Review of Linear Colliders

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Abstract

This paper describes the status of R&D of future e^+e^- linear colliders proposed by the institutions throughout the world.

1 INTRODUCTION

The third international workshop on linear colliders, LC'91, was held at Protvino from September 17 to 27 in 1991. It was really exciting workshop and many fruitful results of research and development were reported. The linear collider projects, CLIC, DESY/THD, NLC, JLC, VLEPP, and TESLA have been in new stage to design the realistic machines beyond the technological feasibility of new accelerators [1].

2 BASIC APPROACH

2.1 Center of Mass Energy

Due to synchrotron radiation losses, the energy of e^+e^- ring colliders cannot be significantly increased beyond the energy of LEP-II, which is designed for 200 GeV center of mass energy. Linear colliders are only remained accelerator to reach center of mass energy higher than LEP-II. The designed beam energies of linear collider projects thorough out the world depend on physics requirements and time schedule of own project. On the earliest stage of the R&D in middle 80 s, designs were started with the energy range from 1 to 2 TeV center of mass energies.

Recent requirements of physics reduced the initial goal to a somewhat lower energy provided that the linear colliders can be realized in several years. The JLC, NLC, VLEPP and DESY/THD would be started from 0.5 TeV center of mass energies. The beam energy is achieved by RF acceleration at accelerating gradient and certain length of linear accelerators. The energy up-grade to 1.5 TeV can be realized by extending the length of linear accelerators [2] and increasing accelerating gradient [3] [4].

2.2 Accelerating Gradient

The total length of linear colliders is approximately given by the ratio of the center of mass energy to the accelerating gradient in the linear accelerators. The necessity of new acceleration methods which realize very high gradient was recognized in late 70 s. The broad theoretical and experimental studies on new schemes of acceleration were then started by using lasers, plasmas, wake fields and so on. Interesting theoretical and experimental studies were carried out to generate very high gradients in a very short accelerating distance. Recently it became apparent that new methods will need long developing years and the one and only method for TeV linear collider is the conventional radio-frequency acceleration.

The attainable accelerating gradient at S-band frequency is basically determined by the configuration of accelerating structures, klystrons and modulators together with power compression system such as SLED cavities. The optimum and attainable accelerating gradient of realistic S-band linear accelerators is ranging approximately from 20 to 30 MeV/m. In order to realize the gradient of 100 MeV/m, the RF frequency ranging from 10 to 30 GHz should be required. Moreover the higher RF frequencies are preferable to increase the RF breakdown limit in accelerating structures [5].

2.3 High Luminosity

The cross sections of electroweak interactions are proportional to the inverse square of center of mass energy and then the luminosity should be increased with the square of center of mass energy. The luminosities higher than several $10^{33}\ cm^{-2}\ s^{-1}$ are required ranging from 0.5 to 1 TeV center of mass. The luminosity is proportional to the square of particle numbers, N in a bunch and repetition rate of collisions, f at the interaction point and inversely proportional to the cross section of bunch beam at the interaction point. The maximum beam power accelerated by the linac is limited by the wall plug power. Therefore the luminosity is proportional to the particle number in a bunch and inversely proportional to the cross section of the bunch. To obtain the narrow spread of beam energies at interaction point, a flat beam is preferable to reduce the energy loss by beamstrahlung [6]. The low emittance beam is highly required to obtain small spot of beam at the interaction point. However the beam size would be limited due to the synchrotron radiation losses in final focus quads [7]. The precise alignment of linear accelerators is required to reduce the transverse beam instability and preserve low emittance throughout the linear accelerator. The theoretical and technical difficulties of future linear colliders are arose from the requirements of high luminosity and high accelerating gradient.

Table 1: Parameters of linear collider proposed.

		C.M.E. (TeV)	Luminosity ($cm^{-2}s^{-1}$)	Ea (MeV/m)	f_{RF} (GHz)	Ne^+e^- (/Bunch)	$N_{bunch} \times f_{RF}$ (collision/s)	P_{AC} (MW)	L_{linac} (km)
KEK	JLC	0.5	2.4×10^{33}	40	11.4	1.3×10^{10}	20×150	120	2×11.5
		1.0	8.8×10^{33}	80	11.4	2.0×10^{10}	20×150	120	2×11.5
		1.5	1.3×10^{34}	120	11.4	2.7×10^{10}	20×150	240	2×11.5
SLAC	NLC	0.5	2×10^{33}	50	11.4	1×10^{10}	10×180	120	2×7
		1.0	1×10^{34}	100	11.4	2×10^{10}	10×180	120	2×7
		1.5	9×10^{33}	150	11.4	3.2×10^{10}	10×60	240	2×7
INP	VLEPP	0.5	10^{33-34}	100	14.0	1×10^{11}	1×100	100	2×3
		1.0	10^{33-34}	100	14.0	1×10^{11}	1×100	100	2×6
		2.0	10^{34}	100	14.0	1×10^{11}	1×100	100	2×12
DESY/THD		0.5	2.2×10^{33}	17	2.856	2.1×10^{10}	172×50	100	2×15
CERN	CLIC	2.0	1.1×10^{33}	80	30	0.5×10^{10}	1700		2×15
	TESLA	1.0	2.6×10^{33}	25	1.3	5.1×10^{10}	800×10	130	2×20

3 LINEAR COLLIDER PROJECTS

The proposed linear collider projects are basically divided into the following three groups. The first one is the linear accelerator of which structures are excited by high power pulse klystrons together with RF pulse compression system to intensify the peak power by reducing pulse length.

NLC and JLC are being designed based on the extended technologies established by the existing S-band linear accelerators, SLC. The differences are higher RF frequencies, 11.424 GHz which is four times higher than S-band frequency and the multi-bunch accelerations to attain higher luminosity.

The R&D work at INP/Protvino is based on their long experiences of high voltage technologies. The main linacs of VLEPP are driven by high power X-band klystrons at 14 GHz together with RF power multiplier with open cavities. The configuration of gridded-cathodes and high voltage power lines of 1 MV gives rise to the omission of many thousands of klystron modulators. The lower losses of electricity can be expected due to the beam pulses produced by grid control and beam focusing by permanent magnets.

DESY in a joint work with University of Darmstadt have designed a conventional low gradient S-band linear collider [8]. Discarding the energy upgrade to 1 TeV center of mass, conventional S-band linear accelerator of about 20 MV/m accelerating gradient was identified as the shortest way to construct a linear collider of 500 GeV center of mass.

The second one is a two-beam acceleration scheme to avoid the several thousands of klystron tubes and modulators. RF sources of CLIC consist of a drive linacs with 30 GHz RF transfer structures and 350 MHz superconducting re-accelerating cavities [9]. This scheme provides high efficiency by eliminating the beam loss in the collectors of klystron tubes. The drive beam loses energy by exciting high power RF in high frequency transfer structures and then re-accelerated in the low frequency cavities. The two-beam acceleration scheme is an RF frequency converter from 350 MHz to 30 GHz by using the low-energy high-current drive beam as a medium. The transfer structures are designed to produce 160 MW/m of peak power [10].

LBL/LLNL have also based their work on the two-beam accelerator by using a multi-stage microwave free-electron laser at 17 GHz driven by an induction linear accelerator [11].

The third one is the superconducting linear accelerators so called TESLA [12]. The present R&D is focused to produce high accelerating gradient in single cell or multi-cell structure. The accelerating gradient of 30 MV/m has been produced in 1.5 GHz single cavity at CEBAF. At KEK the accelerating gradient of 16 MV/m has been attained in a 1.3 GHz single cavity. A 1.3 GHz superconducting structure with 9-cell of 1 m long is being fabricated by CEBAF and it will be tested with high power RF system in KEK. The accelerating gradient of 30 MV/m could be produced in 2.856 GHz 3-cell structure at Cornell. CEN-Saclay has developed a 1.5 GHz 5-cell structure for a re-cyclotron to generate the accelerating gradient of 15 MV/m. TESLA study group has a plan to construct 1.3 GHz superconducting linear accelerators of 30 m long to produce the accelerating gradient from 20 to 25 MeV/m in several years.

4 RF SOURCES

In order to attain the accelerating gradient ranging from 50 to 100 MeV/m in X-band accelerating structures the peak RF power in the range from 60 to 240 MW per meter is required. The necessity of high power X-band RF sources arose and then the initial target of peak power was chosen to be 100 MW in the range from several hundreds ns to 1 μs of pulse duration. However, no X-band sources above few megawatt were in existence and there is no previous experience with X-band linear accelerators at this power level. The absence of an established technologies for X-band high power RF sources has stimulated some novel approaches. The broad studies on new types of RF sources have been performed. At present the following RF sources are under consideration for proposed linear collider projects; conventional high power klystron and two-beam accelerator scheme.

4.1 Conventional Klystron Tubes

The output power capability in klystron tubes scales approximately as the inverse square of RF frequencies on the basis that maximum power is limited by the RF breakdown in output cavity and beam power density available to dissipate in a klystron tube. The maximum operating peak power of the existing S-band pulse klystrons is 67 MW of SLAC-5045 klystons and 100 MW of E3712 klystrons respectively. By scaling down to 11.424 GHz, the peak power would be ranging from 16 to 25 MW. Those S-band klystrons have not been designed to obtain the maximum-limited peak power. However the many technical difficalties should be settled down to generate the peak power of 100 MW from X-band klystron tubes.

The first basic difficulty of high power X-band klystrons is increase in beam power per unit area in klystron tube in an RF pulse. The deflected high density beam hits the inner surface of klystron tube and then the material of inner wall would be melted.

The second difficulty is the RF breakdown in an output cavity. The maximum peak power would be limited by the surface field in the output cavity. A dal-output cavity and travelling wave cavities would reduce the peak surface field [16]. A nose-corn removed pillbox output-cavity gives rise to the decrease of surface field to half with keeping high efficiency [2] [13].

The third difficulty is a large convergence of the beam cross section due to cathode loading. The diameter of cathode should not be scaled down provided the cathode is operated at appropriate current density and cathode temperature consistent with long lifetime. The convergence ratio of 100 to 200 would be required by the confining magnetic field in the rage from 4 to 6 kG. Therefore the AC plug power for a solenoid electromagnet would be dominant over the average RF power obtained from klystron. The solutions are electrostatic compression scheme, superconducting electromagnets and permanent magnets.

The fourth difficulty is an RF window which can penetrate full RF peak power from klystron. The studies have been carried out by using three dimensional code, MAFIA [14]. The RF windows such as large diameter window with taper waveguides and TE_{01} mode window have been developed [15] [2].

SLAC has designed and fabricated four versions of X-band klystron (XC1, XC2, XC3 and XC4) to produce 100 MW peak power in 100–1000 ns pulse duration [16]. The differences between those versions provide the tests for various alternatives to RF windows, single-gap cavity, multi-gap cavities and cathodes. The beam voltage is somewhat low, 440 kV, due to the high perveance, 1.75 to high current of 511 A. The peak power of 72 MW has been generated with a pulse width of 100 ns and 40 MW has been produced at 800 ns. The second family of klystrons (XC4, XC5) has been designed to reduce area convergence to 100:1 by using a cathode of smaller diameter and higher cathode-loading [17]. The XC5 klystron has recently designed with a travelling-wave output-cavity to reduce RF breakdown threshold field [18].

KEK has approached the X-band klystron design in two stages. The first tube (XB-50K) with a perveance of 1.75 μ, was designed to produce 30 MW and was tested up to 18 MW with a pulse width of 100 ns. The breakdown in an rf window limits the attainable maximum peak power. The XB-50K klystron is utilized as an RF source of X-band high gradient experiments to generate the accelerating gradient more than 50 MeV/m in an X-band disk-loaded structure of 20 cm long. The second tube (XB-72K) was designed to produce 120 MW at 550 kV of beam voltage and 1.2 microperveance. The beam voltage is somewhat high due to the low perveance and low area convergence, 110:1. A nose-corn removed pillbox cavity is utilized to reduce surface field in a single-gap cavity without reducing efficiency. From the results of simulation by FCI code [19], the efficiency of 45 percent would be attained at 700 kV/cm surface field. The first tube of XB-72K klystron was tested to 22 MW with 100 ns pulse duration. The failure of a diode ceramics terminated the generation of designed peak power and further test will be continued.

INP/Protvino has designed X-band klystrons of 14 GHz. The power supply is not a conventional PFN klyston modulator but a high voltage power line to produce quasi-DC voltage. The klystron tube is composed of a diode with gridded-cathode and a travelling-wave output section. The designed beam voltage is 1 MV and beam current would be 200 A. The low perveance provides the periodic magnetic focusing with permanent magnets. The advantages of VLEPP klystrons are low cost by avoiding many thousands of klystron modulators and low running cost by eliminating electromagnetic focusing. The peak power of 60 MW has been generated with 700 ns pulse width at relatively lower voltage [2].

4.2 Klystrons and Other Devices

X-band klystrons at 11.4 GHz with high-current electron beam accelerators have been studied to produce peak power higher than 100 MW with a pulse length less than 100 ns. The peak power of 330 MW with 30 ns pulse width has been attained by a relativistic klystron at LLNL/SLAC/Berkely. The RF peak power power of 400 MW with 10 ns pulse width could be obtained by choppertron at LLNL/Haimson and 120 MW with 50 ns at MIT/Haimson. The R$D of other devices such as CFA, pulsed gyrocons, magnicons, gyroklystrons, rippled circuit TWT have been continued to produce RF high peak power.

Table 2: High power X-band klystron tubes.

	Peak Power	Pulse width	Frequency
SLAC	40 MW	800 ns	11.424 GHz
	72 MW	100 ns	11.424 GHz
KEK	22 MW	100 ns	11.424 GHz
VLEPP	60 MW	700 ns	14 GHz

4.3 *RF Pulse Compression System*

The RF compression system is useful tool to obtain high RF peak power without increasing the number of RF sources. A binaly pulse compression system and SLED-II pulse compression system developed at SLAC multiply the peak power available from the klystron by about a factor of four by a single stage configuration. Those RF pulse compression systems have an advantage to obtain the multiplied RF power in a form of square pulse. The SLED-II consists of a 3 dB power divider and two length of shorted delay line with a go and come back RF transit time equal to the required output pulse. The length of line is determined by the filling time of the structure and the length of 25 m is required for the structure of which filling time is 100 ns. The RF output of approximately 30 MW and 800 ns pulse width from XC-2 klystron has been compressed and compressed RF power of 120 MW with pulse length of 70 ns has been obtained [17]. The VLEPP Power Multiplier (VPM) has been developed by using a 'open cavity' to multiply by about a factor four by a single stage open cavity. The low power test has been succeeded and RF power from a 150 MW VLEPP klystron will be carried out [2].

5 ACCELERATING STRUCTURES

The study of accelerating structures is based on the familiar disk-loaded traveling-wave structures with the advantage of common input and output couplers for many structure cells. The RF power is provided in form of a short pulse of which duration is given by the filling time and beam pulse width. The dimensions of structures scale approximately as the inverse square of RF frequencies. The first difficulty is the fabrication technology of accelerating structures with very small size cells. The R&D of fabrication techniques with precision machines and brazing techniques has been carried out at CERN, SLAC, INP and KEK [1] [20].

A design of the detuned structure was performed following the idea of SLAC [21] [22]. The frequency of each cell is distributed as truncated Gaussian through the structure. The frequency should be in the passband which is synchronous the beam. The number of frequencies in this detuning should be more than 150 to reduce the wake field less than 1 % during the following bunches (1.4 to 27 ns) [23].

The damping of $TM_{110-\pi}$ mode is very sensitive to the structure with slots in the disk. The structure with four slots in a cell is under study [24]. It was found that the slot height of 2 mm is enough to damp the TM_{110} mode. The opening of the slot can be reduced to 9 mm while the width of the damping port connected to the slot is 11 mm. In this design, the decrease of the shunt impedance of the accelerating mode is at most about 20 %.

6 HIGH GRADIENT EXPERIMENTS

The fundamental studies on RF breakdown phenomena in S-band, C-band and X-band cavity have been carried out at SLAC and Varian [5]. The experimental studies on the acceleration of electron beam in S-band travelling wave structures at approximately 100 MeV/m of gradient have been carried out at INP [25], LAL [26] and KEK [1]. The dark current extracted from the structures provides the incorrect information to beam position monitors. The understanding of dark current phenomena is highly required to find the way to reduce and avoid the dark current. The recent experiments have been performed in the travelling-wave and standing-wave multi-cell structures. The experimental results at LAL, INP and KEK show that a cell where the front of RF pulse passes through S-band travelling-wave structures is the major source of dark current [26]. The high gradient experiments at X-band structures have been carried out with standing-wave structure at SLAC [18] and travelling-wave structure at KEK [28]. The studies of particle trajectories have been carried out in long structures at accelerating gradient ranging from 50 to 300 MeV/m.

7 ELECTRON SOURCES

Recently studies have been carried out on RF gun using laser-driven photocathode to produce high current low emittance electron beam. The separation of bunched photon from mode-locked laser would be controlled by an optical system. The laser-driven photocathode RF gun is also useful to produce multi-bunch of electrons with a bunch separation equal to the harmonics of RF frequencies in the cavity. An RF gun has been developed at CERN to generate driving bunches for CLIC Test Accelerator Facility [1]. The RF gun for the injector of linear collider has been carried out at KEK [29].

The material of GaAs has many advantages in performance of intensity and time resolution. However the electron spin polarization is limited to be 50 % since the degeneracy between a heavy and light-hole band. SLAC and Nagoya University have achieved the polarization of about 85 % by using strained GaAs independently [30]. KEK have also achieved the polarization of 75 % with AlGaAs-GaAs superlattice photocathode [31].

8 FFTB PROJECT

The Final Focus Test Beam (FFTB) Facility is being constructed with international collaborations as a prototype final focus system for future linear colliders [32]. The target of the facility is to focus the electron beam from the straight beam-line of 50 GeV SLC linac and reduce the transverse dimensions at the focal point to 1000 $nm \times 60$ nm. The FFTB Facility is composed of final focus magnets, final quads, alignment system, beam position monitors and nano-meter beam size monitors [33] [34]. The components are presently under fabrication at the laboratories of the participating institutions, DESY, INP, KEK, LAL, MPI and SLAC. The construction and installation of the facility will be completed by the end of 1992. It is highly expected that success of the FFTB Facility will realize a significant step in the R&D of future linear colliders.

9 ACCELERATOR TEST FACILITIES

Present is the time to construct the accelerator test facilities in order to test the accelerator system composed by developed accelerator components. The constructions of accelerator test facilities throughout the world will lead us to believe that the design goals of future e^+e^- linear collider is close at hand since the accelerator test facilities are really the prototypes of future linear colliders.

9.1 CERN Linear Collider Test Facility — CTF

The CERN Linear Collider Test Facility (CTF) has been constructed to prove the two-beam acceleration scheme [35]. The drive linac of CLIC requires very high current bunched electron beam to generate high RF power in the transfer structures. It consists of a 3 GHz RF gun with a laser-triggered photocathode, beam transport line, post accelerator, pulse compressor, transfer structure and 30 GHz X-band structure. The intense bunches of more than 10 nC of bunch charge generate 30 GHz high RF power by deceleration of the bunches in a 30 GHz transfer structure and produce high gradient in the accelerating structure.

9.2 JLC Accelerator Test Facility — ATF

The JLC-ATF Phase-II project has been started to construct an accelerator test facility in the TRISTAN Assembly Hall [36]. The ATF consists of the following major accelerator components; 1.54 GeV S-band injector, damping ring, bunch compressor, final focus test facility, 1 GeV X-band linac and positron target. The following electron sources will be installed; a conventional thermionic gun with sub-harmonic bunchers, RF gun with mode-locked laser and polarized electron gun. The ATF damping ring is a test facility to obtain the beam with the vertical emittance of $3 \times 10^{-8} rad.m$. An auto-alignment system is under design to adjust the positions of all the units of damping rings in the vertical alignment tolerance of ± 10 μm. The design study on a 1.428 GHz damped cavity and CW klystron has been performed. The final focus test facility is utilized to confirm the demagnification factor of 1/300 and the specification of the auto-alignment system. A beam size monitor by using Compton scattering with laser beam would be installed to observe the beam size of 30 nm in vertical direction. The 1.0 GeV X-band linac will be constructed to study the RF sources, RF pulse compression and accelerating structures as the prototype of main linacs. The accelerating structures would be the JLC-like damped structures and detuned structures to accelerate multi-bunches by accelerating gradient from 40 to 120 MeV/m. The construction and installation of the JLC-ATF will be complete in 1994.

9.3 VLEPP Accelerator Test Facility — ATF

VLEPP-ATF has been constructed at INP/Protvino to study the engineered model of a section of the main linear accelerators of the VLEPP real machine [2]. The VLEPP-ATF consists of electron gun, X-band klystrons, RF power multiplier, qusi-DC power line, X-band accelerating structures with alignment devices and final focus quad with alignment system. The designed accelerating gradient is 100 MeV/m with X-band klystrons together with open cavities. The alignment system with electromagnets provides the precise control of accelerating structures by 5 nm step. The beam acceleration at designed accelerating gradient by full RF power would be completed in 1992. A large building is under construction to extend the beam energy.

9.4 NLC Test Accelerator — NLCTA

SLAC has a plan to build the NLCTA facility to test the reliable operation of engineered model of a section of an NLC high gradient main linac [4]. The NLCTA consists of an S-band injector linac followed by an X-band linac. A thermionic gun with a subharmonic buncher produces multi-bunch electron beam similar to those necessary for NLC. The S-band linac accelerates the beam to an energy of 200 MeV and then the bunches are compressed in length by bunch compressor magnets. The short bunches are injected into the X-band linac of which designed accelerating gradients are ranging from 50 to 100 MeV/m with an RF frequency of 11.4 GHz. The RF sources for the X-band linac consist of 50 MW klystrons together with SLED-II pulse compression system to multiply the peak power by a factor four. The accelerating gradient will be increased to 100 MV/m by using 100 MW klystrons. The designed beam energy gain in the X-band linac is 0.54 GeV at 50 MeV/m and 1.08 GeV at 100 MeV/m of accelerating gradient.

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