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JAPAN LINEAR COLLIDER (JLC)

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Abstract KEK proposes a future project to construct the Japan Linear Collider (JLC) with the center-of-mass energy of 1 TeV. The JLC project is carried by successive stages. At the first stage, an intermediate energy linear collider (JILC) with 400 GeV center-of-mass energy is constructed in order to start experiments on energy frontier physics till the end of this century. The energy can be increased up to 600 GeV by extending the rf power system. The 1 TeV JLC will be constructed at the final stage of the project. The research and development have been carried out on the theoretical and technical problems in order to realize the project.

INTRODUCTION

In 1986, the Japan high energy physics community discussed the future plans of experiments. They decided to pursue the energy frontier physics in TeV region by using an electron-positron linear collider as a post-TRISTAN project.[1-2] In order to realize a linear collider, many technical difficulties should be overcome. There are so many theoretical problems of accelerator physics for inexperienced high energy accelerators. In 1987, a study group has been organized in KEK in order to investigate the feasibility of the linear collider. For the guideline of the R&D, the following parameters[1-2] were initially set up as shown in Table 1:

Table 1. Design parameters of the 1 TeV JLC initially set up for the R&D.

Beam energy	0.5 + 0.5 TeV
Luminosity	1×10^{33} cm^{-2}sec^{-1}
Total length of linacs	5 + 5 km
Accelerating gradient	100 MeV/m
RF frequencies	11.424 GHz
AC power for linacs	100 + 100 MW

ACTIVITIES FOR LINEAR COLLIDER R&D

Numerous advanced ideas have been proposed to settle the technical difficulties for future linear colliders. However, the R&D by extending the conventional schemes seems to be the shortest way to construct the linear collider within approximately ten years. Since 1987, the theoretical and technical R&D programs have been in progress by collaborating with the laboratories of high energy physics of the universities in Japan. In present, seventy persons are contributing to the studies for the JLC project. KEK collaborates with SLAC on rf sources, linear accelerator studies and final focus systems for linear colliders.[3] The collaborations between KEK and CERN will start with an exchange of visitors to intensify the contacts.

The following R&D programs have been carried out:

1) Design of linacs and damping rings,[5,14]
2) Beam dynamics in linacs and damping rings,
3) Studies on the interaction region, such as beam-beam interactions,[6-7]
4) Design of final focus system,[8-9]
5) High power rf sources to generate high accelerating gradients,[10-12]
6) Accelerating structures capable of producing high gradient of 100 MeV/m,[13]
7) Beam monitors,
8) Controls ,[15-16]
9) Alignments, [17]
10) Intense electron and positron sources,
11) Test Accelerator Facility (TAF).[18]

PROJECT OF JAPAN LINEAR COLLIDER (JLC)

For the 1 TeV linear collider, both the coherent and incoherent radiations by pair creations are dominant as the background of detectors. In order to avoid the background due to the radiation, the electron and positron linacs should be installed in the tunnels with a very large crossing angle at the interaction point. The crab-crossing scheme is also required to avoid the decrease of the luminosity.

For the linear collider with a center-of-mass energy around 400 GeV, synchrotron radiations both in the final focus magnets and in the beam-beam interaction region is not so severe. The electron and positron linacs can be installed in the straight tunnel without adopting any crab-crossing schemes. From the results of the R&D since 1987, it presently be considered that the JLC should be constructed by successive stages. The beam energy around 400 GeV is seems to be the optimum to start the experiments till the end of this century.

At the first stage, the JILC (Japan Intermediate Energy Linear Collider) is constructed at 400 GeV center-of-mass energy, which is two times higher than that of LEP-II. The energy can be increased up to 600 GeV by extending the rf power system. At the final stage of the JLC project, the 1 TeV linear collider will be constructed by extending the total length of the linacs.

PARAMETERS OF 400 GeV JILC

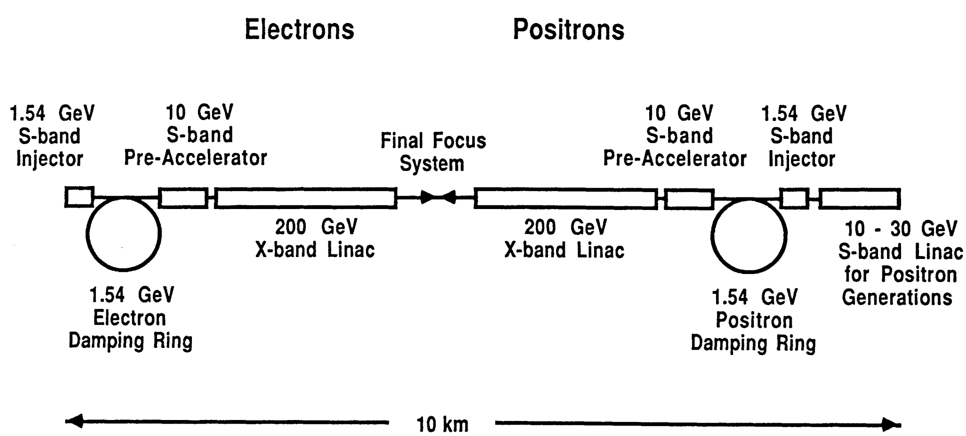
The parameters for a linear collider is a complex of theoretical and technical constraints. A computer program then determines the optimum parameters of the 400 GeV JILC as listed in table 2. It should be noted that these parameters are tentatively obtained. Detailed design studies must still be carried out for each major sub-system, for example the main linacs, damping rings and final focus systems.

The 400 GeV JILC is installed in the tunnel with the total length of 10 km, which is required to increase the energy up to 600 GeV. The multi-bunches of electrons are generated by an rf-gun and they are accelerated up to 1.54 GeV by an S-band linac for the damping ring. The damping ring contains 8 bunch trains of 10 bunches each. One bunch train is kicked out every 5 ms, after reducing the emittance during 16 damping times in the ring. The rf frequency of the ring cavities is 1.428 GHz in L-band to accelerate the bunches with long bunch length. The bunch length is compressed after extracted by a kicker and they are accelerated up to 10 GeV by the S-band preacceleration linac. After the bunch length is re-compressed, the bunches are accelerated up to 200 GeV by the X-band main linac.

Table 2. Design parameters of 400 GeV JILC

Beam energy	E	200 + 200 GeV
Luminosity	L	3.1×10^{33} cm^{-2}sec^{-1}
Total length of the linacs		10 km
Number of particles/bunch	N	1.0×10^{10}
Repetition frequency of linacs	f_{rep}	200 Hz
Number of bunches/rf pulse	N_b	10 bunches
Number of bunches /sec	f_b	2000 bunches/sec
Normalized emittance		
Horizontal	ε_{xn}	3×10^{-6} rad·m
Vertical	ε_{yn}	3×10^{-8} rad·m
Beam power	P_b	0.64 + 0.64 MW

Figure 1. JILC (Japan Intermediate Energy Linear Collider)



Interaction Point and Final Focus System

The parameters for the interaction point and the final focus are listed in Table 3. The transverse beam dimension at the interaction point (I.P.) is chosen as $\sigma_x = 290$ nm and $\sigma_y = 2$ nm in order to obtain a high luminosity of $3.1 \times 10^{33} \text{cm}^{-2}\text{sec}^{-1}$. This gives the disruption parameters $D_x = 0.103$ and $D_y = 13.5$. The bunch length is assumed to be $\sigma_z = 60$ µm. If it is longer, the vertical disruption parameter becomes too large, causing a luminosity reduction due to the kink instability. If shorter, on the other hand, the cancellation of energy spread due to the longitudinal wake in the linac using the off-crest acceleration will become less effective.

Table 3. The parameters of interaction point and final focus system.

Interaction point

R.m.s beam size at IP		
Horizontal	σ_x^*	290 nm
Vertical	σ_y^*	2.2 nm
Aspect ratio	$R = \sigma_x^*/\sigma_y^*$	132
R.m.s. bunch length	σ_z	60 µm
Disruption parameter	D_x/D_y	0.103/13.5
Pinch enhancement factor	H_D	1.5
Beamstrahlung parameter	Υ	0.20 (average)
Energy loss by beamstrahlung	δ	7.1 % (average)
Number of photons per electron	η_γ	1.25

Final Focus System

Beta Function at IP	β_x^*/β_y^*	11/0.05 mm
Momentum acceptance	$\delta p/p$	± 0.4%
Total length (per beam)		193 m
Distance between last quads	L^*	1.0 m
Pole tip field of the last quad		1.4 T
Half aperture of the last quad		0.96 mm
Crossing angle		~ 5 mrad

The requirements on the final focus system are $\beta_x = 11$ mm, $\beta_y = 0.05$ mm and the momentum acceptance of ± 0.4 %. These are satisfied by a design which employs 26 quadruples, 6 dipole and 8 sextuple magnets with the total length of about 200 m. The half aperture and the pole tip field of the last quad are 1 mm and 1.4 Tesla which is feasible at the present technology. Design studies for higher beam energies will be carried out in the near future.

For the parameters of the interaction point described above, the beamstrahlung energy loss will be about 7 % and the parameter Υ (= 2/3 x (critical energy)/(beam energy)) is 0.45 at the maximum and 0.20 in averaged.

One of the recent topics of the beam-beam interaction in the low-energy e^+e^- pair creations. The created pairs are deflected by large angles by the beam-beam field and may be a potential source of background. The most important processes are $\gamma e \rightarrow ee^+e^-$ (γ by beamstrahlung) and $e^+e^- \rightarrow e^+e^-e^+e^-$. The number of pairs through these processes are estimated to be ~ 6 x10^4 and ~ 2x10^4 per collision respectively. Particles below ~ 1 GeV will be trapped by the solenoid flux line and will not cause background. Since the maximum beam-beam deflection of 1 GeV particles is ~ 40 mrad, a large crossing angle of larger than 40 mrad is required to avoid the background. This can only be achieved by the crab-crossing scheme. A tentative conclusion of our studies is that the background caused by the pairs is not fatally serious. A small crossing angle of ~ 5 mrad without crab-crossing might be enough.

Main Linacs

The choice of an rf-frequency of main linac is very important since the rf-frequency determines design parameters of the main linacs. There is no analytic solution to the question of the optimum rf-frequency since the parameters can be obtained by the scaling low. However, the rf-frequency should be selected in the range between 10 GHz and 30 GHz, where the gradient of 100 MeV/m can be produced. The size of the structure is limited by the tolerance requirements to machine tools. It is found that the rf-frequency around 10 GHz is optimum in order to produce accelerating structures by extending the conventional technique.

Table 4. Design parameters of X-band main linacs.

Beam final energy	E_{fin}	200 GeV
Beam injection energy	E_{inj}	10 GeV
RF frequency	f_{rf}	11.424 GHz
Accelerating gradient	G_{acc}	100 MeV/m
Bunch spacing	t_b	16 buckets=1.4 ns
Number of bunches	N_b	10 bunches
Initial r.m.s.energy spread		1 %
R.m.s. bunch length	σ_z	60 μm
Accelerating mode		$2\pi/3$
Structure length	L_s	0.866 m (99 cell)
Attenuation parameter	τ	0.50
Filling time	t_f	90 nsec
Normalized elastance	S_0	0.71 Vm/pC
Extraction efficiency	η_b	15.1 %
Beta function	$\beta(s)$	$3.0(E_b/10)^{0.5}$ m
Energy difference		
for BNS damping		± 0.3 %
due to longitudinal wake		± 0.5 %

The tentative parameters of the main linacs are listed in Table 4. The structure assumed for the JILC is a conventional $2\pi/3$ mode, constant gradient disk-loaded structure. A cold model has been tested and prototypes of the structure for high-power test will be constructed. The other type of structures are also studied to investigate the possibility of these structures, for example damped cavities of higher order modes and the structures of the other modes.

The rf sources assumed for the main linac are X-band klystrons driven by high-voltage and short pulse. In order to increase the peak power from the klystrons, the following two methods are possible: If the klystron is applied by the shorter pulse less than 1 μs, the higher voltage can be applied to the diode without breakdown. By using the X-band klystron and the MPC (magnetic pulse compression) scheme, the rf peak power of 200 MW will be obtained at 600 kV in the 200 ns pulse duration. The study group is developing the X-band klystrons and modulators by means of MPC scheme. The second method is an rf-pulse compression scheme.

Preacceleration Linacs

The bunch length is assumed to be σ_z = 60 μm at the final focus. The bunch length in the damping ring is estimated to be 4.5 mm, and two stages of bunch compression are required. The beam from the damping ring is compressed by the first bunch compressor with the compression ratio of 13. The bunch length is reduced from 4.5 mm to 340 μm. The bunch should be re-compressed to 60 μm by the second bunch compressor after re-accelerated by the preacceleration linac. The design parameters of the preacceleration linacs are listed in Table 5. The preaccelerators consist of conventional S-band linacs driven by 100 MW klystrons. The structure is a conventional $2\pi/3$ mode, constant gradient disk-loaded structure.

Table 5. Design parameters of preacceleration linacs

Beam final energy	E_{fin}	10 GeV
Beam injection energy	E_{inj}	1.54 GeV
Rf frequency	f_{rf}	2.856 GHz
Accelerating gradient	G_{acc}	40 MeV/m
Bunch spacing	t_b	4 buckets=1.4 ns
Number of bunches	N_b	10 bunches
Initial r.m.s. energy spread		1 %
R.m.s. bunch length	σ_z	350 μm
Accelerating mode		$2\pi/3$
Structure length	Ls	3.0 m
Attenuation parameter	τ	0.50
Filling time	t_f	600 nsec
Normalized elastance	s_0	0.8 Vm/pC
Extraction efficiency	η_b	3.3 %
Beta function	$\beta(s)$	$2.0(E_b/1.54)^{0.5}$ m
Energy difference		
for BNS damping		± 0.05 %
due to longitudinal wake		± 0.14 %

Damping Ring

A computer program has been prepared to design the damping ring for JILC. The normalized emittance required for the damping ring is 2.5 μmrad. The required damping time should be less than 2.5 msec. In order to achieve these extremely low emittance and short damping time, the wigglers with the total length of 76 m is combined to the ring. The 7.6 m-long wiggler unit is composed of the permanent magnets, and the designed wiggler field is 1.8 Tesla, which is limited by the permanent magnets. The arc is composed of 27 separated function FODO cells since the simple lattice makes it possible to obtain operational simplicity. The rf-frequency of ring cavities is 1.428 GHz in L-band. The ring contains 8 bunch trains of 10 bunches each. The bunch separation of each bunch is two buckets of the rf-frequency. One bunch train is kicked out every 5 ms second, after the bunches circulate in the ring during 16 damping times. The design parameters given by the program are optimized to obtain a smallest ring which satisfies low costs and simplicity. Table 6 shows the parameters of the damping ring design for JILC.

Table 6. Design parameters of the damping rings

Type		$FODO_{arc}$ + Wiggler
Beam energy	E_b	1.54 GeV
Circumference	C	176.0 m
Bending magnet	B_0	1.15 T
Bending radius	r_b	4.46 m
Normalized emittance	$\gamma\varepsilon_0$	2.1×10^{-6} rad·m
Damping time	τ_x/τ_y	2.5/2.5 msec
Repetition rate	f_{rep}	200 Hz
Rf frequency	f_{rf}	1.428 GHz
RF peak voltage	V_{rf}	0.92 MV
Bunch spacing	t_b	2 buckets=1.4 ns
Number of bunches	N_b	10 bunches
Number of bunch train	t_b	8
Bunch current	I_b	3.35 mA
Total current	I_{tot}	218 mA
R.m.s. bunch length	σ_z	4.5 mm
Energy spread	$\Delta E/E$	0.76×10^{-3}
Momentum compaction factor	α_p	2.2×10^{-3}
Number of FODO cells in arc		54
Wiggler length	L_w	76 m = 7.6 m/unit x 10
Wiggler field	B_w	1.8 T

Injector Linacs

The injector linac produces the multi-bunches with the bunch separation of 4 buckets at S-band frequency. An rf-gun is applied to generate the multi-bunches with the longer bunch separation, since the separation can easily be selected by the mode-locked laser. The rf-gun provides the low-emittance beam of high-current. The design parameters of the injector linac is listed in the Table 7. The rf power sources and the accelerating structures are of the same parameters of the preaccelerating linacs.

Linac for Positron Production

For linear colliders, the intense positrons is required to obtain high luminosity since the positrons are swept out after collision at the interaction point. The R&D for the positron production is highly required. A program has been prepared to design both the positron target and the high gradient accelerating region. The beam energy is determined by the yield of the positrons at the target and the trapping efficiencies in the high gradient structures. The results of the calculations show that the electron bunches with the beam energy higher than 10 GeV are required. The rf-gun is utilized as the electron source of the linac for positron productions. The design parameters of the linac for positron production is listed in Table 8.

Table 7. Design parameters of the injector linacs

Beam final energy	E_{fin}	1.54 GeV
RF frequency	f_{rf}	2.856 GHz
Accelerating gradient	G_{acc}	40 MeV/m
Bunch spacing	t_b	4 buckets = 1.4 ns
Number of bunches	N_b	10 bunches
Normalized emittance	$\gamma\varepsilon_0$	1.0×10^{-2}
R.m.s. bunch length	σ_z	3 mm
Accelerating mode		$2\pi/3$
Structure length	L_s	3.0 m
Attenuation parameter	τ	0.50
Filling time	t_f	600 nsec
Normalized elastance	S_0	0.8 Vm/pC
Extraction efficiency	η_b	3.3 %

Table 8. Design parameters of the linac for positron production

Beam final energy	E_{fin}	10 - 30 GeV
Rf frequency	f_{rf}	2.856 GHz
Accelerating gradient	G_{acc}	40 MeV/m
Bunch spacing	t_b	4 buckets =1.4 ns
Number of bunches	N_b	10 bunches
Accelerating mode		$2\pi/3$
Structure length	L_s	3.0 m
Attenuation parameter	τ	0.50
Filling time	t_f	600 nsec

TEST ACCELERATOR FACILITY (TAF)

As for the linear collider, the beam should be stably accelerated so as to collide the sub-micron beams at the interaction point. Therefore, the R&D is required how to obtain the stability of linacs and damping rings. The KEK R&D group has decided to construct a new experimental facility as a major R&D program.

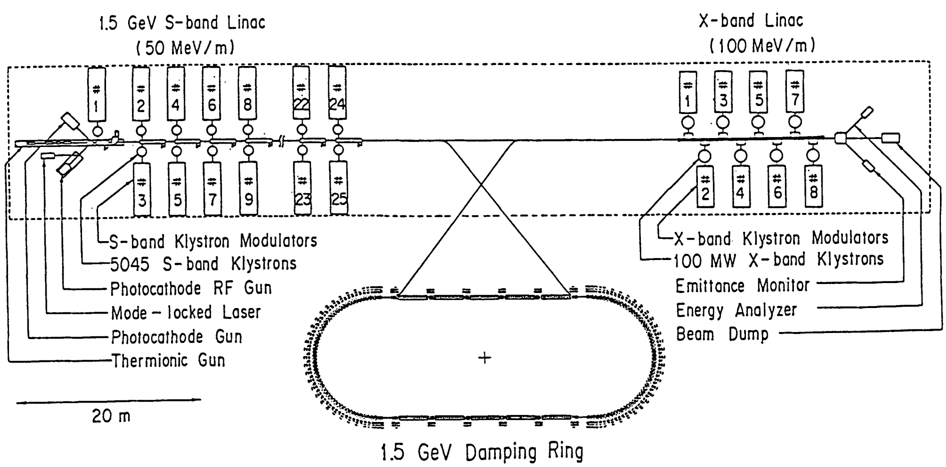
The proposed Test Accelerator Facility (TAF) is a prototype of the JILC. The TAF consists of a 1.54 GeV S-band linac, 1.54 GeV damping ring and 1.0 GeV X-band linear accelerator. The major part of the JILC can be tested by using the test facility. The S-band linac is an injector of the damping ring. A high current single bunch and multi-bunches are accelerated up to 1.54 GeV. The low emittance beam from the ring is re-accelerated by the high gradient X-band linac up to 2.5 GeV. The beam from the X-band linac will be utilized for the test of the prototype final focus system.

The TAF project will be progressed through three phases. Both the S-band and X-band linacs will be constructed through phase-I and phase-II, and the damping ring will be completed in phase-III. Table 9 shows the parameters of the linacs for the TAF. The 0.3 GeV S-band linac is under construction at the TRISTAN Nikko experimental hall. In order to complete the whole accelerator test facility, a new building with an accelerator tunnel has been proposed.

Table 9. Design parameters of the linacs of TAF

Linac	S-band		X-band
Phase	I	II	II
E_b(GeV)	0.3	1.54	1.0
E_a(MeV/m)	50	50	100
f_{rf}(GHz)	2.856	2.856	11.424
P_{rf}(MW/structure)	200	200	50
N_k(Klystrons)	4	24	10
N_s(structures)	2	12	20
L_s(m/structure)	3	3	0.5
N_e(electrons/bunch)			
Single bunch	5×10^{10}	5×10^{10}	5×10^{10}
Multi-bunches	1×10^{10}	1×10^{10}	1×10^{10}

Figure 2. The Test Accelerator Facility (TAF)



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The work discussed in this papaer represents the dedication and effort of the linear collider study group. A number of contributions to this conference contain more specific and detailed reports on the various aspects of the JLC project.

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