production by companies to meet ILC requirements ・CPI: Monthly production of 3–5 MBKs possible (currently one every three months)
				Japan Toshiba Electron Tubes & Devices	■Prototype(s) ・10 MW multi-beam klystrons (E3736H) made by Toshiba Electron Tubes & Devices ・7 units already delivered to E-XFEL ・Can be adapted to ILC with existing technology ●Required performance achieved	■Technical issues ・N/A (ILC TDR specifications satisfied) ●Manufacturing-related issues ・Need to expand vacuum pumping/baking and test device capacity for mass production (test stands exclusively for MBK) (As installation will require considerable space and height, a decision on expanding capacity will be made taking into account economic feasibility.) ・Implementation of parallel aging and testing using capacity of laboratories involved with ILC (for delivery optimization) ・General issue: Improvement of work efficiency, including adjustment of MBK operational parameters	◎	●Manufacturing (mass production) ・Toshiba Electron Tubes & Devices (Japan) Capability of mass production by companies to meet ILC requirements ・Toshiba Electron Tubes & Devices: Potentially capable of mass production of MBK, but will need to expand capacity assuming orders for other projects if annual production exceeds 20 units

	Couplers	16,000	■Frequency: 1.3 GHz	*Europe* LAL (for conditioning) Thales, RI	■Prototype(s) ・TTF-III input couplers for E-XFEL manufactured and delivered by Thales, RI consortium ・Coupler technology already established ●Required performance achieved	■Technical issues ・N/A ●Manufacturing-related issues ・Problems existed at the initial stage of E-XFEL coupler production with coppering (10% defect rate) and EBW with ceramics, but these have been resolved. ・Expansion of production facilities for mass production ・Acceleration of manufacturing process for mass production (improvement of RF station and clean room) ・Increase of manpower (workers skilled in EBW) for mass production	◎	■Tests and conditioning ・LAL ●Manufacturing (mass production) ・RI (Germany), Thales (France) Capability of mass production by companies to meet ILC requirements ・Thales: Capable of doubling pace of production (to 1,000 units annually) without new capacity investment
				US CPI	■Prototype(s) ・TTF-III and LCLS-II input couplers have been manufactured and delivered for E-XFEL by CPI ・Coupler technology for ILC already established ●Required performance achieved	■Technical issues ・N/A ●Manufacturing-related issues (examples) ・Many defects identified in the initial stage of coupler production for E-XFEL (including a large volume of gas leak) already resolved ・Further reduction of cost for mass production ・Increase and training of workers for mass production	◎	■Tests and conditioning Undecided ●Manufacturing (mass production) ・CPI (US) Capability of mass production by companies to meet ILC requirements ・CPI: Annual production of ~1,200 units possible using current production facilities and introducing a two-shift system
				Japan Toshiba Electron Tubes & Devices	■Prototype(s) ・Prototypes of couplers for E-XFEL have been delivered to LAL and performance evaluation has been completed. (However, no mass-production couplers for E-XFEL have been delivered yet.) ・Coupler technology for ILC already established ●Required performance achieved	■Technical issues ・N/A ●Manufacturing-related issues (including operational issues) ・Adjustment of high-quality copper plating technology for mass production, which is key to coupler production ・Expansion of capacity for mass production (high-level clean room, EBW facilities, vacuum brazing facilities, etc.) ・General issue: Supervision, maintenance, and repair of large number of couplers (System of large-scale maintenance, reduction of failure rate, etc.) ・General issue: Preparation for conditioning of large number of couplers by research institutes or companies	◎	■Tests and conditioning Undecided ●Manufacturing (mass production) ・Toshiba Electron Tubes & Devices (Japan) Capability of mass production by companies to meet ILC requirements ・Toshiba Electron Tubes & Devices: Annual production of 890 couplers not feasible with the current plant facilities, but should be possible with additional measures such as construction of high-level clean rooms
	LPDS (local RF power distribution system) Waveguides and waveguide components		■RF supply with minimum loss ■Remote control of input power and phase of cavities ■Maximization of average accelerating gradient taking dispersion into consideration	*Japan* KEK, Nihon Koshuha, Furukawa C&B, etc.	■ Prototype(s) (waveguides and waveguide components) ・Possible to manufacture 500-kW-class waveguides for ILC (Nihon Koshuha) ・Waveguides, circulators, dummy loads, RF microwave vacuum windows, directional couplers, and power dividers for KEK STF have been delivered by Nihon Koshuha and the other companies. ・Variable H-hybrid and variable phase shifter (developed at KEK) ・Variable power divider (developed at SLAC) ●Required performance almost achieved ・Technology for ILC waveguides and waveguide components largely in place ・Still room for improvement	■Technical issues ・Examination of how to mount LPDS on the cryomodule ・Manufacture and testing of integrated cryomodule and LPDS ■Technical issues ・Conversion from welding to casting of waveguides and components ・Improvement and reduction of costs of wave absorbers for dummy loads ・Improvement of certain components (including variable H-hybrids and variable phase shifters) ●Manufacturing-related issues ・Improvement of methods of treating nitrogen and SF_6 (sulfur hexafluoride) gas to prevent electrical discharge inside waveguide ・Maintenance of procurement quality of magnets and ferrites to be placed in circulator	◎	●Manufacturing (mass production) ・Nihon Koshuha, Furukawa C&B, etc. Capability of mass production by companies to meet ILC requirements ・Nihon Koshuha: Mass production for ILC (25 units weekly) possible with addition of 100 workers and measurement jigs. Maximum order size is currently several dozen per year.

Summary of all survey results (beam technology)

Key technologies/products		Quantity required for ILC	Specifications and requirements for ILC	Research/testing/ manufacturing entity	Progress ■Prototype status ●Progress on required performance for ILC	Issues ■Technical ●Manufacturing-related (mass production)	Feasibility of development and mass production	
							Outlook	Entities involved
Beam technology	Polarized electron sources	2	■Bunch repetition rate: 3 MHz ■Average current: 32 μA ■Peak current: 4.8 A ■Bunch charge: 4.8 nC/ bunch ■Polarization: ≥80% ■Quantum efficiency: ≥0.5%	JLab SLAC Nagoya University	■Photocathode technology ・Superlattice cathode (combination of GaAs and GaAsP) offers high performance. ●Required performance achieved ・Polarization 90%, Quantum Efficiency 1.6% →ILC goals achieved ・Cathode lifetime: Continuous operation of more than one month with output of 32 μA achieved under ILC conditions (CEBAF) ■Electron gun prototypes exist ・Nagoya University: NPES-3 (with 200 kV load-lock) ・Jlab: CEBAF electron gun (100 kV inverted-gun type electron gun equipped with load-lock) ●Required performance not fully achieved ・Single-bunch charge required for ILC (NPES3, 5.6 nC) achieved ・Simultaneous generation of a charge of 4.8 nC (1 ns) and repetition rate of 3 MHz not yet demonstrated ■Laser system (multi-bunch) not yet verified ・No reports on progress regarding development of laser system with multi-bunch time structure (SLAC) ・Specifications of laser system for FLASH FEL seeding similar to those of ILC laser and useful for ILC (DESY)	■Technical issues (photocathode) ・Further improvement of the quantum efficiency of cathodes for higher polarization, although the target values for ILC have been achieved ■Technical issues (electron gun) ・Electron gun technology has basically been proven capable in projects such as SLC and may be considered complete. ・Development of higher-voltage electron guns to improve performance of electron beam and reduce beam spread and loss in transportation. (DC electron guns with ≥500 kV are actually now being developed and there have been some successes.) ■Technical issues (laser system) ・Development of demonstration device capable of adjusting pulse width repeatedly for use as ILC electron source, while laser system with multi-bunch time structure can be realized with OPCPA method ・Creation of laser with wavelength of 780 nm ■Technical issues (in general) ・Preparation of general tests (electron gun, photocathode, laser system, and beam diagnostics system as a whole)	○	■Development and testing ・SLAC, Jlab ・Nagoya University, KEK, JAEA ・DESY (laser) ・Mainz University, Bonn University (electron gun) ・Novosibirsk (photocathode)
	Positron source (helical undulator)	1 (60)	■Bunches per pluse: 1,312 ■Positron energy: 5 GeV (for DR injection) ■Undulator type: helical ■Undulator length: 147 m	STFC-Daresbury Lab SLAC	■Undulator prototype exists ・Superconducting helical undulator module (4 m) for ILC (developed at STFC) ●Required performance partially achieved ・Magnetic performance exceeded the field level required by ILC by 30% (achieved). ・Regarding magnetic field accuracy, amplitude was stable and magnetic field integral value was 0 (slightly insufficient). ・Cryogenic performance of the module was not satisfactory (later improved).	■Technical issues ・Performance of beam tests (demonstration that beams can pass through 6-mm beam pipes) ●Manufacturing-related issues ・Manufacture of prototype modules for mass production in collaboration with companies	△	■Development and testing ・STFC-Daresbury Lab ●Manufacturing (mass production) ・UK companies, etc.
	Positron source (targets)	1		RAL LLNL ANL	■Prototypes of the positron source target under development ・Water cooling system has not worked well. ・There are two types of target cooling method that do not use the water cooling approach: (1) sliding contact cooling and (2) radiation cooling ●Required performance not achieved ・For type (1), contact parts are being developed. ・Type (2) is still in the design optimization stage.	■Technical issues (targets) ・Establishment of cooling technology and development of prototype (will be at least two years before cooling technology is ready) ・Beam testing to guarantee performance (alternatively, demonstration using laser will be necessary) ・For any of the cooling methods, development of technique for remotely replacing target modules (consumables)	△	■Development and testing ・Undecided

	Positron source (backup) (electron-driven system)	1		KEK	■Prototype in production (targets) ・The model will be manufactured during FY2015-16. ■Partial prototypes exist (element technology) ・Electron beam linac for driving (KEK), AMD (SuperKEKB), etc. ●Required performances partially not achieved ・Target rotating speed of 5 m/s ・Positron yield (simulated value) of 3×10^{10}/bunch (experience at KEKB, etc., shows simulations correspond to reality) ・Target (shaft seal on rotating body) not yet tested	■Basic issues ・Adaptation of electron-driven system to ILC particle experimentation scheme as it cannot currently obtain polarized positrons ■Technical issues (targets) ・Demonstration of target prototypes ・Development of model for shaft seal of rotating body (testing of radioresistance of seal on rotating body, verification of seal material degradation) ■Technical issues (whole system) ・Design of AMD and booster linac ・Comprehensive testing of single system combining established element technologies	△	■Development and testing ・KEK (Japan)
	Damping ring (DR)		■DR circumference: 3.2 km ■Low vertical emittance	INFN-LNF SLAC KEK	■Prototypes exist (extensive experience in experimentation and development of state-of-the-art element technology). ・Element technology demonstrated with third-generation light sources (e.g., Diamond, ASLS, ESRF, SLS, and SSRF). ●Required performance almost achieved ・Several existing electron-positron colliders and synchrotron light sources have achieved performance equivalent to the beam performance required for ILC DRs (in terms of ultra-low emittance, bunch number, and bunch distance)	■Technical issues (beam injection/extraction technology) ・Continuation of R&D to simultaneously achieve goals of important elements of the beam injection and extraction systems for ILC (pulse rise time and fall time, pulse repetition rate, kick amplitude and amplitude stability). Most elements have been achieved independently. ・Evaluation of stability and reliability of long-term operation of fast kickers ・Improvement of performance of the pulsed power supply used in fast kickers (now being developed at KEK) ■Technical issues (the technology to reduce electron clouds) ・Development of vacuum system to reduce instability of electron clouds (to be established using the instability reduction technology adopted for SuperKEKB)	◎	■Development and testing ・INFN-LNF (Italy) ・SLAC (US) ・KEK(Japan), etc.
	Beam control (fast feedback system of the DR circulating beam)	1		INFN-LNF	■No prototypes ・Possible to use some of the technologies used for the DAΦNE at INFN-LNF (strip line and cavity kicker, etc.) ・Possible to use the SuperKEKB system now under construction (because some parameters, including energy, bunch number, and beam current, are similar to those for ILC) ●Required performance not achieved ・Performance of feedback system using ILC DR parameters has not been verified.	■Technical issues ・Continuation of R&D on fast feedback system (prototype system) based on ILC DR specifications (achievement of high sampling frequency, development of high number of bits in the analog-to-digital conversion technology) (development of technologies, including mass processing of short-distance bunches and introduction of extremely low noise systems)	△	■Development and testing ・INFN-LNF (Italy)
	Beam control (fast beam feedback system at the interaction point)	1		JAI KEK	■Prototype(s) ・Prototype system (multi-bunch beam monitoring and control systems) has already been developed at JAI. ・This system has already been installed on the ATF2 beam line at KEK and tested. ●Required performance achieved ・BPM spatial resolution, BPM signal processing latency, operating speed of the digital controller, performance of driver amplifier, closed loop feed-back latency, etc.	■Technical issues ・Research on transverse measuring technology for the beam diagnostic equipment used for ILC ・Development of high-resolution BPM system for ATF but not for ILC (e.g., by developing circuit to process BPM signals at virtual interaction point of ATF) ●Manufacturing-related issues ・Reduction of costs through industrialization of cavity-type beam position monitors (CBPMs)	◎	■ Development and testing ・JAI (UK) ・KEK (Japan) ・SLAC (US)

	Beam dump	4	■Container shape: Cylindrical stainless container (1.8 m diameter × 11 m length) ■Inside container: 10-atm high pressure water ■18 MW × 4 units (2 units respectively for electrons and positrons)	None	■No prototypes ・No prototype of beam dump designed for ILC (There is, however, a design based on the SLAC 2.2-MW beam dump.) ●Required performance not achieved ・Performance has not been demonstrated (simulation has been done on the basis of the SLAC 2.2-MW beam dump).	■Technical issues ・Development of accident prevention and containment measures to be taken when window is accidentally destroyed due to concentration of beam bunch on one point of window ・Verification of corrosion resistance of window materials caused by cooling water in a highly radioactive environment ■Technical issues ・Development of safety management technologies for radioactive substances (e.g., tritium) produced by dumped beam	△	■Development and testing ・Undecided
	Crab cavity system	2 (cavities)	■Cavities: 3.9-GHz superconducting nine-cell cavities ■Cryomodules ■Couplers: LOM, SOM, and HOM	Cockcroft Institute FNAL SLAC	■No prototypes ・Cavities: No prototype exists for nine-cell cavities with couplers designed to ILC specifications. Experiments are limited to one-cell cavities. ・Cryomodule/cryostat: No design ・Coupler: HOM coupler needs to be redesigned. Designs for LOM and SOM couplers have been completed. ●Required performance not achieved ・Cavities: Experiments involve two one-cell cavities. Performance has not been demonstrated. ・Couplers: Experiments have shown that the HOM coupler cannot adequately dump the beam.	■Technical issues ・Manufacture and demonstration of prototype of superconducting nine-cell cavities with couplers ・Design of cryomodule/cryostat, manufacture and demonstration of prototype ・Redesign, manufacture, and demonstration of HOM coupler ・Synchronous operation and demonstration of two crab cavities ●Manufacturing-related issues ・Realization of commercial production of the 3.9 GHz LLRF boards necessary for synchronization of cavities	△	■Development and testing ・STFC (Cockcroft Institute) (UK) ・FNAL (US) ・SLAC (US)

Outlook rating	Definition
◎	Prototype developed and demonstrated. Actual manufacture and mass production capable with improvements to current technology or small-scale R&D.
○	Prototype developed and demonstrated. Actual manufacture and mass production will require certain technological advances or medium-scale R&D.
△	Prototype not yet developed or demonstrated. Prototype development will require technological breakthroughs and large-scale R&D.
×	Basic technology not yet established or demonstrated. Feasibility of the prototype remains unclear.

Table 3 Processing capacities of manufacturing, assembly, and test lines for mass-produced ILC components (currently and in the future in Europe, US, and Japan)

(1) Europe: Comparison of processing capacities of manufacturing, assembly, and test lines for mass-produced ILC components (based on results of questionnaires)

Comparative indexes ⇒

Volumes of mass-produced components required for the ILC (as a model study for the production period of six years)

(number of units)

	Production volume required for entire ILC		Annual production volume required (production period: six years)		
	Total	Per region (JP, US, EU)	Total	Per region (JP, US, EU)	Per company in each region*
Accelerator cavities	18,000	6,000	3,000	1,000	500
Cryomodules	1,855	618	309	103	52
Couplers	16,000	5,333	2,667	889	444
Klystrons	440	147	73	24	12

*Assuming components are produced by two companies in each region.

Present/future	Category	(unit)	Companies and research institutes							
			RI	Zanon	DESY	DESY	ALSYOM	RI	THALES	LAL
Present	■Equipment type		**Accelerator cavities (for E-XFEL)**	**Accelerator cavities (for E-XFEL)**	**Accelerator cavities (for E-XFEL)**	**Cryomodules**	**Cryomodules**	**Couplers**	**Couplers**	**Couplers**
	■Line type		**Manufacturing**	**Manufacturing**	**Performance tests**	**Performance tests**	**Assembly**	**Manufacturing**	**Manufacturing**	**Performance tests**
	・Line 1: process		Mechanical manufacturing		Vertical tests on cavities (accelerator module test facility (AMTF))		Assembly line	Manufacturing		Clean room operation
	・Line 2: process		Surface treatment		Retreatment and repair of cavities (HALL3)			Surface treatment		RF conditioning
	・Line 3: process				Cryomodule tests (AMTF)					
	■Processing capacity (weekly)	units	4	4–4.5	10	1.2 (recently 1.5)		8	8	8–10
	■Processing capacity (monthly)	units		16–18	40	4	5	32	32	40–50
	■Processing capacity (yearly)	units	200	192–216	480	50	55	400	400	480–600
	■Total facilities area	m^2	3,000	1,500	2,460		2,500			150
	・Line 1: area	m^2	2,000	500	480		2,500			60
	・Line 2: area	m^2	1,000	1,000	530					90
	・Line 3: area	m^2		(lines 2+3 ↑)	1,450					
	■Total number of workers	persons	60	50	103		33			9
	・Management and clerical work	persons	4	2	17		8	4		3
	・Skilled workers and engineers	persons	56	48	86		25			6
	■Capacity investment (cumulative)	million €	12		41 (AMTF only ↑)					3.4
	■Operating cost (yearly)	million €			3.5 (electricity + liquid He ↑)					0.3
Future (when ILC is operational)	■Processing capacity (weekly)	units	10		15	1.5		20	20	
	■Processing capacity (monthly)	units					10			80–100
	■Processing capacity (yearly)	units	500				100	1,000	1,000	960–1,200
	■Total facilities area	m^2					3,500–5,000			300
	・Line 1: area	m^2								120
	・Line 2: area	m^2								180
	・Line 3: area	m^2								
	■Total number of workers	persons					62–65			17
	・Management and clerical work	persons					12–15			5
	・Skilled workers and engineers	persons					50			12
	■Capacity investment (additional)	million €								8
	■Operating cost (yearly)	million €								0.7

(2) United States: Comparison of processing capacities of manufacturing, assembly, and test lines for mass-produced ILC components (based on results of questionnaires)

Comparative indexes ⇒

Volumes of mass-produced components required for the ILC (as a model study for the production period of six years)

(number of units)

	Production volume required for entire ILC		Annual production volume required (production period: six years)		
	Total	Per region (JP, US, EU)	Total	Per region (JP, US, EU)	Per company in each region*
Accelerator cavities	18,000	6,000	3,000	1,000	500
Cryomodules	1,855	618	309	103	52
Couplers	16,000	5,333	2,667	889	444
Klystrons	440	147	73	24	12

*Assuming components are produced by two companies in each region.

Present/future	Category	(unit)	Companies and research institutes										
			ROARK	AES	Jefferson Lab	Jefferson Lab	Jefferson Lab	Jefferson Lab	Fermi Lab	Fermi Lab	Fermi Lab	CPI	CPI
Present	■Equipment type		**Accelerator cavities (ILC specifications not achieved yet)**	**Accelerator cavities**	**Accelerator cavities**	**Accelerator cavities**	**Cryomodules**	**Cryomodules**	**Accelerator cavities**	**Cryomodules**	**Cryomodules**	**Couplers**	**Klystrons**
	■Line type		**Manufacturing**	**Manufacturing**	**Manufacturing**	**Performance tests**	**Performance tests**	**Assembly**	**Performance tests**	**Performance tests**	**Assembly**	**Manufacturing**	**Manufacturing**
	・Line 1: process		Machine manufacturing only	Manufacturing excluding tests	Surface treatment and tuning	Vertical tests on cavities, cryomodule tests, and assembly			Vertical tests on cavities, cryomodule tests, and assembly			Manufacturing in general	Manufacturing in general
	・Line 2: process												
	・Line 3: process												
	■Processing capacity (weekly)	units							2		1		
	■Processing capacity (monthly)	units	2		25	72*	1	2		1*	4*	16–24	0.3–0.4
	■Processing capacity (yearly)	units		50			12	22	150	12*			4
	■Total facilities area	m^2		2,043	5,574							17,000	
	・Line 1: area	m^2		1,486	3,521	2,322							
	・Line 2: area	m^2											
	・Line 3: area	m^2											
	■Total number of workers	persons	~*9	19	*10	37		10					
	・Management and clerical work	persons	~*1	4	4	24		1					
	・Skilled workers and engineers	persons	~*8	15	6	13		9					
	■Capacity investment (cumulative)	million $											
	■Operating cost (yearly)	million $											
Future (when ILC is operational)	■Processing capacity (weekly)	units											
	■Processing capacity (monthly)	units										60*	3–5
	■Processing capacity (yearly)	units		100*									
	■Total facilities area	m^2	No additional concrete capacity investment plans drawn up assuming construction of the ILC were confirmed. Production will largely be carried out using the facilities required for existing research projects.										
	・Line 1: area	m^2											
	・Line 2: area	m^2											
	・Line 3: area	m^2											

	■Total number of workers	Person											
	・Management and clerical work	Person											
	・Skilled workers and engineers	Person											
	■Capacity investment (additional)	Million $											
	■Operating cost (yearly)	Million $											
	Remarks		-	*Assuming maintenance of current number of workers and adoption of two-shift system.	*Estimated by NRI assuming allocation of around 10% of entire workers	*Up to 144 units can be treated for LCLSII.	-	-	-	*Assuming processing capacity on a par with Jefferson Lab.'s.	*1 CM/month can be added if CEBAF line is converted to ILC use.	*This is a maximum and will require a preparatory period of at least around two years to achieve.	-

(3) Japan: Comparison of the processing capacities between the manufacturing, assembly, and test lines of ILC mass-production components (based on the results of questionnaires and interviews)

Comparative indexes ⇒

Volume of mass-production components required for the ILC (as a model study for the production period of six years)

(number of units)

	Production volume required for the entire ILC		Annual production volume required (production period: six years)		
	Total	Per region (JP, US, EU)	Total	Per region (JP, US, EU)	Per company for each region*
Accelerator cavities	18,000	6,000	3,000	1,000	500
Cryomodules	1,855	618	309	103	52
Couplers	16,000	5,333	2,667	889	444
Klystrons	440	147	73	24	12

*Assuming components are produced by two companies in each region.

Present/future	Category	(unit)	Companies			
			Mitsubishi Heavy Industries	Toshiba Electron Tubes & Devices	Toshiba Electron Tubes & Devices	Nihon Koshuha
Present	■Equipment type		**Accelerator cavities (TESLA-like type)**	**Multi-beam klystrons**	**Couplers**	**Waveguides and components**
	■Line type		**Manufacturing**	**Manufacturing**	**Manufacturing**	**Manufacturing**
	・Line 1: process		Manufacturing of accelerator cavities			
	・Line 2: process		Cavity surface treatment			
	・Line 3: process		Cavity inspection and performance evaluation			
	■Processing capacity (weekly)	units				
	■Processing capacity (monthly)	units				
	■Processing capacity (yearly)	units		Potential for mass production		Several dozen
	■Total facilities area	m^2				
	・Line 1: area	m^2				
	・Line 2: area	m^2				
	・Line 3: area	m^2				
	■Total number of workers	persons				
	・Management and clerical work	persons				
	・Skilled workers and engineers	persons				
	■Capacity investment (cumulative)	million €				
	■Operating cost (yearly)	million €				
Future (when ILC is operational)	■Processing capacity (weekly)	units				Required quantity determined by calculating backwards: 25 units[4]
	■Processing capacity (monthly)	units				
	■Processing capacity (yearly)	units	~500[1]	~20[2]	Annual production of 890 couplers not possible with current plant facilities[3]	
	■Total facilities area	m^2				
	・Line 1: area	m^2				
	・Line 2: area	m^2				
	・Line 3: area	m^2				
	■Total number of workers	persons				
	・Management and clerical work	persons				
	・Skilled workers and engineers	persons				
	■Capacity investment (additional)	million €				
	■Operating cost (yearly)	million €				

[1] Possible if use is made of four-cavity simultaneous electron beam welding technology.

[2] Will need to expand capacity assuming orders for other projects.

[3] Feasible if high-level clean rooms, etc. are added.

[4] Production possible with the additional employment of about 100 workers and the introduction of new measurement jigs.