THE e^+e^- LINEAR COLLIDER JLC

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Abstract

Since mid 1980s the accelerator technologies for JLC have been continuously developed. Feasibility of producing an ultra-low emittance beam has been successfully tested at the Accelerator Test Facility (ATF) at KEK. For the main linac system, both X-band and C-band RF-systems are developed to meet the requirement of urgency as well as the long term plan of the important physics programs. Now the basic components of JLC has been developed and the studies on cost reduction towards the engineering design has been started. JLC has to start operating around the same period when the high luminosity run of LHC will start in 2009-2010. The center of mass energy of the first phase JLC should be 250-500 GeV, which covers the expected thresholds of light Higgs boson and hopefully the light SUSY particles. The collider will be eventually upgraded to an energy greater than 1 TeV, hence the project is foreseen to be evolved for a quarter of the century from now. Considering the recent industrial development of the accelerator technology in Asia, the e^+e^- linear collider is an ideal project for the Asian high energy physics community to contribute to the world.

1 PHYSICS MOTIVATION OF LINEAR COLLIDER

It can perhaps be said that a revolution is at hand in Elementary Particle Physics. If the current understanding of physics is correct, the precise measurements in electroweak physics is suggesting the existence of a light Higgs boson. The presence of a light Higgs boson naturally leads us to a new paradigm beyond the Standard Model, which includes ideas such as Supersymmetry (SUSY) and a Grand Unified Theory (GUT). This may lead us to the realm of the Superstrings, in which gravity is unified with the other interactions, presumably near the Planck scale. The Linear Collider will play an essential role in exploring a new paradigm beyond the Standard Model[1].

There are several advantages in e^+e^- collisions compared to pp or $p\bar{p}$ collisions. Since electrons and positron are elementary particles, a new particle (or a pair of new particles) can be produced from the fundamental process of e^+e^- annihilation. These fundamental processes are directly observed by e^+e^- experiments. In e^+e^- collisions the center of mass (CM) energy of the fundamental processes is equal to $2E_{beam}$. Therefore four-momentum conservation can be applied for reconstructing the events[1]. e^+e^- collisions cross section for the main background process is about the same order as for the signal process[2]. Radiation level is significantly low except for the limited region very close to the interaction point. The event rate is several order of magnitude lower than for LHC because of the lower cross section for the usual processes and the long interval between the bunch trains. With the advantages given above, the new physics up to the CM energy, which can be increased step by step, can be discovered and studied at the e^+e^- linear collider. The aim of LHC experiments is to scan the distinctive new physics at the highest collision energies. Therefore, the physics complementary to those in LHC are the first target of the linear collider. In any case, the most crucial issue for the e^+e^- linear collider project is the accelerator technology and not the detectors.

Now it becomes a world-wide consensus in the high energy physics community that an e^+e^- linear collider is the next major high energy physics project. The Asian high energy physics community definitely needs an energy frontier accelerator in the near future. Considering the recent industrial development of the accelerator technology in Asia, the e^+e^- linear collider is an ideal project for the Asian high energy physics community to contribute to the world.

2 THE CONCEPT OF THE LINEAR COLLIDER

e^+e^- colliders which have so far been constructed are circular colliders, except for the SLC. The highest energy e^+e^- collider is LEP at CERN with a circumference of 27 km which recorded the maximum center-of-mass energy of 209 GeV. The high energy circular e^+e^- collider has a serious problem of energy loss by synchrotron radiation which is emitted when the beams are bent by the magnetic field to follow the nominal orbit in the circular beam pipe. The energy loss per one turn of the circular ring is proportional to the fourth power of the particle energy and inversely proportional to the bending radius of the ring. It is not economical to construct circular e^+e^- colliders above the LEP energies. Hence Linear Colliders, which do not suffer synchrotron energy loss, are required.

For the Linear Collider, the beam particles are accelerated to the full energy on a single path in the main linac. The acceleration gradient has to be high (30–100 MeV/m) in order to keep the collider compact. The R&D of the RF power system is therefore essential. To obtain a high luminosity for the experiments, the size of the beams (emit-

[1]Minor corrections to the e^+e^- collisions kinematics are initial state photon radiation and beamstrahlung effects, both of which can be evaluated with high precision. The beamstrahlung is a kind of synchrotron radiation. At the interaction point of e^+e^- linear colliders electrons (positions) emit synchrotron radiation during the collision due to electromagnetic (several kilo Teslas) created by on coming beam.

[2]For example $\sigma(e^+e^- \rightarrow ZH)/\sigma(e^+e^- \rightarrow ZZ)$ is about 0.2 pb/0.6 pb $\approx 1/3$ for $\sqrt{s} = 250$ GeV and $m_H = 120$ GeV.

tance) has to be small, since the repetition rate and the number of electrons or positrons per bunch are limited by the RF power.

3 THE PHYSICS PROGRAM AND THE SCHEDULE

The design concept of the $\mathrm{e^+e^-}$ Linear Collider and its upgrade program have to be determined by the physics capability considering the timing of the project, and the available technology at the time. The study of the light Higgs boson is the most urgent and crucially important subject in determining the direction of Elementary Particle Physics in the near future. The physics threshold unambiguously known is the top quark pair production. Therefore the center of mass energy of the LC should be 250–500 GeV where these urgent and critical physics is expected. The SUSY threshold might also be reached by the 500 GeV Linear Collider. The $\mathrm{e^+e^-}$ LC must start operation when the high luminosity run of LHC starts around 2009–2010. To meet these targets within the relevant timing, the first phase Linear Collider should be constructed with minimum time duration and with relatively low construction cost. The first phase Linear Collider should therefore be designed with a basically existing technology which fulfills the energy and luminosity requirements for the physics program.

Contemplating on the past transitions between LEP1 and LEP2, and TEVATRON Run1 and Run2, it is expected to take at least seven years to fully study the physics in the energy range during the first phase. Now R&D on high gradient acceleration technologies are carrying out at KEK, SLAC and CERN. During the first phase, the R&D has to be continued and the upgrade strategy must be investigated by examining (1) physics results from LHC, (2) those from the initial runs of the Linear Collider, and (3) the status of the accelerator technology development at the time. The collider will eventually be upgraded to an energy greater than 1 TeV to investigate physics issues beyond LHC. Although it is not clear at the moment which accelerator technology is the best to reach above 1 TeV, we hope that further accelerator R&D for more than 10 years from now opens up the TeV energy range. Considering the whole program of the project, it is foreseen to evolve for a quarter of the century from now.

4 R&D ON THE LINEAR COLLIDER COMPONENTS

The Linear Collider is made up of three subsystems: the injector system, the main linacs, and the beam delivery system. Extensive R&D on each system and its components is going on towards the engineering design of the Linear Collider.

4.1 Injector System

In order to focus the beams to very small beam spots at the collision point, it is necessary to cool the beams to very small emittance in the injector system.

The injector system consists of beam sources, damping rings, injector linacs and bunch compressors. The Accelerator Test Facility (ATF) at KEK is a facility to test the feasibility of producing an ultra-low emittance beam as a prototype for the Linear Collider injector. ATF includes a beam source, an injector linac and a damping ring. For single bunch operation the horizontal emittance (ϵ_x) of 1.3–1.5 nm and the vertical emittance (ϵ_y) of 0.015–0.030 nm, both of which are world records, are obtained at ATF. These values already satisfy the specification of JLC [2]. Devices to measure very small emittance, such as a laser wire scanner, have been developed. The multi-bunch operation has started [3]. To obtain a smaller emittance beam without loss the gun and the buncher system are being improved. For this purpose a RF-gun is being tested. ATF operation and these tests are carried out by an international collaboration also involving universities.

Polarized electron beams are extremely useful for reducing the W-pair background and to determine the quantum numbers of new particles. For this purpose the polarized electron beam source has been developed. It uses the superlattice photo-cathode developed mainly at Nagoya University [4]. The polarization and the number of electrons per bunch have already reached the specification of the Linear Collider: the polarization is above 80% and the number of electrons per bunch is about 10^{10} with two bunches in a time interval of 2.8ns. Further improvement to the lifetime of the photo-cathode and a new laser system to generate the full multi-bunch are expected for the next realistic prototype of the polarized electron source which satisfy the full JLC specifications.

4.2 Main Linac

The main linac part of the Linear Collider is a repetition of thousands of accelerator units. Each unit consists of a power supply (modulator), klystrons, pulse compressor/distribution system and accelerator structures. Because of the large number of components for the main linac system, the Linear Collider should be designed taking into account the following items: (1) reliability, (2) stability, (3) easy maintenance, (4) easy operation, (5) high efficiency, and (6) low cost. To collect a high integrated luminosity, the first five items are all important. Because of the large number of RF units, a few components in the system can break down at any running period. The possibility of repairing these components in parallel to the physics run is required to achieve a high integrated luminosity.

The choice of the frequency of the RF-system for acceleration is very important. For low frequency machines, the acceleration field is lower and hence the length of the accelerator becomes longer and the construction cost becomes higher. However, the precision of fabrication and the alignment tolerance of the accelerator structures (cavities) can be attained easily, since the single bunch transverse wake field is lower. For a higher frequency RF-system the accelerating gradient is higher and hence the total length of the main linac is shorter, while the tolerance of the alignment and the fabrication precision becomes harder to achieve.

The RF-frequency currently used for various electron linear accelerators is the S-band (2.8 GHz). The S-band technology was established about 40 years ago, and it has had a long experience in various electron linear accelerators, such as the 2 mile linac at SLAC, the Photon Factory (TRISTAN/KEKB injector linac) and the ATF injector linac at KEK. KEK is developing both X-band (11.4 GHz) and C-band (5.7 GHz) RF-systems for the main linac. X-band and C-band frequencies are four and two times higher, respectively, than the S-band frequency.

Figure 1: X-band PPM Klystron: The second PPM-klystron designed by KEK has successfully achieved the output power of 73 MV with an efficiency of 54% and a pulse width of 1.4 μ.

The merits of the X-band are a high gradient and a high efficiency. To make the best use of these merits the high power RF-system as well as the precise machining and alignment of the accelerator structures are essential. Extensive R&D is therefore needed for each component and it has been carried out in close collaboration with Stanford Linear Accelerator Center and Protvino branch of Budker Institute of Nuclear Physics of Russia. The basic design of the X-band modulator based on the solid state switching device (IGBT) is completed, and the fabrication of the first module should start in 2002 [5]. The klystron with periodic permanent magnets (PPM) for a good energy efficiency has been developed. The second PPM-klystron designed by KEK has successfully achieved the output power of 73 MV with an efficiency of 54% and a pulse width of 1.4 μs [6]. The third PPM klystron has already been designed. The X-band uses the DLDS (Delay Line Distribution System) for the pulse amplification. The pulses from klystrons are divided sequentially into shorter ones and are distributed to different accelerator structures to coincide with the timings of the beams. Since the pulses are merely distributed to the accelerator structures, the energy efficiency of the system is high [7]. As for the accelerator structures, the technology for the precise machining and bonding of the disks to form cavities has been developed at KEK [8]. The test on the damping of the higher-mode wake-field in these structures is being successfully performed at ASSET, SLAC. In the high power test of these structures at NLCTA, SLAC, it was found that the inner surfaces of the copper structures are damaged after a long operation. To understand and to overcome this problem, extensive studies are being carried out under the collaboration of KEK, SLAC and CERN [9]. For this purpose, several different types of the accelerator structures are being tested and some hints to solve the problem are being seen in these studies.

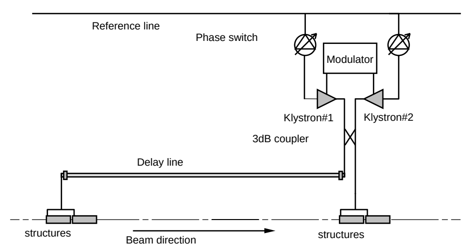

Figure 2: The concept of the Deley Line Distribution System (DLDS). This schematic diagram is for the simplest factor-2 DLDS. The current X-band design uses 2×2 DLDS. To reduce the number of waveguides TE_{01} and TE_{02} modes are fed into the same waveguide and each of the modes is extracted just before a coupler at an accelerator structure. Although DLDS is a quite complicated system, the power loss is small.

The C-band system is currently considered to be a realistic back-up for the X-band system, since the technology is more conservative. It is a relatively small technological extension to go from the S-band system to the C-band system. To make the system simple and reliable, several novel ideas have been invented and applied to the components. The modulator uses the inverter power supply for filling the energy into the L-C chain and a conventional thyratron switch for the pulse generation [10]. The C-band klystron has already satisfied the specification of 500 GeV LC, and the long term stability was tested with the modulator a few years ago [11]. A simple but novel pulse compressor, which improves the pulse height by a factor of 3.5 to 4, was developed and the principle of operation was proven in the low power test [12]. The high power test of the pulse compressor will soon be done at KEK. The accelerator structures, the so-called choke-mode cavities, in which the problematic transverse wake-field is absorbed locally inside the structures, was also developed at KEK [13]. The wake-field absorption was successfully tested at ASSET of SLAC. The design of the C-band accelerator structure takes into account the results of extensive high power tests on the S-band structures. Nevertheless the actual high power test and beam acceleration test of the whole unit of the C-band RF-system will be performed at the SCSS (SPring-8 Compact SASE Source) project[3]. Seeing that the components of the C-band main linac system already satisfy the 500 GeV LC specifications, the second phase R&D on mass-production and cost reduction have started. Civil engineering (tunnel, accelerator installation, electricity and cooling water supply) is also studied based on these working components.

To strengthen and to widen the technology of the main linac system, it is crucial to develop both X-band and C-band RF-systems in parallel. Since both designs use the warm accelerator structures, a common design and development of components such as the modulator are feasible, and this will contribute to the efficient execution the project. Both of the RF-systems are vital in order to meet the requirement of urgency as well as the long term plan of the important physics programs.

4.3 Beam Delivery System

The electron and positron beams from main linacs are delivered to the final focus system, where they are squeezed to have a small cross section and they finally collide with each other. At the collision point of the Linear Collider the beams are focused to a tiny size ($\sigma_x^*/\sigma_y^* = 200$–300 nm / 2.5–5 nm). Such a small beam size and the accurate beam position have to be measured and controlled. A series of tests on focusing the beam and measuring its size was performed by an international collaboration at FFTB (Final Focus Test Beam) in SLAC. For these tests the laser-Compton interferometer (Shintake-monitor) was developed at KEK and the tiny beam size was measured successfully [15]. The cavity type of the nanometer beam position monitor (cavity BPM) was also developed at KEK [16]. Therefore the basic instruments to measure the beam size and position already exist. Recently, there was a new idea on the design of the final focus system at SLAC. The design is based on a short length optics, and the length is almost independent of the beam energy.

[3] The SCSS project was approved by the Japanese government in 2001. The aim of the project is to construct a compact X-FEL facility. The C-band technology developed for the Linear Collider and the SASE (Self-Amplification of Spontaneous Emission) is planned to be used [14]. The undulator is installed inside the beam pipe aiming for very small magnet gaps to achieve an excellent coherence of the X-ray beam. The first step is to achieve the wave length of around 10 nm (water window) for studies on structural biology.

4.4 Site Studies

For a stable operation of the Linear Collider, the alignment of the accelerator structures is essential. The selection of a site with an acceptable level of ground motion and the development of a suitable alignment feed-back system are crucial for this purpose. Mountain ranges of stable granite rock are ideal considering the ground motion. There are several such candidate sites in Japan. These mountain ranges of granite rocks are quite stable even under big earthquakes. Preliminary site studies have been performed since 1993. From the summer of 2000, a new site study group was formed. Since then they have been studying the scientific and technological requirements of the site, such as the ground motion, the electricity and cooling water supplies, recent developments on tunnelling technology, the access to the site, as well as the sociological issues. The first report has been completed after one year of work. The second site study group was formed and they started evaluating several candidate sites after the first screening.

5 REASONS WHY THE ASIAN REGION NEEDS THE LINEAR COLLIDER

BEPC, KEKB and other accelerator-based Particle Physics in Asia have demonstrated the maturity of accelerator technology and High Energy Physics in this region. The economy, the science and the technology are growing rapidly. The immediate next step for us is to establish a new scheme for stronger collaboration and to create Asian laboratories that are open to all Asian and world scientists. Now we are confident that the time is ripe to go forward in this direction. In the past we only had TRISTAN as the energy-frontier machine in this region. It is a natural consequence for us, therefore, that we construct the next energy-frontier machine, the JLC electron-positron collider, in Asia.

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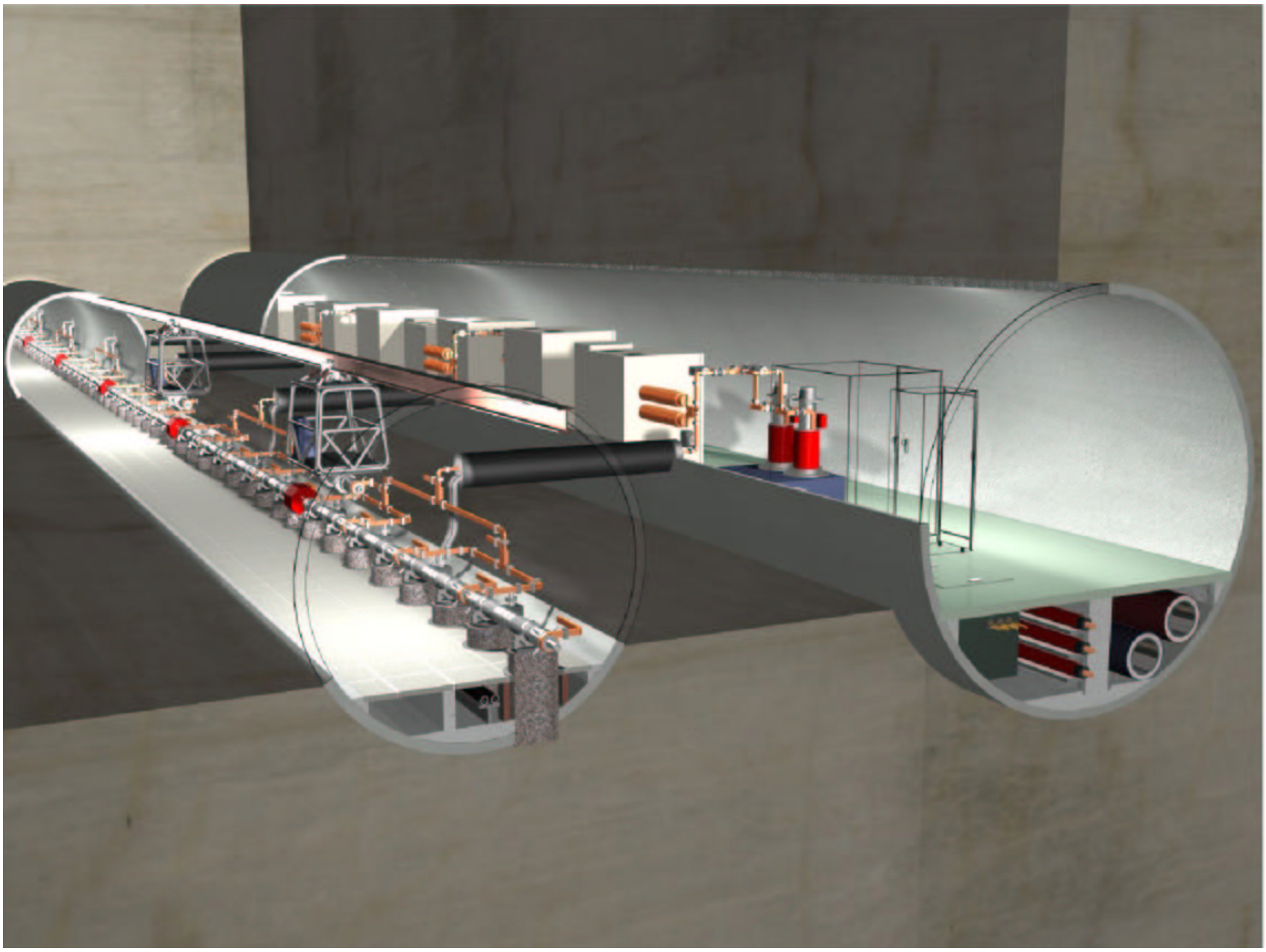

Figure 3: Layout of the accelerator components in the JLC tunnel: Modulators, klystrons and pulse compressors are installed in a tunnel and the accelerator structures are installed in the other tunnel. This system is designed based on the existing C-band components. The lines for electricity and water supply are also designed

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