Present Status of R&D for Linear Colliders

Koji TAKATA
KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305 Japan

Abstract

This review is concentrated mainly on the present status of linear collider R&D work done at KEK together with university teams. But it has been carried on in almost all areas under a solid frame of international collaboration. The KEK team prepared a design study note of an X-band TeV linear collider. We hope in a couple of years a more realistic engineering design will appear, which would lead to actual construction of such a collider early in 2000's.

1 Introduction

An electron-positron linear collider in an energy region on the order of 1 TeV in the center of mass energy (E_{CM}) is one of the energy frontier machines, its construction in early 2000's being eagerly awaited by high energy physicists. Linear collider designs for which R&D work is under way may fall into three categories which, respectively, are based upon normal conducting linac technologies, superconducting linac technologies and two-beam accelerator principles. R&D works along each lines have intensively been carried out at several representative laboratories all over the world for over 10 years. The first type has been considered mainly at KEK (Japan) under the name of JLC (Japan Linear Collider), SLAC (USA) under the name of NLC (Next Linear Collider), at DESY (Germany) under the name of SBLC (S-band Linear Collider) and BINP (Protvino, Russia) under the name of VLEPP. The second one at DESY(Germany) under the name of TESLA. The third one at CERN (Switzerland) under the name of CLIC and partly at LLL (Livermore, USA) under the name of TBNLC (Two-beam Next Linear Collider).

My talk will be mainly concentrated on the first type and particularly on the results ever obtained at KEK through collaboration with SLAC, BINP and other institutes both inside and outside Japan. For the R&D works of the other types, the reader may be referred to a report[1] and information on the Web[2] site. But at first I will make a brief review of results of all the three works.

2 Review of General Design Parameters

The most important parameter besides the energy E_{CM} is the luminosity given by

$$L \approx \frac{N^2 f_{rep} n_b}{4\pi\sigma_x\sigma_y} \qquad (1)$$

which is required to be on the order of at least several times 10^{33} $cm^{-2}s^{-1}$ at E_{CM} = 0.5 TeV and should be proportionately larger at higher energies, if searches for the Higgs boson and physics beyond the standard model should bring out meaningful results within several to ten years. In Eq. (1), N is the number of particles per bunch, f_{rep} the linac repetition rate, n_b the number of bunches per linac pulse and σ_x (σ_y) the horizontal (vertical) size of the bunch cross section at the collision point.

Parameters have been surveyed by primarily considering two important sociological boundary conditions: the total AC power ≤ a few MW and the length ≤ a few 10 km. Those are now not so much scattered among different design options. As a typical example, let us cite those studied at KEK[3] with the name JLC. Assuming an X-band (fRF = 11.424 GHz) main linac operating at a gradient of 56 MV/m, we have the following numbers: N = 7×10^9, frep = 150 Hz, n_b = 85, $\sigma\xi$ = 260 nm and $\sigma\psi$ = 3.1 nm. In most designs, two beams collide at an finite crossing angle of about several mrad, the bunch length σ_z is chosen around 100 μm in order to avoid a luminosity decrease due to an incomplete overlapping of two colliding bunches.

The very flat beam at the interaction point is a very conspicuous feature for any design option. It is to reduce the self magnetic field of a bunch and accordingly the pair creation rate by beam strahlung when a particle runs through an opposing bunch.

Figure 1 shows a schematic picture of the layout for the JLC. Basic ingredients are an injector, main linac and beam delivery line. The main component of the injector is a 2 GeV damping ring where beam emittances are damped enough so that the above small beam sized can be achieved at the interaction point. Beams for the damping ring are provided by an S-band linac of the same energy. For positron beams, another electron linac operating at around 10 GeV is necessary for positron production. Between the damping ring and the main linac, a bunch compressor section is necessary to reduce the bunch length by almost one fiftieth. The main linac is a simple sequence of a unit comprising four 1.3 m long X-band traveling wave structures and focusing quads. The beam delivery line comprises a scraper section where unwanted backgrounds are cut off and a matching section where bunch shapes at the linac exit are transformed into those required at the interaction point.

One of the most important requirements is severe alignment tolerances on the order of 0.1 μm to several μm for quads, position monitors and accelerating structures from the output of the damping ring through the main linac to the interaction point. Misalignments in those components would deflect particles in various ways, which results in emittance blow up at the interaction point.

3 Low Emittance Beams

In a linear collider complex, the damping ring is the only accelerator where beam emittances can be squeezed. In the main linac and beam delivery line, the normalized emittances ($\gamma\varepsilon$, where γ is the Lorentz factor and ε the actual emittance) are conserved as long as each components are completely aligned, otherwise an emittance blow up occurs to a degree depending on the magnitude of misalignments. The normalized emittances to achieve the above mentioned sizes of the beam cross section are $\gamma \varepsilon_x = 3\text{x}10^{-6}$ rad·m and $\gamma \varepsilon_y = 3\text{x}10^{-8}$ rad·m.

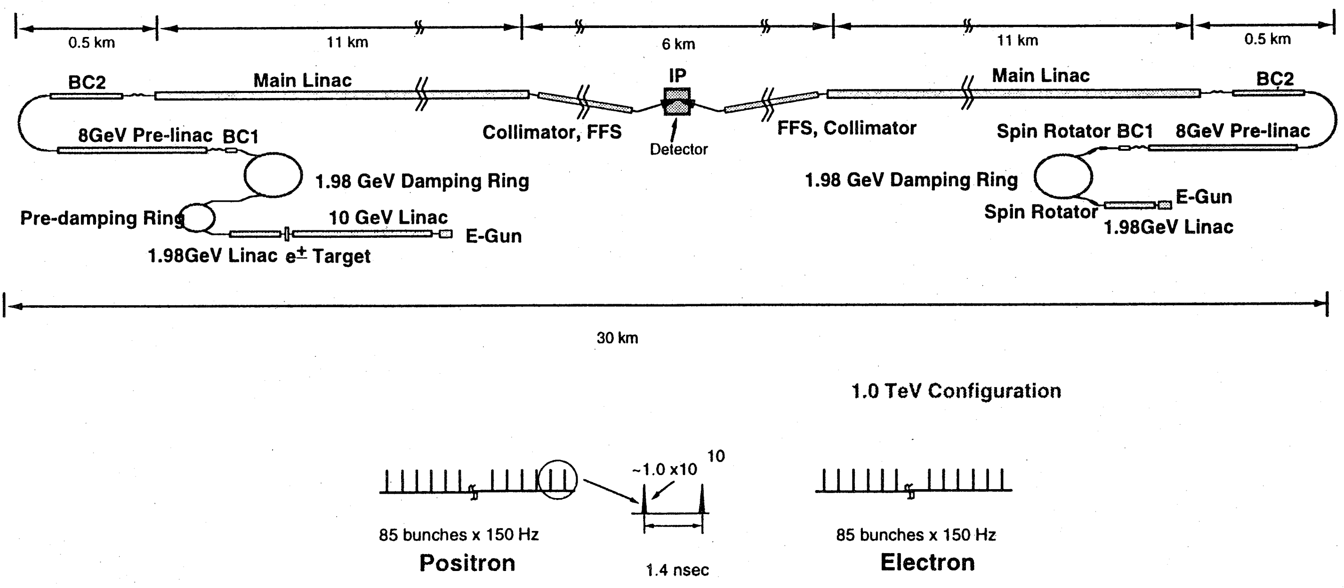

Figure 1 JLC general layout: 500 GeV JLC-1 → 1.5 TeV JLC

Therefore the damping ring is a very crucial element in a linear collider. But there was no ring which had achieved such small emittances. Hence one of the major R&D programs at KEK has been to construct a test damping ring and verify that those normalized emittances are actually achievable. Although an optimized energy is nearly 2.0 GeV, we started to construct a 1.54 GeV test ring because of a limited space, together with its S-band injection linac of the same energy at the KEK ATF(accelerator test facility) in 1990.

Since its commissioning started November 1995, the S-band linac was under operation until the end of June 1996. Then our efforts were directed toward commission of the damping ring, which started January 22, 1997. The operation was on a single-bunch mode at an energy of $\approx$ 1.0 GeV. On February 26, beam made 2 turns and on February 7, a stored current of 1 mA was attained with a life time of $\approx$1 sec. Now the ring is operated at an energy of 1.3 GeV with a single bunch of 7 x 10^9 electrons being stored.

In the following typical design features of the injection linac and test ring are summarized. For details the reader may be referred to a status report in this conference[4].

1 *1.54 GeV Linac*

The linac, being 90 m long, accelerates 20 bunches per pulse to 1.54 GeV with a bunch population of 2.0 X 10^{10} electrons and bunch spacing of 2.8 ns. In total 19 2856 MHz structures of 3 m in length are employed, among which one is a buncher and two are energy compensating structures (ECS), with the others regular structures. Every two regular structures are fed RF power by an 80 MW klystron, whose output pulses 4.5 μs in length are compressed into 1 μs pulses by a SLED system. The unloaded gradient of around 45 MV/m has been achieved without problems. The ECS is operated either at (2856-4.33) MHz or (2856+4.33) MHz, thus enabling to compensate an energy droop from the 1st to 20th bunch due to beam loading and also a droop inside individual bunches. Structures are aligned with an accuracy of 50 μm in order to get a normalized emittance of 3 x 10^{-4} rad·m or less.

At present the linac is being operated at a beam energy of 1.3 GeV, with an average accelerating gradient of 26 MV/m. The repetition rate is only 0.4 Hz contrary to a design value of 20 Hz due to radiation problems. The high radiation background may be arisen from beam energy tails which are expected to be cured by reinforcing the present 357 MHz subharmonic buncher system.

2 *Damping Ring*

A main function of a damping ring should provide beams of smallest emittances to the main linac at such a repetition rate as 150 Hz. Since the natural emittance is proportional to γ^3, a low energy ring is preferred. But the damping rate decreases similarly. A ring of too low an energy suffers also a short Touschek life. Therefore a compromise is made at an energy around 2 GeV, with adding damping wigglers to make the damping time shorter. A FOBO lattice is employed at the ATF ring, where the bending magnet is of a combined function type with a defocusing component. For a lattice of this type the betatron dispersion function η is made very small at a bending magnet where particles emit synchrotron radiation and thus small emittances are achieved. By considering possibilities of handling polarized particles, the energy are chosen as 1.54 GeV, 1.98 GeV, 2.42 GeV···· , at which the spin depolarization is most invulnerable, while particularly for the ATF ring the energy is 1.54 GeV.

The presently achieved beam parameters are as follows where the numbers in parentheses are the target values: beam energy = 1.3 GeV (1.54 GeV), bunch population = 7 x 10^9 (2 x 10^{10}), injection rate = 1.65 Hz (25 Hz), RF voltage = 200 kV (800 kV), horizontal/vertical COD's = 6 mm (1 mm), tunes at $\nu_x = 14.2$, $\nu_y = 8.4$, $\nu_z = 0.005$, beam life time ≈ 120 sec (80 sec), damping times with wigglers on τ_x = 18 ms (6.8 ms), τ_y = 41 ms (9.1 ms), τ_z = 18 ms (5.5 ms), bunch length = 7 mm (5.8 mm), emittances $\varepsilon_x \approx 1.7 \times 10^{-8}$ rad·m (1.4 x 10^{-9} rad·m) and ε_y ≈ 2.0 x 10-9 rad·m (1.0 x 10^{-11} rad·m).

3 Polarized Sources

The availability of polarized beams would be of vital importance for high energy machines. I would like to stress that a great contribution was made by a Japanese team[5] in developing polarized electron sources using strained GaAs layers or superlattices. Guns based on that technique is now incorporated into SLC and routinely operated with a high and stable polarization.

For polarized positron generation, an idea based on pair creation through compton scattering with circular-polarized laser lights[6] has been pursued at the ATF.

3 Main Linac

JLC as well as NLC assumes a main linac operating at 11. 424 GHz, 4 times the S-band frequency 2856 MHz. The most typical feature of accelerating structures for a linear collider is a relatively large ratio of the aperture radius to wave length, a/λ, compared with conventional linacs. It is because short range transverse wake fields, which are excited by off-centered particles, are proportional to a^{-4} and as large an aperture radius a as possible is required to make an emittance blow-up of individual bunches as small as possible.

A beam blow-up in a bunch train has to be also considered. Regarding this effect, long range wake fields should be made smallest in the time length of one train (about 120 ns). Since a dominant component of the long range wake is the TM_{11} mode, structures under consideration are made to have a cell-to-cell dispersion of the TM_{11} resonance frequency so that contributions of each cells are canceled out as a whole. Such a structure, called DS (detuned structure), is similar to a constant gradient (CG) structure where the aperture radius is made gradually smaller for a cell farther from the structure entrance. Such a modification of cell dimensions is optimized to get ever smaller TM_{11} wake fields for a DS, while it is to get a uniform acceleration field for a CG structure. A similar type of structure, called DDS (damped detuned structure) is also under development. It has not only the cell-to-cell TM_{11} frequency dispersion but also a small damping port at each cell to lower external Q's of transverse modes.

The a/λ range for the JLC design of a 1.3 m long structure is from 0.20 at the structure entrance to 0.14 at the exit with an average of 0.166. With such a rather large aperture and a high accelerating gradient as described above, the peak power of input pulses to each structures has to be as high as 130 MW. A single klystron is practically unable to cope with such a high rating. It is rather essential to add some pulse compression system between a klystron and structures to enhance the peak power by reducing the pulse length. The SLED system is a typical one. Pulse shapes of a SLED is too spiky and not fitted with linear collider linacs. Several improved versions have been invented to get flat pulses: BPC (binary pulse compression), SLED II, VLEPP open resonator and DLDS (delay line distribution system). The last one is now being seriously considered for JLC as well as NLC, whose technical features are discussed below.

Taking those factors into consideration, we have a design scheme for a unit of the JLC main linac as shown in Figure 2.

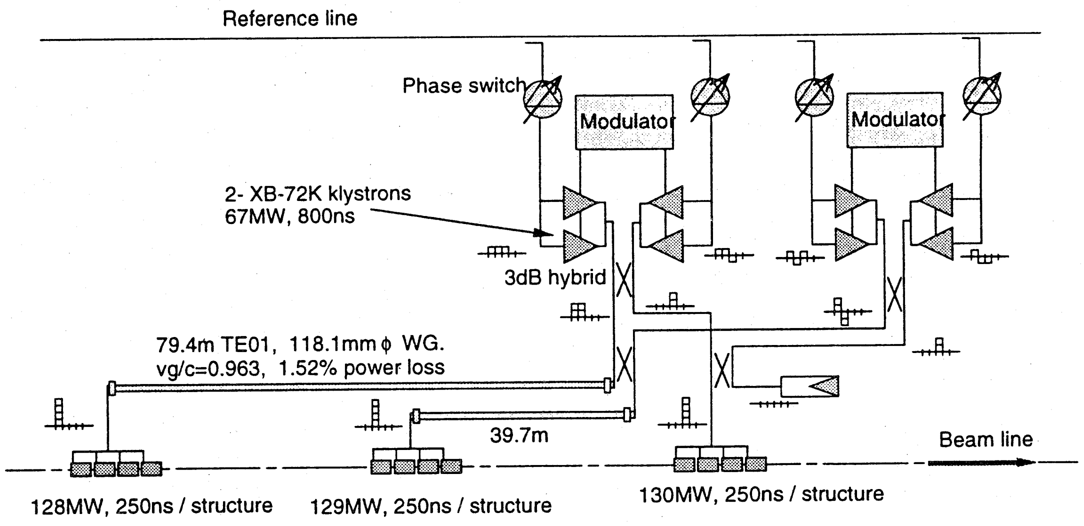

Figure 2 Unit of the JLC main linac with a 4/3 - DLDS

1 *Accelerating Structure*

The 1.3 m long JLC DS is of a conventional 2π/3 TW structure with a pitch of 8.75 mm and the aperture a varying from 5.23 mm to 3.67 mm. The average shunt impedance is about 75 MΩ/m and filling time around 106 ns. The frequency distribution of the TM_{11} mode over 150 cells is such that a gaussian σ of about 2% is achieved around 15.5 GHz. Each cell is fabricated from OFHC copper with an accuracy better than 1 μm by fine machining processes developed at KEK. Most cells for the DDS's installed at the SLAC NLC Test Accelerator Facility (NLCTA) were also machined in the same way in Japan. In order to stack cells together into a 1.3 m structure, a diffusion bonding technique is used which is absolutely free from any brazing materials. The technique, developed at KEK, has successfully been applied for several JLC DS's. The diffusion bonding was also applied at SLAC to stack DDS cells machined in Japan.

Our most concern is the long range transverse wake field. With one JLC structure, the wake was measured at the ASSET facility in the SLC of SLAC last summer. At the experiment a leading bunch passes through the structure at a off-axis position. Transverse wake fields generated thus are measured by a trailing monitor bunch injected into the structure at various timings. Field patterns in time domain were in a good agreement with simulation results obtained by codes in independently developed at SLAC and KEK[7].

High gradient test have been carried out for shorter (about 30 cm) structures and there are no serious problems encountered in order to achieve the above mentioned design values.

2 *RF Source*

Klystron

For JLC, a klystron with a peak output power of 67 MW and pulse duration of 750 ns is under consideration. The output is distributed to 4 accelerating structures after a four-fold compression through the DLDS. The tube is expected to operate at a beam voltage of 430 kV and a current of 338 A (micro-perveance = 1.2) for the above output rating. The current is produced by an Iridium coated matrix cathode 72 mm in diameter. In order to save the power loss at focusing solenoids, a PPM (periodic permanent magnet) focusing scheme is conceived, though all test tubes fabricated up to now have used conventional solenoids.

There are three key technical issues for completing a klystron of the above ratings: dc beam generation, output cavity, and output window. With respect to the first issue, dc beam powers of 330 MW with 2 μs duration at a beam voltage of 600 kV, generated by the 72 mm diameter cathode, have been successfully transmitted through the drift tube 10 mm in diameter and 40 cm in length. As for output windows, we are using two output windows of a TE_{11} mode type with tapered section to reduce electric field intensities on the ceramic surface[8]. It has been shown that a single window of this type can be operated at ratings of 84 MW and 700 ns, which is well above the design values.

The most serious problem as yet not fixed is that of the output cavity. For a single cell cavity, we achieved only 30 MW x 100 ns rating levels, where surface breakdowns limit a further increase of power. In order to reduce the surface fields, we are now testing a traveling wave structure comprising 4 to 5 cells with larger apertures. With this new structure, it seems promising to fix breakdowns. But the dc power to RF power conversion efficiency is yet so low as around 25%. It seems to critically depend on beam-cavity interaction behaviors at the output cavity. Only one dimensional codes are available to simulate the interaction in multi-cell structures. But a 3 dimensional treatment is indispensable for such high density beams in these extremely high power klystrons and preparations are being made to install a 3D code MAGIC.

A short review of klystron R&D results at SLAC may be made herewith. At the same X-band frequency, several tubes with a solenoid focusing (type XL4) have been fabricated which stably produces 75 MW, 1.1 μs output pulses at a repetition rate over 60 Hz and an efficiency of 48%. SLAC has developed also a PPM tube which produces 56 MW, 1.1 μs output pulses at an efficiency as high as 60%. These good results seem solely due to full exploitation of a 3D code.

Modulator

Efficiency improvement is also an essential issue for modulators. Energies contained at the rising and falling parts of a pulse are not negligible for conventional modulators where the ramping time is typically over 500 ns. Since for the JLC design the flat top length is only about 1 μs, it would considerably improve an overall efficiency if shorter ramping times are achieved.

For this purpose, modulators with a Blumlein PFN have been developed[9]. With the step-up ratio of the pulse transformer being halved in this scheme, the rise time can also be approximately halved. A modulator of this type has actually been routinely used with a rise time less than 300 ns to test the X-band klystrons.

Power Distribution

The idea of the DLDS for RF pulse compression was conceived at KEK[10] and some preliminary R&D work is under way. A unit comprises 2^n klystrons whose output powers are combined with 3-dB couplers as shown in Figure 2. The output pulse is segmented into m sections in the time domain where $m \leq 2^n$. Thus we have m pulses with a pulse width of 1/m of the original one with a peak power multiplied by the factor 2^n. A segment with an early timing is sent upstream of the linac with an oversized round waveguide. This system uses no resonant element as SLED II or others do, thus of only concern being power losses in waveguides and 3-dB couplers which would be made very small.

The JLC design chooses the case with n=2 and m=3, dubbed 4/3 DLDS. As shown in Figure 2, a waveguide is as long as 80 m. This arises an issue of how to achieve a sufficient phase stability in such a long transmission line. It is being considered to use waveguide materials like super-invar which has a very small thermal expansion coefficient and also to use a signal RF of another frequency as a reference.

3 *C-band Alternative Technologies*

As a backup technology to the X-band ones as described above, a test linac unit operating at a C-band frequency of 5.712 has also been under development. It comprises a pulse compressor of coupled cavity type which makes a SLED II pulse line much shorter, a heavily damped accelerating structure of choke-mode type and klystrons generating 50 MW x 2.5 μs pulses[11].

4 Final Focus

Experimental studies have been carrying on by using 46.6 GeV electron beams at the FFTB (Final Focus Test Beam) facility at SLC of SLAC. It is a test stand, designed, constructed and commissioned by a world wide linear collider community. The Japanese group contributed in the optics design, construction and installation of the final quad family, a beam profile monitor and a precise beam position monitor, and a series of beam studies in commissioning including beam tunings.

In May 1994, a spot size was measured to be as small as 70 nm by a novel profile monitor based on compton scattering from a standing wave of a laser light[12]. An RF cavity type beam position monitor was also tested yielding a resolution of 30 nm. Focused spot sizes were found larger than predicted from linac emittances. Furthermore they can not be extrapolated to 0 in the 0 emittance limit. This problem is not yet fixed and is intensively surveyed by the Japanese team.

5 Civil Engineering

Basic studies are launched to survey reliable and economic methods to construct a tunnel as long as 30 km or more[13]. At present the following two methods seem promising: NATM (New Austrian Tunneling Method) and TBM (Tunneling Boring Method). In the first method, a tunnel is made by blasting with explosive materials, then spraying shotcrete and left for a while until walls became mechanically stable through a redistribution of rock stresses. In the second method, a full-aperture boring machine continues to excavate the tunnel, with concrete linings being followed afterwards. The tunnel cross section would be an elliptic one with a flat floor in the case of NATM while a circle in the case of TBM. In both cases, however, a good waterproofing is a serious issue not only for avoiding underground water contamination but for guaranteeing a solid support for linac structures.

6 International Collaboration

R&D work has been carried out under intensive international collaboration. In the design and commissioning of the ATF accelerator complex, many researchers of oversea institutes have been and will be eagerly participating, among whom SLAC people are playing a dominant role. For the construction of X-band structures, we are tightly coupled with SLAC team. At high gradient tests of X-band structures, people from CERN and IHEP (Beijing) contributed a lot. For wake field calculations, we got contributions not only from SLAC but from Tsinghua University (Beijing). For S-band and X-band klystron development, a lot of technical information was brought from SLAC and BINP. Particularly in developing X-band klystrons, BINP has contributed at designs of output cavities and windows together with developing many waveguide components. A prototype DLDS will be constructed at a 120 m long tunnel at BINP by a joint team of BINP, KEK and others.

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