

INTERNATIONAL LINEAR COLLIDER, LATEST STATUS TOWARDS RELALIZATION*

Sachio Komamiya[†]

The University of Tokyo, International Center for Elementary Particle Physics, Tokyo, Japan

Abstract

This presentation describes the International Linear Collider (ILC), an e^+ and e^- collider based on the superconducting linear accelerator with a center of mass energy of 500 GeV in the first stage, upgradeable to 1 TeV. According to the statement of the Science Council

of Japan, MEXT (Ministry of Education, Science, and Sports) and the Japanese government have investigated the feasibility of the ILC project, not only from the scientific view, but also the political, economic, and sociological points of view. The latest status of the project as well as the scientific objective will be presented.

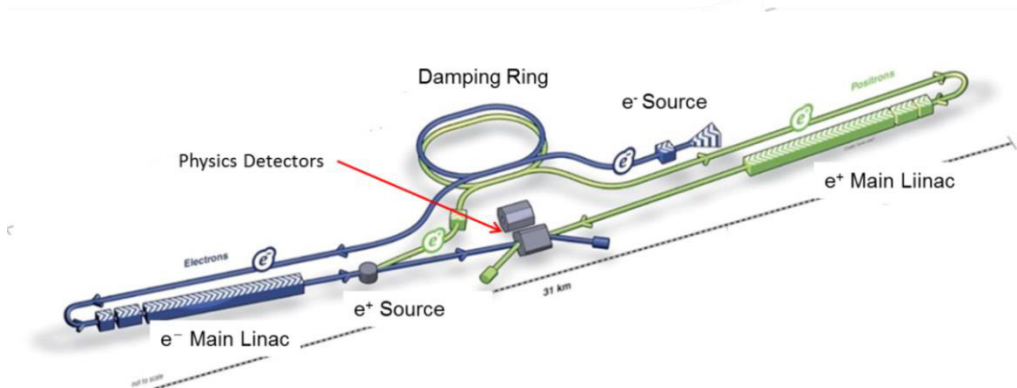


Figure 1: Schematic illustration of the ILC. Electron and positron sources, damping rings, electron and positron main linacs and the physics detectors are shown. The total length of the 500 GeV machine is about 31 km, which is close to the circumference of the LEP/LHC (27 km).

ADVANTAGES AND SHORT HISTORY OF ILC

There are several advantages of the electron-positron linear colliders. First of all the experimental environment is much cleaner than that for the hadron colliders, since the collision rate is significantly lower, and the ratio of possible new particle signal to background is much higher for electron-positron colliders. Since electrons and positrons are elementary particles, the fundamental processes can be directly observed in their collisions. Whereas protons are composite particle made of quarks and gluons, their collision is complicated, and $O(100)$ of soft collisions occur for every beam crossing. At LHC, therefore, calorimeter signals pile up with hadrons from the soft collisions. The momentum component along the beam direction and the total collision energy cannot be used in physics analyses for the LHC experiments due to high momentum particles escaping into the beam pipe, therefore transverse momentum conservation can only be used at LHC. Whereas the total energy-momentum conservation can be used for e^+e^- colliders, hence the beam energy dependent cross section measurement (energy scan) makes sense.

High energy circular e^+e^- electron-positron colliders

suffer from the energy loss due to the synchrotron radiation. The energy loss per turn is proportional to $(E/m)^4 R^{-1}$, where E and m are the energy and the mass of a beam particle and R is the bending radius of the circular orbit. Therefore it is very difficult to increase the beam energy due to the energy loss for circular e^+e^- colliders.

Beam energy of linear e^+e^- colliders can be increased by extending the length of the main linac. Also the energy can be increased by improving the acceleration gradient. The beam polarization is a very powerful tool for ILC to investigate the spin properties of interactions with new particles and to suppress specific background processes.

Linear Collider accelerator technologies have been developed since 1980s mainly at SLAC, DESY, KEK, CERN and Novosibirsk. DESY developed technologies of superconducting RF, whereas SLAC and KEK developed normal conductivity RF of X-band and C-band frequencies. In 1990s five major accelerator technologies were under hard competition, i.e. superconducting RF technology (TESLA), S-, C-, and X-band normal conducting technology, and CLIC technology (two-beam acceleration). To solve this overcompetition ICFA established International Linear Collider Steering Committee (ILCSC) in 2002. In the next year the International Technology Recommendation Panel (ITRP) was set up to choose one accelerator technology for the

[†]E-mail address: sachio@icepp.s.u-tokyo.ac.jp

global linear collider machine, and in 2004 superconducting technology was chosen by ITRP. This global accelerator was named “International Linear Collider” by ICFA. In the next year a world-wide designing team for ILC, which was called Global Design Effort (GDE), was formed and was led by Barry Barish of Caltech. The GDE issued Reference Design Report in 2007, and finally Technical Design Report in 2013 [1]. The ILC design in TDR is enough mature to be used for the international negotiation.

ACCELERATOR TECHNOLOGY

Although there are significant advantages in ILC, there are mainly two technological challenges: (1) high gradient superconducting RF system and, (2) very small emittance flat beam of $\sigma_y = 6$ nm at the interaction point. The high acceleration gradient is essential to accelerate particles in a single path within a reasonable length. To save wall-plug power superconducting RF is preferred. Small beam size is essential to increase the luminosity by keeping the power consumption low. Since particles in a beam with round cross section are scattered away by the Coulomb force, the beams should have a flat shape ($\sigma_y \ll \sigma_x$). A schematic illustration of ILC is shown in Fig. 1.

Superconducting RF System

The superconducting RF (SCRf) system has been developed at Fermilab, DESY, KEK, CERN and other laboratories for more than 20 years. The technology, overall design, cost estimation of the SCRf are all matured as described in TDR.

SCRf system for the Euro-XFEL at DESY is just similar to ILC SCRf, except for the specification of the acceleration gradient. The scale of the SCRf of the Euro-XFEL is about 1/20 of that of the ILC main linac. The industrial cavity production for ILC has to be closely followed the experiences in the Euro-XFEL project. All the superconducting RF modules are already installed in the tunnel as shown in Fig. 2. The average gradient reached 30 MV/m. The specification of the gradient for Euro-XFEL is 24 MV/m which is lower than 31.5 MV/m of ILC, hence they tested the gradient up to only 30 MV/m. Two French laboratories, CEA-Saclay and CNRS-LAL are collaborating with DESY for the SCRf construction. The production flow for SCRf items, including transportation of the cryomodules, is a reference model for the ILC SCRf construction.

At Fermilab the gradient of the ILC-type cryomodule CM2 reached 31.5 MV/m two years ago. The KEK-STF (Superconducting RF test facility) is shown in Fig. 2. The gradient of individual cavity reached above 35 MV/m at the vertical test. The gradient of a few cavities degraded after installation into a cryomodule. It is understood that these cavities suffer from the field emission due to contamination of particles during the connection of two

cryomodules in an imperfect cleanroom. The beams are going to be commissioned in 2017.

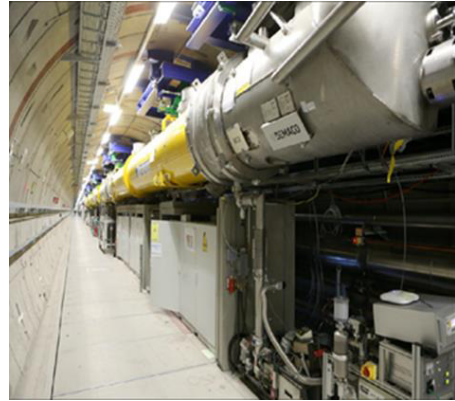


Figure 2: Line-up of all the 77 cryomodules of the Euro-XFEL. The SCRf is about 1/20 of the ILC main linacs.

At Fermilab the gradient of the ILC-type cryomodule CM2 reached 31.5 MV/m two years ago. At the KEK-STF (Superconducting RF test facility) gradient of individual cavity reached above 35 MV/m at the vertical test. The gradient of a few cavities degraded after installation into a cryomodule. It is understood that these cavities suffer from the field emission due to contamination of particles during the connection of two cryomodules in an imperfect cleanroom. The beams are going to be commissioned in 2017.



Figure 3: KEK STF Accelerator (400 MeV beam energy).

Recently the LCLS-II project has been approved in the USA. LCLS-II will use the similar cavities to the ILC. The Fermilab and the Jefferson Lab are involved in the project. The laboratories involved in Euro-XFEL or LCLS-II will be powerful hub-laboratories during ILC construction.

Beam Delivery and Final Focus System

For the optics of the final focus system for ILC so called the local chromaticity correction will be used. The advantage of this optics is that the length of the final focus system depends little on the beam energy. At the Accelerator Test Facility (ATF) of KEK, small emittance beams have been produced with the ATF dumping ring. The beams from the dumping ring are extracted to the final focus test line of ILC (ATF2). In 2013 the vertical beam size of 44 nm averaged over many measurements was measured at ATF2 as shown in Fig. 4. The tuning time to reach this beam size becomes a few hours and the

stability is increasing. This beam size is corresponding to 7 nm of ILC and very close to the goal of 37 nm corresponding to 6 nm at ILC. Very recently the average σ_y of 41 nm was reached. The beam size has been measured by the Compton scattering rates of beam electrons with photons in a laser light interference pattern (Shintake beam size monitor)

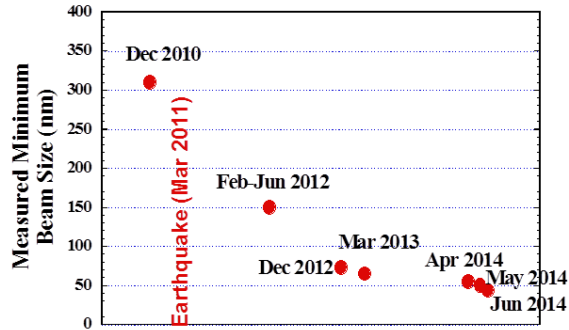


Figure 4: Development of vertical beam size squeeze at ATF2 of KEK using the local chromatic correction.

Stable beam can be obtained by fast feedback system. The FONT (Feedback On Nanosecond Timescales) group is working on this subject. The two bunchlet beams are delivered from ATF to ATF2 and the feedback back system is tested for the reduction of beam jitter. An artificial beam jitter was created upstream and it was proven that the feedback dumped beam size of the second bunchlet. Further studies of the beam position monitor for the feedback is working on.

The Site of the ILC

The candidate site of the ILC is along the Kitakami Mountains in the north of the main island, Japan. It is located in the earthquake-proof stable bedrock of granite. No faults cross the ILC. The site is rather in hills than in a mountain range.

PHYSICS AT ILC

Prospect of Particle Physics

In the previous century the Standard Model of particle physics has been established through the synergic interactions of experiments and theories. In the Standard Model constituents of the matter are leptons and quarks, and the interactions are governed by the gauge principle. The generation of the masses of elementary particles is due to condensate of the Higgs boson field in the vacuum (Brout-Englert-Higgs mechanism). Finally the Higgs boson was discovered by the ATLAS and CMS experiments at LHC of CERN in July 2012 [2], thus all the elementary particles expected in the Standard Model have been discovered. Although the Standard Model explains almost all the phenomena of particle physics at the energy scales of the current experiments, it includes following fatal flaws:

- (1) It does not include gravity. i.e. There is no satisfactory theory to consolidate the general theory of relativity and the quantum mechanics.

- (2) Although the origin of the elementary particle masses can be due to the condensation of the Higgs field in the vacuum, the mechanism of the Higgs field condensation itself is unexplained.
- (3) The identity of the Dark Matter in our universe is unexplained.
- (4) The mechanism of the matter and anti-matter asymmetry in our universe is unexplained.
- (5) The origins of the inflation of the universe and the accelerating expansion of the current universe (Dark Energy) are unexplained.
- (6) The origin of the three dimensional space and the one dimensional time of our universe is unexplained.

The aim of the ILC is to find the new direction of the particle physics beyond the Standard Model and to solve some of the above problems.

Precise Studies of the Higgs Boson [3]

The most robust way to find physics beyond the Standard Model is to precisely study the Higgs boson, and we need whole of the following three steps:

- (1) At ~ 250 GeV just above the threshold energy of $e^+e^- \rightarrow HZ$, the mass will be measured with an accuracy of $\sigma_M \sim 15$ MeV. Relative values of the coupling constants of the Higgs to elementary particles are measured.

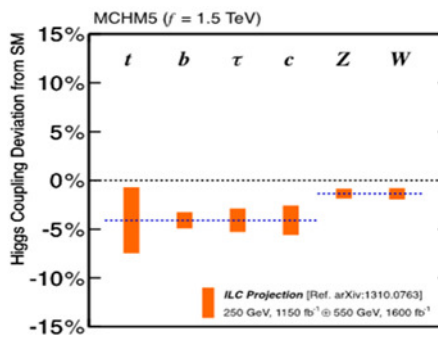
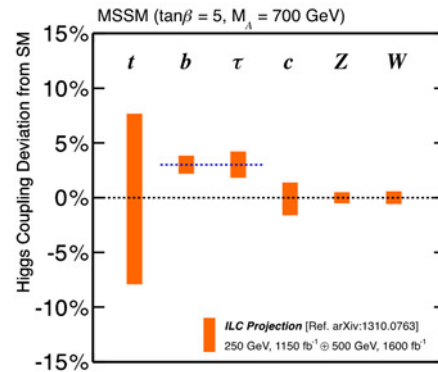


Figure 5: Expected accuracy of the Higgs Boson coupling to elementary particles normalized by the Standard Model values. The upper figure is the expectation for the supersymmetric theory (MSSM) and the lower plot is for a typical composite Higgs Boson Model.

- (2) At ~ 500 GeV the full decay width of the Higgs Boson can be accurately determined using the measured W to Higgs coupling, hence the absolute values of coupling constants can be determined by normalizing with the full decay width. The pattern of deviations of the coupling constants from the SM expectations can distinguish supersymmetric (SUSY) models from the composite Higgs models as shown in Fig. 5. In this way the direction of the particle physics beyond the Standard Model can be determined.
- (3) At 500 GeV and above the triple Higgs coupling can be determined. This measurement may be connected to the baryon/anti-baryon asymmetry in the universe.

These three steps are necessary for the full elucidation of the Higgs Boson. This is possible only with the ILC.

Top Quark Studies [3]

The top quark mass can be precisely measured by the energy scan with an accuracy of 60 MeV. Using also the α_s value information the vacuum stability of the Higgs field can be tested with a high precision. The right handed and left handed top quark to Z-boson couplings can be determined using the beam polarization. This information can be used to distinguish different models of composite Higgs boson or other exotic models.

New Particle Searches [3]

Ability of new particles searches beyond the Standard Model at ILC is also very powerful. For example, in the large parameter space of the supersymmetric (SUSY) models the mass difference between the lightest SUSY particle and the second lightest one is small, and hence the energy of the visible decay products from the second lightest one is too small for LHC experiments to identify them. Even for the case of very small mass difference ILC can discover these events by tagging the initial state photon radiation. Also the beam polarization and the energy scan are the powerful tools to identify new particles.

PROJECT STATUS AND PLAN

The Current International Organization

The current International organization for the preparation of the ILC project is shown in Fig. 6. The International Committee for Future Accelerators (ICFA) creates the Linear Collider Board (LCB) and the Linear Collider Collaboration (LCC) in 2013. LCB is the overseeing board of LCC which is the main execution body for the project promotion and R&D. These organizations continue till the end of this year and will be upgraded. The director of LCC is Lyn Evans, who was the former leader of the LHC construction.

Supports from the World

In June 2013, the European Strategy of Particle Physics under the CERN Council issued their report. In this report support of ILC is clearly shown; “The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation.” [4]. In September 2013, representatives of particle physics community of Asian countries and a region (ACFA-HEP) issued a similar document, “Statement on ILC” [5]. In May 2014, the Particle Physics Project Prioritization Panel (P5) of USA issued a report, in which ILC is also supported [6].

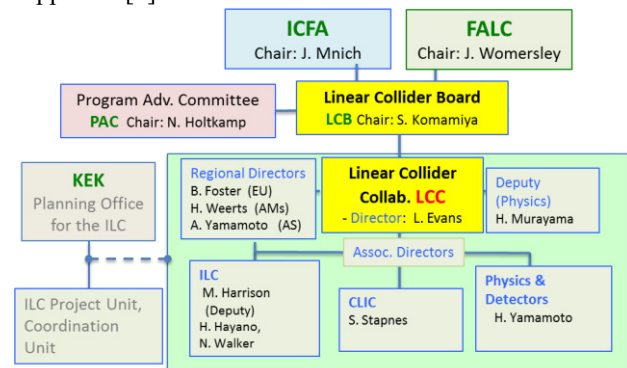


Figure 6: International organization to promote the linear collider projects.

The Position of Japanese Government towards the ILC

In the spring 2013 the MEXT of the Japanese Government asked the Science Council of Japan (SCJ) to provide a recommendation of the ILC project. In September 2013 SCJ delivered the recommendation on ILC to MEXT. In the next step the MEXT set up the ILC Taskforce lead by the Senior Vice Minister of MEXT. In spring 2014 the Taskforce set up the ILC Advisory Panel, which consists of scientists from diverse fields and a few from industry.

Physics Working Group and TDR Validation Group are set up under the Panel. They have extensive discussions during the years of 2014 and 2015 and provided reports. Human Resources Working Group was set up by the Panel in 2015, and the discussions still continue. The Panel issued an Interim Report in August 2016. ICFA chair responded to the unclear part of this Report.

The Federation of Diet Members to Support ILC

In June 2008 “Federation of Diet Members to Promote a Construction of International Laboratory for ILC” was established as a suprapartisan group in Japan. Now the number of the members is increased to about 150. The members meet frequently, and the representatives of the Diet members visited USA and Europe to start preliminary discussions with politicians and government officials.

Advance Accelerator Association of Japan (AAA)

The AAA is an ILC supporting organization from the industry sector in Japan. More than 100 industrial companies, such as Mitsubishi Heavy Industry, Hitachi, Toshiba, Mitsubishi Electric, Kyoto Ceramic, and more than 40 research institutes and universities from academic sector participate in the AAA. Working groups, such as accelerator technologies, large facilities and public relations are formed in AAA, and are very active. This organization works closely with scientists as well as the Federation of Diet Members.

Project Plan

In Table 1, necessary steps towards the project approval is given. In the beginning inter-governmental discussions on the sharing of cost and human resources, and on the organization and schedule are going to start without commitment. After the Japanese cabinet's approval of ILC project, international agreement with commitment will be signed by the governments and the ILC lab will be established. Since the budget system, the budget profile of other large projects, and the approval convention are different from country (region) to country (region), deliberate agreements should be contracted after extensive discussions.

Table 1: Necessary Steps Towards the Approval

Step	Item	timeline
(1)	Technology Choice	2003
(2)	R&D and design of the machine and detector by international team ⇒ Technical Design Report	2013
(3)	Official investigation and reviews of the ILC project by MEXT	Now
(4)	To facilitate/prepare intergovernmental discussions for sharing of cost, human resources and the schedule without commitment	Starting
(5)	MEXT green signal	
(6)	Endorsement of Council of Science, Technology and Innovation (CSTP, chaired by the Prime Minister)	
(7)	Cabinet Decision	
(8)	International agreement with commitment ⇒ establishment of the ILC laboratory	

The timeline of the ILC project is shown in the Table 2. After the green sign of the Japanese Government it is necessary to have 4 years of the preparation period before the construction. In this period management structure, procurement and inspection methods, especially for the SCRF items, handling of intellectual properties, etc. must be established. The project management should be done

by a combined team of scientists, government officials and experienced persons from industries, who have involved in management of large scale projects.

Table 2: Timeline for the ILC Project

Years need	Item
2	Preparation period Continuation of high-tech R&D (now)
4	Preparation for the ILC construction (with real budget)
9	Construction 6 th year Start Installation 7 th year Start of step-by-step accelerator test
1	Beam Commissioning
~8	Physic Run (500, 350, 250 GeV)
~	Run with Luminosity upgrade (250, 500 GeV)
TBD	Energy Upgrade to ~ 1 TeV

CONCLUSION

Grounded on the discovery of the Higgs Boson at the LHC, the aim of the ILC is to determine the direction of particle physics beyond the Standard Model. The ILC accelerator technology is mature and ready to construct as described in the TDR issued in 2013. Since the ILC project is truly international, it is essential to discuss share of project cost and human resources, and the project management and schedule, among the governments before the construction. Japanese government is seriously investigating the feasibility to host the project. Preliminary diplomatic discussions have been started among governments.

ACKNOWLEDGEMENT

The author thank Prof. Akira Yamamoto, Prof. Hitoshi Hayano and Prof. Yasuchika Yamamoto for providing several slides on SCRF.

REFERENCES

[1] Editors T. Behnke et al., ILC Technical Design Report, Volume1-5,2013
<http://www.linearcollider.org/ILC/Technical-Design-Report>

[2] ATLAS Collaboration, Phys. Lett. B716 (2012) 1, CMS Collaboration, Phys. Lett. B716 (2012) 30

[3] LCC Physics Working Group, K. Fujii et al., arXiv:hep-ph1506.05992v2

[4] The European Strategy for Particle Physics, Update 2013, CERN-Council-S/106
<http://council.web.cern.ch/council/en/EuropeanStrategy/esc-e-106.pdf>

[5] AsiaHEP/ACFA Statement on ILC
http://www.acfaforum.net/ACFA_AsiaHEP%20Statement%20on%20ILC_13091.pdf

[6] Report of the Particle Physics Project Prioritization Panel (P5), DOE/NSF <http://www.usparticlephysics.org/p5/>