Survey of Linear Collider Test Facilities

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Abstract

This paper describes the status of accelerator test facilities for future e^+e^- linear colliders, CLIC, DESY/THD, JLC, NLC, TESLA and VLEPP.

1 INTRODUCTION

The R&D for the future linear colliders has been performed for the following projects, CLIC, DESY/THD, JLC, NLC, TESLA and VLEPP[1]-[2]. The common targets at the initial stage of these projects are to realize the e^+e^- collision experiments at 500 GeV center of mass energy and $10^{33-34}cm^{-2}s^{-1}$ of design luminosity. The differences among the projects are accelerating schemes and RF frequencies of main linear accelerators (see Table 1). TESLA is the only linear accelerator using 1.3 GHz superconducting cavities for the main linac and the other machines are used normalconducting linear accelerators in the rangr of RF frequency from 2.856 GHz to 30 GHz. CLIC has adopted the two-beam accelerator scheme for the main linac in stead of klystrons which are using in the conventional linear accelerators. Other four projects, DESY/THD, JLC, NLC and VLEPP have adapted the conventional accelerating scheme with normalconducting cavities and klystron tubes. The difference among these four projects is the RF frequencies. DESY/THD is designed at 3 GHz of conventional S-band frequency. NLC and VLEPP are designed at 11.424 GHz and 14 GHz of X-band frequencies respectively. JLC has three options of main linear accelerators of which RF frequencies are 11.424 GHz, 5.712 GHz and 2.856 GHz respectively.

Recently the R&D of RF power sources has been advanced and the RF peak power of 60–80 MW at X-band and 100–150 MW at S-band frequency could be generated by klystrons[3]. The peak power of 70 MW has been produced by two-beam accelerator scheme.

The structure studies results in the small dark current at least up to 80 MV/m at X-band frequency and up to 52 MV/m at 3 m-long S-band accelerating structure. The accelerating field up to 52 MV/m has been produced in an S-band Shintake (choke-mode) structure which damps the higher order mode generated by the bunch-cavity interaction. The accelerating field of 71 MV/m has been produced in 30 GHz structure by two-beam accelerator scheme.

FFTB experiment at SLAC by international collaborations succeeded in conversing the SLC beam to 67 nm in vertical beam size and measuring the beam spot size by both the Shintake (Compton-scattering) beam size monitor and LAL-ORSAY gas monitor[4]. At the spring experimental run in 1994, it has been proved that the SLC beam could be focused to 67 nm beam size and a nonometer beam size monitor will be practical. The success of the FFTB collaboration will realize a significant step in the R&D of future e^+e^- linear colliders. A few nanometer beam size is well within the reach at the next step.

The next issues to be studied will be the wake field effects such as wake-free correction, multi-bunch effects such as beam-loading and beam-breakup, linac alignment and correction, and beam instrumentation for multi-bunches. Some of these can be studied at 100 m-long test linac. Eventually, these are the "Linear Collider Test Facilities".

2 LINEAR COLLIDER TEST FACILITIES

The TESLA Test Facility (TTF) composed of a 500 MeV superconducting linac and the S-band Test facility (SBTF) of 480 MeV linac prototype are under construction in DESY. The Next Linear Collider Test Accelerator (NLCTA) consisting of a 540 MeV X-band linac is under construction in SLAC. BINP is constructing the VLEPP Accelerator Test Facility (VLEPP-ATF) of X-band linac prototype. CERN has constructed the CLIC Test facility (CTF) to ensure the two-beam accelerator scheme. The Accelerator Test Facility (ATF) composed of the accelerator components from e^+e^- sources to bunch compressor is under construction in KEK as the prototype of JLC(see Table 2).

3 TESLA TEST FACILITY (TTF)

The object of TTF is to establish the technological base needed to construct and operate a superconducting e^+e^- linear collider TESLA. The first R&D item is the production and test of high performance superconducting cavities to achieve near term goal 15 MV/m in accelerating gradient. The other items are the development of a cost effective low heat leak cryostat. The construction of a prototype facility will lead to the understanding of cost drivers of engineering design and extrapolated cost to TESLA. The facility is under construction at DESY in

Table 1: The list of linear collider projects.

Accelerating Structure	RF Sources	Accelerating Bunch	Project	RF Frequency (GHz)
Superconducting			TESLA	1.3
Normalconducting	Klystron	Multi-bunch	DESY/THD	3.0
			JLC	2.856
				5.712
				11.424
			NLC	11.424
		Single Bunch	VLEPP	14.0
	Two-beam	Multi-bunch	CLIC	30.0

Table 2: The list of linear collider facilities.

Project	Test Facilities	Facilities
TESLA	TTF (TESLA Test Facility)	500 MeV 60 m Linac
DESY SBLC	SBTF (S-band Test Facility)	480 MeV 45 m Linac Prototype
JLC	ATF (Accelerator Test Facility)	1.54 GeV 80 m S-band Linac 1.54 GeV Damping Ring Positron Target Bunch Compressor Main Linac Unit Prototype
NLC	FFTB (Final Focus Test Facility) ASSET (Acceleration Structure SETup) NLCTA (NLC Test Accelerator)	SLC + Final Focus System SLC + Wake Field Measurement 540 MeV 15 m X-band Linac
VLEPP	VLEPP-ATF (VLEPP Accelerator Test Facility)	X-band Linac Prototype
CLIC	CTF (CLIC Test Facility)	Two-beam Linac Test Facility

the framework of an international collaboration[5]. The TTF consists of a 500 MeV superconducting linear accelerator of 60 m-long in total length. The linear accelerator consists of 4 cryomodules and each cryomodule is composed of eight 1 m-long cavities. A cavity consists of 9 cells with the filling time of 0.53 ms. The RF system consists of two units of 4.5 MW klystron and modulator to drive one cryomodule at 2 MW. A 15 MeV injector-I is under construction produces 174,000 multi-bunches with the bunch separation of 5.6 ns and bunch population of 2.3×10^8. A 15 MeV injector-II will be constructed to produce 800 bunches with the bunch separation of 1.0 μs which is required for the TESLA machine. The infrastructure such as cleanroom, chemistry, furnace has been completed and two model cavities were fablicated to test the infrastructure itself. The cryosystem and RF system were completed and the processing of the first six superconducting cavities will be performed soon. The accelerating gradients have been generated up to 32 MV/m in a single cell and 25 MV/m in a 5-cell structure. As for the maximum accelerating gradient, 50 MV/m is the limit by theory and 35 MV/m is regarded as the engineering limit in a single cell cavity. The final goal of the accelerating field in 9-cell structures is 25 MV/m. The beam acceleration in first cryomodule will be performed by the end of 1995. Total system of 500 MeV TTF superconducting linac will be completed by the end of 1997.

Table 3: Parameters of TTF(TESLA Test Facility)

Beam energy	500 MeV	
Total length	70 m	
Injector	10 m	
Linac	60 m	
Accelerating gradient	15 MV/m	
RF frequency	1.3 GHz	
Number of cryomodule	4 cryomodules	
Cryomodule		
Total length	~8 m	
Number of cell	9 cells	
Filling time	0.53 ms	
Klystron		
klystron peak power	4.5 MW	
Klystron pulse length	1.33 ms	
Number of klystrons	2	
Injector	Injector-I	Injector-II
Beam energy	15 MeV	15 MeV
Number of bunches	174,000	800
bunch population	2.3×10^8	5×10^{10}
Bunch separation	5.6 ns	1.0 μs

4 DESY/THD S-BAND LINAC TEST FACILITY (SBTF)

The S-band Linac Test Facility (SBTF) consisting of several units of S-band main linac for DESY/THD S-band linear collider. In order to test the prototype unit of main linac, the basic parameters and the specifications have been designed as close as possible to those of a typical module of the DESY/THD S-band linear collider. The units of main linac such as klystron and modulator, accelerating structure and support, quadrupole magnets and instrumentations are designed and under fabrication[1].

The maximum beam energy is 480 MeV at zero current and 400 MeV with beam-loading. A 6 m-long $2\pi/3$ mode constant gradient structure has HOM couplers to minimize the effect of beam-breakup and an active alignment system will be adopted so that the beam can pass through the axis of the structure[6]. The linear accelerator consists of two RF units and four accelerating structures. A 150 MW S-band klystron excites two accelerating structures and the accelerating gradient of 20 MV/m would be obtained. The active and total lengths of the linac are 24 m and 27 m, respectively. The injector consists of sub-harmonic bunchers, a regular accelerating structure to produce and accelerate multi-bunches up to 3–4 MeV. The bunch populations are 1.5, 3.0 and 4.5×10^{10} electrons for the bunch separation of 8, 16 and 24 ns respectively[7].

Table 4: Parameters of SBTF(S-band Test Facility)

Beam energy	
Zero current	480 MeV
With beam loading	400 MeV
Total length	37 m
Injector	3.5 m
Linac	27 m
Spectrometer	6.5 m
Accelerating structure	$2\pi/3$ mode CG structure with HOM couplers
Total length	6 m
Accelerating gradient	20 MV/m
RF Frequency	2.998 GHz
Klystron	
klystron peak power	150 MW
Klystron pulse length	3 μs
Number of klystrons	2
Injector	
Beam energy	3 MeV
Number of bunches	250, 125, 85
bunch population	1.5, 3.0, 4.5×10^{10}
Bunch separation	8, 16, 24 ns

The injector is under construction and it will be completed by the end of 1994. The fabrication of the first accelerating structure is completed. The first 150 MW klystron tube developed by the collaboration with SLAC is under RF processing to increase the pulse length from 1μs to 3μs at 150 MW designed peak power. The quadrupole magnets, BPM and their supports will be installed soon. The beam commissioning of 480 MeV SBTF will be in 1996.

5 NEXT LINEAR COLLIDER TEST FACILITY (NLCTA)

The first object of NLCTA is to construct and reliably operate an engineered model of a section of the NLC high-gradient linac[8]. The system integration, test bed for RF system and instrumentation development are the main purpose as the test facility. The second object is to test those beam dynamics questions coupled to acceleration of multi-bunches in NLCTA linac such as multi-bunch beam-loading compensation, multi-bunch beam-breakup and field emission effects in high accelerating gradient[1].

NLCTA consists of X-band injector and three units of NLC X-band main linac. A 90 MeV 7 m-long X-band injector provides multi-bunch with 1/16 the bunch spacing, 88 ps, and 1/16 the bunch charge of the NLC bunch train, 7×10^8 electrons[9]. The injector would be modified to produce multi-bunches with the bunch spacing of 1.4 ns which is required for NLC real machine. On that occasion, the bunch population would be increased to 0.65×10^{10} electrons/bunch of NLC design value. The multi-bunches are accelerated by X-band linac up to 540 MeV after the bunch compressed in length by a 10 m-long chicane. The active length of X-band linac is 10.8 m and total length is 15 m. The X-band linac consists of three RF units. An RF unit consists of 50 MW, 1.5 μs klystron and SLED-II RF pulse compressor with power gain of 4.0 to produce 200 MW peak power. An RF unit excites two 1.8 M-long $2\pi/3$ mode detuned structures for higher-order-mode suppression to produce 50 MV/m accelerating gradient without beam-loading. The bunch train is close to one filling time in length. The beam-loading will reach a steady state value of 25 % by the tail bunch. The energy compensation will be possible by controlling the shape of the RF power envelope to the structures. The compensated energy spread of 0.1 % among the multi-bunch would be expected. The net accelerating gradient with beam-loading in the structures would be 37.5 MeV/m.

Table 5: Parameters of NLCTA

Beam energy	540 MeV
Total length	50 m
Injector	7 m
Chicane	10 m
Linac	15 m
Active length	10.8 m
Spectrometer	18 m
Accelerating structure	$2\pi/3$ mode detuned structure
Total length	1.8 m
Total number	6
Accelerating gradient	50 MV/m
RF Frequency	11.424 GHz
Klystron	
klystron peak power	50 MW
Klystron pulse length	1.5 μs
Number of klystrons	3
RF pulse compression	SLED-II
Power gain	4.0
X-band injector	
Beam energy	90 MeV
bunch population	7×10^8
Bunch separation	88 ps

Type XL1 klystron achieved the required peak power of 50 MW with the pulse length of 1.5 μs and utilized to test SLED-II RF pulse compressor. A 1.8 m-long accelerating section with double-feed couplers was tested and reached 55 MV/m at ASTA[10]. The wake field produced in a detuned structure was measured at ASSET by using SLC single bunch beam and the experiment results in good agreement with theory. The design of 90 MeV X-band injector was completed by computer simulation. A shielded enclosure close to the FFTB facility was completed. The total facility will be completed by the end of 1996 and beam commissioning is scheduled in 1997.

6 CLIC TEST FACILITY (CTF)

The main object of CTF is to produce an electron beam of high charge and short bunches suitable for testing CLIC structures, and to establish the two-beam accelerator scheme. The second object is to explore the possibilities of an RF gun with a laser driven photocathode and instrumentations for 30 GHz X-band linac[1]. CTF

Table 6: Parameters of CLIC

Drive beam energy	50 MeV
Total length	~20 m
Drive Beam Source	Photocathode RF gun
RF frequency	3 GHz
Repetition rate	10 Hz
Accelerating field	100 MV/m
Laser wavelength	209 nm
Number of bunches	8
Bunch population	$10^{10} \sim 10^{11}$
Bunch separation	4 ns
Accelerator section	
RF frequency	3 GHz
Klystron	24 MW, 2.0 μs
Beam energy	80 MeV
Transfer structure	
Produced RF frequency	30 GHz
Produced RF peak power	70 MW
RF pulse length	32 ns
Decelerating field	107 MV/m
Accelerating structure	
Accelerating beam	Drive beam
Reaccelerating field	71 MV/m
Reaccelerating beam energy	13-30 MeV/m

consists of an RF gun with a laser driven photocathode and a test bed for two-beam accelerator. The RF gun produces 8 bunches with the bunch separation of 4 ns and bunch population of 10^{10}-10^{11}[11]. The accelerating field in the cell of the RF gun is 100 MV/m. The accelerator section consists of 3 GHz accelerating structures and 24 MW klystron to accelerate the multi-bunches up to 80 MeV. Those bunches injected in a transfer structure and RF power of 70 MW at 30 GHz frequencies are produced therein. The produced RF power is fed into a 30 GHz accelerating structure and 71 MV/m of accelerating field is produced. The multi-bunch decelerated in the transfer structure is re-accelerated in the 30 GHz structure.

In order to test the unit of CLIC main linac, the drive beam facility producing longer pulse beam is required. The next step of the CLIC R&D is the drive beam facility to produce 360 bunches with 20 nC per bunch. One of the drive beam study is performed by free electron maser scheme by an induction linac in CEA, Bordeaux. The facility consisting of drive beam source and 1.3 m-long accelerator sections with two transfer structures and four 30 GHz structures has been proposed.

7 VLEPP TEST FACILITY

The object of VLEPP Test Facility is to construct and operate a model of a section of the VLEPP 14 GHz high-gradient linac with active alignment system. As the first step the facility was installed in 25 m-long shielded enclosure settled in a warehouse. The facility consists of electron gun, high gradient linac, instrumentations and quadrupole magnets[1]. As the second step, a 100 m-long tunnel has been constructed for 400 MeV main linac of 100 m-long in total length. The linac consists of twelve $2\pi/3$ mode structures of 1 m-long in length and three 120 MW klystrons with quasi-DC power supply[12]. The peak RF power from a klystron is 5 times increased by the VPM (VLEPP Power Multiplier) and fed into two accelerating structures. The accelerating gradient up to 100 MV/m would be produced in the structure. The injector linac produces a single bunch with 4×10^{11}-1×10^{12} electrons. The linac would be operated at the maximum repetition rate of 300 Hz.

Table 7: Parameters of VLEPP-ATF

Beam energy	400 MeV
Total length	
Tunnel-1	25 m-long shielded enclosure
Tunnel-2	100 m-long new tunnel
Linac	10 m
Linac	~20 m ⇒ ~100 m
Accelerating structure	$2\pi/3$ mode structure
Total length	1 m
Total number	12
Accelerating gradient	100 MV/m
RF Frequency	14 GHz
Klystron	
klystron peak power	120 MW
Klystron pulse length	0.7 μs
Number of klystrons	3
Repetition rate	300 Hz
RF pulse compression	VPM
Power gain	5
Number of bunch	Single bunch
Bunch population	$4\sim10\times10^{11}$

The facility is under testing in the 25 m long shielded enclosure. The klystrons produce 60 MW peak power in 0.7 μs pulse duration. The VPM achieved the power gain of 5 with open cavities. The active alignment system has achieved the resolution of 1 nm for the alignment of structures and instrumentations.

8 JLC ACCELERATOR TEST FACILITY (ATF)

The object of JLC Accelerator Test Facility (ATF) is to construct and operate an engineered prototype of the JLC total system. ATF consists of electron and positron sources, 1.54 GeV injector linac, damping ring, beam instrumentations, active alignment system and control[1][13]. As the future plan, a bunch-length compressor, final focus system and unit of main-linac would be installed. The first object of ATF is to produce multi-bunch beam with the vertical emittance of $3\times10^{-8} rad.m$ which is the same value required for the JLC machine. The second object is to establish the reliable operation of accelerator system and understand the cost drivers of engineering design for the large scale linear accelerator.

The 1.54 GeV S-band linac is an injector linac for the damping ring. The linac consists of 80 MeV preinjector, beam diagnostic section and accelerator linac. The role of the pre-injector is to produce 20 multi-bunches of 2×10^{10}

electrons/bunch with 2.8 ns bunch spacing[14]. The multi-pulsed beam is extracted from the 200 keV thermionic gun by applying RF wave of 357 MHz to the grid. The multi-pulsed beam is compressed from 1 ns to 20 ps in length by two 357 MHz SHB cavities and four single cell 2856 MHz buncher cavities. After the bunching, the multi-bunches are accelerated up to 80 MeV by a 3 m-long accelerating structure.

The linac consists of 8 RF units and each RF unit consists of a klystron, modulator, two-iris SLED and two 3 m-long accelerating structures. The peak power of 85 MW in 4.5 μs from a klystron is fed into the SLED cavity and then the peak power of 400 MW can be produced in 1.0 μs pulse duration. The maximum accelerating field in a 3 m-long constant gradient structure is 52 MV/m. The average accelerating gradient with beam-loading is 40 MeV/m. The new type of energy compensation system compresses the energy spread of multi-bunches from 5 % to 0.2 %. The energy spread of single bunch is 0.5 % which is larger than the spread among the multi-bunches. The stages of the linac possesses an active mover mechanism and wire position sensors to align the linac within ± 50 μm. The beam instrumentations installed along the linac provide the positions, profiles, populations and length of individual bunch with 2.8 ns bunch separation.

The facility is under construction in the TRISTAN Assembly Hall of KEK by world-wide collaborations with DESY, PLS-POSTECH, SEFT, SLAC and universities in Japan. The preinjector is under operation to test the multi-bunch production, beam instrumentations, high gradient experiments and control. The accelerator section of 1.54 GeV linac except energy compensation sections has been completed. The RF processing of the first section of accelerator linac has been completed. The completion of 1.54 GeV linac will be in 1995 and damping ring will be in 1995 and 1996 respectively. The beam commissioning is scheduled in 1996.

9 CONCLUSION

The accelerator test facilities are under construction in order to test the accelerator system composed of developed accelerator components. The constructions of accelerator test facilities lead us to believe in that the design goals of future e^+e^- linear colliders are close at hand since the accelerator test facilities are really the prototypes of future e^+e^- linear colliders. We will reach the milestone to the design goal of 500 GeV C.M.E. linear colliders in 1997 when the facilities will be all on hand.

Table 8: Parameters of JLC-ATF

ATF Injector Linac	
Beam energy	1.54GeV
Total length	80 m
Injector	10 m
Linac	70 m (active length 48 m)
Accelerating structure	$2\pi/3$ mode CG structure
Total length	3 m
Total number	16
Accelerating gradient	
Maximum field	43 [52] MV/m
with beam-loading	33 [40] MV/m
RF frequency	2.856 GHz
Feed peak power	200 MW/structure
Klystron	
klystron peak power	80 [85] MW
Klystron pulse length	4.5 μs
Number of klystrons	8
RF pulse compression	Two-iris SLED
Power gain	5.0
S-band pre-injector	
Beam energy	80 [105] MeV
Number of bunch	20
Bunch population	2×10^{10}
Bunch separation	2.8 ns
ATF Damping Ring	
Beam energy	1.54GeV
Circumference	138.6 m
Horizontal emittance	4.3–5.1$\times10^{-6}$ mrad
Vertical emittance	3×10^{-8} merad
Beam current	600 mA
Number of batch	5 — 2
Repetition rate	25 Hz
RF frequency	714 MHz

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