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ILC ACCELERATOR STATUS

H. Sakai† on behalf of IDT
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

The international linear collider (ILC) is a Higgs Factory, where electron-positrons are accelerated by the linear accelerators using Superconducting RF (SRF) cavities to 125 GeV. In 2013, the GDE, an international organization of researchers, already compiled the TDR. It is currently being studied under the International Development Team (IDT). Especially, from 2023, the ILC Technology Network (ITN), specifically under the IDT, will work on the development through international cooperation. This presentation will show an overview of the ILC and the recent developments under the ITN. First, an overview of the latest proposed Higgs factories of more than 250 GeV energy will be given. Second, we introduce the ILC accelerator, including the design, key technologies, accelerator systems. Finally, the detailed ongoing key technology developments, such as SRF cavities, nano-beam, and sources, for ILC project over a few years will also be presented.

INTRODUCTION

The Higgs boson was discovered at the LHC in 2013, and the next major challenge for high-energy physics is to investigate the Higgs boson itself in detail and to search for higher-energy particles beyond the standard model. To research Higgs boson and new physics beyond standard model, a cleaner process by using an electron-positron collider is necessary. The Higgs boson energy is 125 GeV and therefore the center-of-mass energy of more than 250 GeV must be needed for next electron-positron collider. While the electron-positron circular collider (FCC-ee [1], CEPC [2],) with a center-of-mass energy of 250 GeV has been proposed in recent years, the linear collider such as ILC [3], CLIC [4] and C^3 [5] is the electron-positron colliders that can reach energies in the 500 GeV to 1 TeV range. At present, the circular electron-positron colliders are difficult to reach higher center-of-mass energy than 350 GeV at present due to the severe synchrotron radiation loss. The International Linear Collider (ILC) has been proposed as a global project for a long time and is being developed worldwide. ILC published its Technical Design Document (TDR) in 2013 [3], demonstrating the fundamental technologies for the Higgs Factory.

Figure 1 shows a schematic view of ILC. Table 1 shows the basic parameters of ILC. ILC used the superconducting RF technologies and total length is 20 km for 250 GeV center-of mass (CM) energy to make compact Higgs factory with the luminosity of more than 1×10^{34} cm^{-2} s^{-1}. This luminosity is realized by focusing high-current electron and positron beams to less than 10 nm in vertical on the collision point after producing low emittance beams in the damping rings. The excellent merit of linear collider is the extendibility for higher energy than 250 GeV of CM, which will make new era for high energy physics.

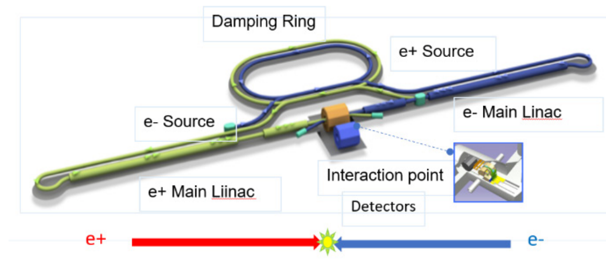

Figure 1: Schematic view of ILC.

Table 1: Basic Parameters of ILC for 250 GeV CM

Parameters	**Value**
Beam Energy	125 GeV (e+) + 125 GeV(e−)
Luminosity	1.35×10^{34} cm^{-2} s^{-1}
Beam rep. rate	5 Hz
Pulse duration	0.73 ms
# bunch / pulse	1312
Beam Current	5.8 mA
Vertical beam size (y) at interaction point	7.7 nm
SRF Field gradient & Q-values	< 31.5 > MV/m (+/−20%) $Q_0 = 1\times10^{10}$
AC-plug Power	111 MW

Table 2: List of Work Package-Prime

WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	Electron source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	DR System design
WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

In recent years, the International Development Team (IDT) has been established to promote the development of

† hiroshi.sakai.phys@kek.jp

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the ILC [6], and the ILC technology network (ITN) has been proposed to promote the development of critical accelerator technologies necessary for the ILC [7]. The most important development accelerator technologies in the ITN are "Superconducting RF (SRF) cavity technology", "Nano-beam technology", and "electron/positron particle generation technology" as categorized to work-package prime (WPP) listed in Table 2 to be selected as urgent and important R&D accelerator technologies to realize ILC construction. In Fig. 2, the orange shows SRF technologies. The green shows source technologies. And the bule shows the nanobeam technologies.

Three work packages are listed for the SRF parts of the project. WPP-1 will demonstrate that high-performance cavities can be manufactured worldwide. WPP-2 will finalize the design of a cryomodule for ILC and peripheral equipment such as input couplers, tuners and so on. WPP-3 is prepared for the development a crab cavity to be placed near the electron-positron collision point.

Seven work packages are listed for source. Electron sources, which need high polarization more than 80%, listed in WPP-4. Two methods proposed for positron production. One is the undulator based positron source, which can make polarized positron by the irradiation high energy gamma-ray produced by undulator with 125 GeV electron beam, are listed in WPP-5 and WPP-6. The other is electron driven based positron source are listed from WPP-7 to WPP-10.

For nanobeam development, WPP-12 and WPP-14 listed for damping ring and WPP-15 and WPP-16 listed for final-focus system. These are developed at KEK-ATF facility [8]. Finally, WPP-17 listed to develop main dump.

Under the ITN, we have much progress about accelerator developments with international collaboration. Especially, we held the ITN Information Meetings every year from 2023. Figure 2 shows our progress on ITN in 2024. Most of WPPs are in progress under ITN scheme. For WPP-1&2 (SRF cavity, CM), single cell cavity production in Korea/Europe started. JAI (UK) started WPP-14 (DR Injection/extraction) with synergy of Diamond Light Source upgrade. For WPP-15 (Final Focus System), European and Korean researchers have joined to the KEK-ATF experiments since 2023. Especially, many R&D are on-going by the help of MEXT-ATD program in Japan, whose budget was approved from 2023 to 2027. On next section, we will pick up our progress of R&D about SRF, positron source and nanobeam under ITN with this MEXT/ATD program in Japan in details.

Figure 2: ITN in progress in 2024 on each WPP.

THE LATEST R&D ACTIVITIES ON ITN

In Japan, the development of accelerator technologies is conducted by the approved budget from 2023-2027 as "Advanced Accelerator element Technology Development" by Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan (called MEXT-ATD program). This activity overlapped with ITN WPPs as follows

1) Superconducting RF accelerator (SRF)
2) Sources
3) Nanobeam

Superconducting RF Accelerator (SRF)

We will try cost-effective cavity fabrication and realize high-gradient and high-Q cavities and cryomodules based on a globally common design. With the latest surface treatment technology and improved magnetic field environment, the average field performance of 35 MV/m (range: +/− 20%) with high Q-value of 1.0×10^{10} will be achieved in the vertical test. Our target of WPP-1 is to demonstrate 35 MV/m (range: +/− 20%) with high Q-value of 1.0×10^{10}.

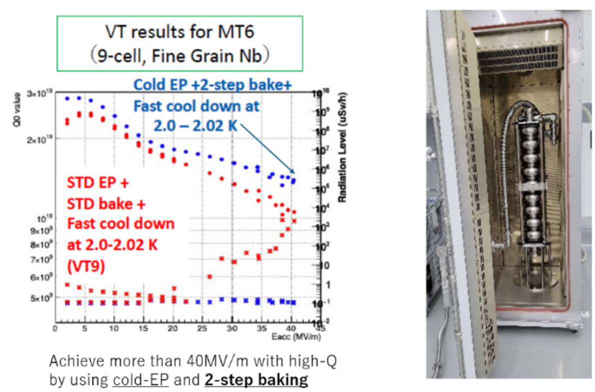

Figure 3: The results of vertical test by using 2-step baking method (left) and cavity heating system for 2-step baking in a clean room (right).

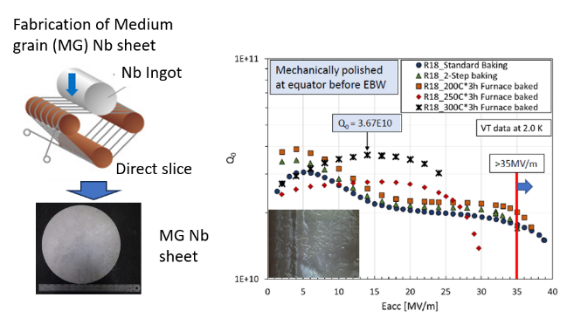

Figure 4: Fabrication method of MG Nb sheet (left). Results of vertical test of single-cell MG cavity (right).

The recent surface treatment technology based on the low temperature electropolishing, and 2-step baking improved the cavity performance. For example, 2-step baking treatment, in which the temperature is controlled by changing the temperature in two steps of 75 ºC and 120 ºC, resulted in an accelerating gradient of 40 MV/m with higher Q-value of more than 1×10^{10} as shown in Fig. 3 done in KEK for 9-cell Nb cavity [9]. We also try to use the low-

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cost niobium material for cavity fabrication by using medium grain (MG) Nb sheet. Merit of MG sheet is expected to be cheaper than FG (fine grain) sheet, which is normally used for Nb cavity, due to the simple slicing method from Nb ingot. But it seems difficult to fabricate cavity. Therefore, we need to check this MG cavity performance. Figure 4 shows the results of vertical test of MG cavity. More than 35 MV/m with more than 1×10^{10} of Q-values achieved with this MG cavity in KEK [10]. MG cavity study was also done by Korea University and obtained good performances with high-gradient and high-Q under ITN in KEK [11].

From these results, now we performed 9-cell cavity fabrication under ITN collaboration. 2 MG 9-cell cavities are under fabrication in KEK. More than 6 FG 9-cell cavities are under fabrication worldwide to be installed in one cryomodule in KEK. These cavities need to satisfy the Japanese High-Pressure Gas low. Therefore, cavity design through international collaboration with three regions of EU, US and Asia is necessary. For these cavity fabrications, EU contributes the fabrication of 9-cell cavities under ITN collaboration [12].

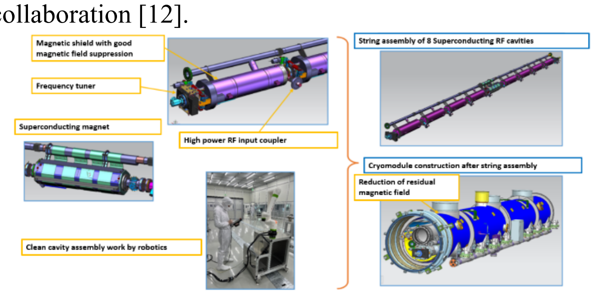

Figure 5: Development of cryomodules incorporating SRF cavities and sub-components.

For WPP-2, we will design the ITN cryomodule. However, the cavity performance test is also important after cryomodule assembly to fulfill our target of ILC of average gradient of 31.5 MV/m with Q-values of 1×10^{10} with 8 cavities in one cryomodule. For MEXT-ATD program in Japan, we will proceed cryomodule test with eight ITN 9-cell cavities. For obtaining the improved higher performance of the cryomodule, we developed the sub-components, which is essential for cryomodule assembly, as shown in Fig. 5. These sub-components basically consist of superconducting magnets, magnetic shields, frequency tuners, and input couplers. The clean cryomodule assembly work has been performed manually at present to keep higher cavity performance. However the key to the work (connecting parts with clean condition) should be replaced by robots to improve the quality of the work not to degrade the cavity performance under string-assembly work. Finally, we will perform the cryomodule test and evaluate our cavity performance in the cryomodule. These activities about sub-components, assembly work, refrigerator system and RF system will be totally evaluated through this cryomodule test in KEK.

Concerning about WPP-3 of crab cavity, two types of crab cavity will be tested under ITN (basically in EU and US).

Sources

For electron source, the development with 80% polarization was already done [3].

For positron source, there are two-type positron source; undulator type and electron driven type were proposed as shown in Fig. 6. The undulator type positron source is the baseline of ILC positron source. For undulator type, 125 GeV electron beam pass through helical undulators, and produces gamma rays, which hit the target and finally positrons are produced. This method can create polarized positrons (30%). However, 125 GeV electron beam, which produced at ILC electron source, is needed to create positrons on this method. For electron driven (e-driven) method, 3 GeV electron beam hit the target to produce positron. Merit of this e-driven method is that high-energy electrons are not required, and the commissioning of the positron source is independent from commission of main linac.

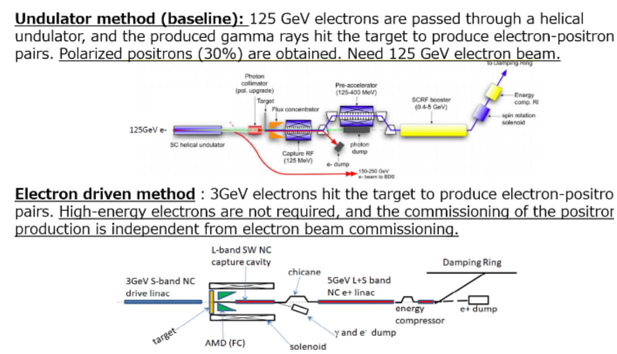

Figure 6: Two types of positron sources for ILC.

Requirement of positron source for ILC is a few tens of times larger than previous SLC positron source [13]. Both of positron sources need to develop new rotating target, which must be robust for both heat load and radiation damage. Sophisticated design of flux concentrator, capture cavity and solenoid are also important.

For the development of the undulator-type positron source, the rotating target of magnetic bearings and target tests have been performed mainly in Europe [13]. We are proceeding with the detailed technical design of the radiation-cooled rotating target and testing the prototype of the rotating target.

For the development of e-driven positron source, a set of key components are under fabrication under MEXT-ATD program in Japan. Figure 7 shows a cross-sectional view of the protype of the e-driven positron source [14]. The design is based on the experience of Super-KEKB positron source, which is the most intense positron source in operation. Compared with the positron source for Super-KEKB, the e-driven positron source for ILC requires 24 times higher electron beam power on the target. For this reason, we developed a rotating target system to reduce the heat load in target. We also design to use L-band accelerator RF structure to enlarge the physical aperture to obtain large acceptance of positron beam and reduce the heat load especially on the iris of the cavity by electromagnetic shower coming from the target via e+,e- pair-creation.

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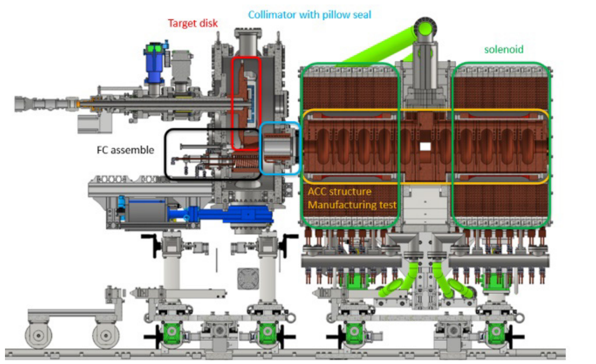

Figure 7: A cross-sectional view of the prototype of e-driven positron source in KEK.

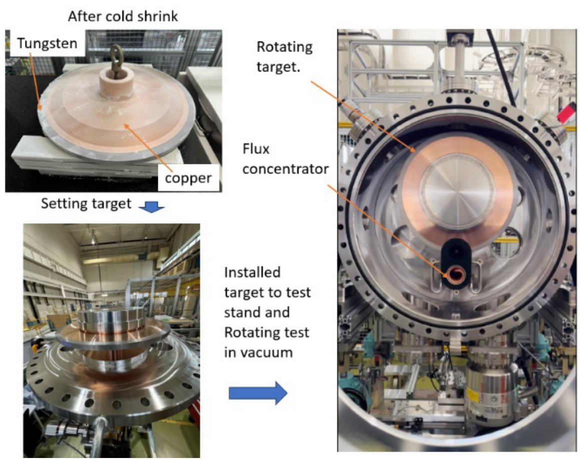

Figure 8: Test of rotating target system.

To evaluate this sophisticated design for e-driven positron source, we started to fabricate the prototype in KEK. Figure 8 shows the test of rotating target system. The target disk is made of W-ring which is fitted to Cu-disk by cold shrink method. The target disk is attached to the rotating system and installed in a vacuum chamber in the test bench with flux concentrator. To achieve the required vacuum condition, a three-stage differential pumping system is adopted. The latest experimental results show that the ultimate pressure is around 10^{-6} Pa level, with the target disk rotating at the speed of about 200 r.p.m with cooling water flowing.

In 2025, we fabricate the solenoid and accelerating structure and plan to test these components and continue the detailed simulation for positron production [15]. Significant advancements have been achieved in the installation, design, and testing of key components in this positron source demonstrator.

Nanobeam

For ILC, the electron and positron beam emittances are reduced to the same order of the latest 3rd and/or 4th generation light sources by 5 GeV damping rings. These small beam emittances keep the main linac, which beam size is about a few 10 micron-size horizontally and a few micron-size vertically. After beams are accelerated to 125 GeV, the beam sizes are squeezed into 580 nm horizontally and 7.7 nm vertically with well optimized final focus beam optics. To demonstrate these small emittance and final beam optics, the development of nanobeam is basically performed in KEK-ATF. Figure 9 shows the schematic view of KEK-ATF. The KEK-ATF consists of 1.28 GeV S-band linac, 1.28 GeV damping ring and final focus beam line (named as ATF2 beam line), which applied the same optics for ILC. This means that 37 nm vertical beam size is our target in ATF2 beam line. The extremely small emittance was achieved in the damping ring [16] and 41 nm beam size was achieved in ATF2 beam line [8] in 2016. Now we kept studying to reproduce this beam size of 37 nm in ATF2 beam line stably with comprehensive understanding about the corrective effect of wake field effect and non-linear effect of beam line. Therefore, our target of ITN is to stabilize this small beam size of 37 nm for a long time in KEK-ATF at a final focus point. For this purpose, the developments of hardware components such as magnet and chamber and kicker system, RF system and beam instrumentation are conducted for producing extremely small vertical emittance beams.

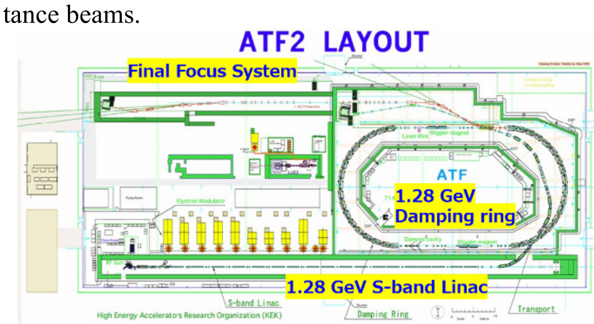

Figure 9: The schematic view of KEK-ATF.

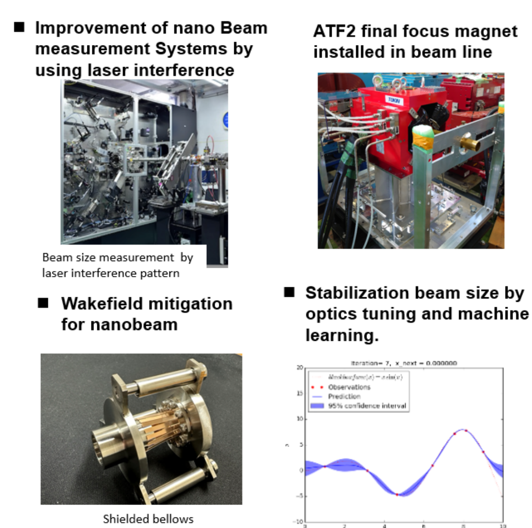

Figure 10: The improvements for realization of small beam size in ATF2 beam line.

Under MEXT-ATD program, recently we tried to realize the small beam size of 37 nm with many hardware upgrades. Figure 10 shows the preparations about the improvement of hardware and beam tuning method for realization of small beam size in ATF2 beam line. This small

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vertical beam size was measured by the laser interferometer in ATF2 beam line [8]. To measure this beam size more stably, we are improving the laser for this laser interferometer. To demonstrate higher-order aberration correction for nanobeam generation, the multipole magnets of ATF2 beam line were renewed. We also prepare the precise movers for these magnets. A machine learning study for nanobeam generation was performed for beam size tuning and stable beam transportation from Linac to damping ring shown in bottom-right figure in Fig. 10. We also prepared a new kicker ceramic chamber for stable beam extraction from damping ring to ATF2 beam line. RF stabilization was applied by the improved LLRF system from Linac to damping ring [17]. After these improvements in 2025, we will perform nanobeam generation with good stability.

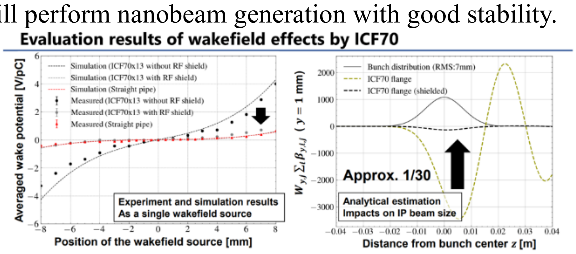

Figure 11: The improvement for realization of small beam size in ATF2 beam line. (left) measured results and simulation of wake potential of with/without flange compared with horizontal position of beam position. (right) simulated wake function with/without flange along the bunch profile.

We also tried to reduce wake field effects for nanobeam generation. To evaluate what components are crucial for the mitigation, we prepared the test chamber of wake field measurements in ATF2 beam line [18]. Figure 11 shows the measured results of wake field with/without RF shield of ICF flange. Simulation results are also plotted. Simulation and measurement agreed well with each other, and the wake field was drastically reduced by applying the RF shield to ICF70 flange. By using this test chamber, we understand that the precise alignment of each component and the smooth vacuum components in ATF2 beam line are important. In the Ref. [19], it is noted that this big wake field affected beam size growth in the final focus beam line. Finally, we replaced the suspicious vacuum components such as flange and bellows to the improved RF shielded flange and bellows as shown in Fig. 11.

We note that the nanobeam R&D in ATF are conducted under ATF international collaboration. In 2024, ATF operated in 20 weeks. During these beam times, Korea University, Univ. of Oxford, RHUL, IJC/Lab, IFIC, CERN contributed to perform the stable beam operation for nanobeam generation and prepared the beam position monitor in ATF. They also contribute the beam optics simulation for ATF and ILC.

Finally, we introduced WPP-17 activitiy. The main dump technologies in WPP-17 were based on water-dump, which is based on SLAC and JLAB technologies. The present design is that 18 MW of 500 GeV beam will be absorbed. The detailed design will be finalized under ITN.

FUTURE PROSPECTS

As mentioned above, ILC is one of the most promising linear colliders. Recently, this ILC cost estimate was just updated in 2024 [20]. Now the upgrade of linear collider is discussed under LC vision program by using the advanced technologies [21]. When the advanced technologies such as high-gradient and high-efficient cavity technology will be matured, we can extend the CM energy of 500 GeV or 1 TeV. We need to continue our accelerator R&D mentioned above for not only the realization of ILC but also the future upgrade of linear collider.

Furthermore, these accelerator R&D such as SRF, positron and nanobeam technologies will give synergies to the other scientific fields. For example, R&D for positron source production directly influenced not only linear collider but also future circular collider. Furthermore, these R&Ds will be applicable for the slow positron irradiation for material science. We note that the matured SRF technologies of elliptical 9-cell cavities (so-called TESLA cavity) based on ILC technologies have already given the large impacts to a XEFL production such E-XFEL [22], LCLS-II [23] and SHINE [24] and so on. Furthermore, ERL-based FEL such as EUV-FEL [25, 26] will be promising for the industrial application. R&D on nanobeam have many synergies for the latest 4^{th} generation synchrotron radiation facilities. We will learn low emittance generation technologies with each other.

CONCLUSION

The ILC is a very promising next-generation accelerator for energies higher than 250 GeV. ILC accelerator development is on-going under the framework of ITN and mainly supported on MEXT-ATD program, JFY2023-2027 in Japan. Until now, we conducted 3 critical accelerator technologies, such as SRF, positron and nanobeam under MEXT-ATD program in Japan. In addition, the three main developments are being carried out through ITN collaboration. We believe that these accelerator developments are crucial not only for the realization of ILC but also for the improvements of future accelerators and various industrial and medical applications.

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