THE JAPAN LINEAR COLLIDER PROJECT

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Abstract

The research and development for the Japan Linear Collider have been concentrated on X-band and C-band linac technologies as well as the Accelerator Test Facility (ATF). The ATF, which comprises a 1.54-GeV S-band linac and a damping ring, is a test facility for verifying feasibility of the multi-bunch scheme in the front-end of linear colliders. Since commissioning in January, 1997, the research priority at the ATF has been put on studying first-order optics and achieving small emittances. We succeeded in precise measurement of the beam size of the order of 10 μm. In the developments of the X- and C-band linac technologies are included the diffusion bonding of accelerating structures of the X-band linac, the invention of the delay line distribution system (DLDS) for rf pulse compression, the development of X- and C-band klystrons, a compact modulator system, a C-band accelerating structure of the choke mode cavity type. Results of the R&D and future prospects will be reported.

1 INTRODUCTION

The JLC project assumes a 500-GeV linear collider applying X-band linacs as the main accelerators. In parallel, a C-band linear collider design has been pursued as well, to back up the X-band linear collider plan. In the JLC design, as shown in Table 1, are required the multi-bunch beam of electrons and positrons with very low emittances to achieve the design luminosity. The activity at KEK regarding the JLC, therefore, has been focused on the construction of the Accelerator Test Facility (ATF), the development of technical components of the main accelerator as well as the overall design study. The results of the R&D was published in April, 1997 as the JLC Design Study Report [1].

The X-band linear accelerator is the most crucial technical component of the JLC in engineering and cost aspects. Among all sorts of technical challenges, we have devoted ourselves to the development of fabrication techniques of accelerating structures, in an accuracy as high as 10 μm which is unprecedented in the conventional accelerator technology. Microwave sources are crucial as well. The development of klystrons has been our first priority effort during the R&D. Regarding the rf power distribution system, we have made a noticeable contribution. Mizuno has invented a new rf power distribution system [2], now called as the Delay Line Distribution System (DLDS). This has been recognized as a promising technique of X-band linear colliders, because of high power-efficiency.

Table 1: Comparison of main parameters between JLC and ISG.

		JLC	ISG
Energy	GeV	500	500
Luminosity	10^{33}	8.3	6.3
$\gamma\varepsilon_x$ at IP	nm-rad	3400	5000
$\gamma\varepsilon_y$ at IP	nm-rad	50	100
β_x/β_y at IP	mm	10/0.1	12/0.16
σ_x/σ_y at IP	nm	260/3.1	350/5.7
Repetition rate	Hz	150	120
Bunch charge	10^{10}	0.7	0.98
Bunches/RF pulse		85	87
Bunch separation	ns	1.4	2.8
Structure type		DS	RDDS
Unloaded gradient	MV/m	73	77
Structure length	m	1.31	1.8
Klystron Peak Power	MW	67	75
Klystron Pulse Length	μs	0.75	1.5
Pulse method		4/3 DLDS	4/4 DLDS
RF system efficiency	%	28	38

DS: Detuned Structure
RDDS: Round Damped Detuned Structure
DLDS: Delay Line Distribution System

We also have made remarkable progresses in the C-band rf technology [3]. They include successful developments of 50-MW C-band klystrons, a 110-MW compact modulator, a coupled-cavity pulse compressor, and a choke-mode cavity type accelerating structure.

The purpose of the ATF [4] is to verify feasibility of the multi-bunch scheme in all parts of the front-end; from generation, acceleration to damping and compression of multi-bunch electron and positron beams. The ATF can also provide realistic experience regarding instrumentation systems for very low emittance, multi-bunch beams and machine tuning processes using the instrumentation.

It should be noticed that these R&Ds have been done in international collaboration. The collaboration with SLAC, in particular, has been close. The JLC and the NLC of SLAC have similar designs, and the collaboration is quite natural. It has been directed in the framework of the Agreement of U.S./Japan Cooperation in High Energy Physics for more than ten years. In February, 1998, Directors of KEK and SLAC have signed Memorandum of Understanding regarding International Linear Collider Optimization Study Group (ISG), and agreed to jointly pursue further design studies. In Table 1 are shown a new set of design parameters recently proposed by ISG, which will be referred to as the work reference in the joint study. It is also noted that KEK has been in collaboration with BINP as well, in the development of X-band microwave technologies.

2 ATF ACTIVITIES

The ATF consists of the 1.54-GeV S-band Linac and the Damping Ring (DR). To simulate the JLC scheme, the Linac is designed to accelerate trains of 20 electron bunches at intervals of 2.8 ns with a bunch charge of $2x10^{10}$. The horizontal emittance of the DR is 1.1 nm-rad, the smallest of all existing storage rings. The DR utilizes combined function bends (horizontally defocusing) and horizontally focusing quads. With this combination, we are able to achieve this small emittance. The design goal of the vertical emittance is 1 % of the horizontal one.

The construction of the ATF started in 1991. The Linac has operated since November 1995, and the DR since January 1997. Results of commissioning of the Linac and the DR have been reported in [5] to [7].

2. 1 ATF Linac

Trains of electron bunches are extracted from a thermionic gun with a bunch length of 1 ns (FWHM) at an energy of 170 kV, and, after further bunched to 20 ps (FW) with a subharmonic buncher (357 MHz) and a buncher (2856 MHz), they are accelerated with high-gradient accelerating units to 1.54 GeV.

Technical problems still exist with the modulators, and the energy has been limited to 1.4 GeV. The bunch charge attained so far is $1.7x10^{10}$ in the single-bunch mode, close to the design value. The existence of energy tail, however, is a problem. We are now improving the sub-harmonic buncher, to resolve the energy tail problem, in collaboration with scientists of SLAC.

Tuning of the Linac in the multi-bunch mode is still premature. So far, we have attained a total bunch charge per train of $7.7x10^{10}$, compared with the design value of $4x10^{11}$. For ease of further tune-up of the Linac, implementation of single-pass BPMs in the Linac is under way.

The energy of accelerated beams decreases from head to tail in a bunch train due to beam loading effects, when the Linac is operated in the multi-bunch mode. Development of multi-bunch energy compensation systems is one of the main subjects to be investigated at the ATF. We have proposed two energy compensation methods; the $-\Delta f$ energy compensation method and the phase compensation method. In the $-\Delta f$ method, the rf frequency is sightly changed from the nominal one to bring about phase slips between bunch and rf. The results of the test was promising [8]. Recently, we have just started preparation for the test of the phase compensation method. In this method, the phase of rf is changed on the bunch-by-bunch basis to compensate energy variations among bunches.

2. 2 ATF Damping Ring

(a) First-Order Optics and Lattice Modeling

The first priority of our DR activities right now is to confirm the performance of the ring with respect to first-order beam optics and to develop the method of beam-based diagnosis of lattice magnet parameters.

Lattice modeling requires information of actual field strengths of the magnets. Correction factors to the design values (sometimes called "fudge factor") are obtained with beam-based diagnosis. The method is to kick the beam at a point of the orbit and to measure resultant position changes along the downstream orbit. For these purposes, precise measurements of transverse beam positions are essential. We have been developing a single-pass BPM system capable of bunch-by-bunch position measurements in an accuracy of 5 μm. This is quite unique compared with the BPM system of ordinary storage rings, and is a challenging task in linear collider technologies. Until recently the achieved resolution was 40 μm. We have confirmed to obtain 20 μm with an improved circuit, and efforts will be continued [9, 10].

Agreement between measured and calculated optics functions is good, considering the accuracy of the present instrumentation system [11]. In the calculation of optics functions, we use measured fudge factors for the magnet parameters. We have now convinced that the present beam-based diagnosis of lattice magnet parameters works as expected. We will continue more detailed studies on the first-order optics, by refining the instrumentation systems and the lattice modeling algorithm.

Energy spread of the DR is deduced from the horizontal beam size of the extracted beam, measured at a point of high dispersion. Some other beam parameters have been measured; damping time [12], lifetime [13], and impedance [14].

(b) Beam Size Measurement (Emittance)

Two methods have been implemented to measure beam sizes of the DR; an SR-interferometer (Mitsuhashi monitor) and a wire scanner method at the extraction line. The SR interferometer, an application of the Young interferometer, is a method invented by T. Mitsuhashi [15]. The beam size can be deduced from measurements of interference patterns, i.e. by measuring visibility as a function of distance between slits. The measurement limit of the present system is 5 μm in the vertical plane in practice, not the fundamental limit, though. This is a very versatile and useful beam size monitor in the μm range. Important is that this can be used as realtime monitor, which measures change in beam size during tuning.

For the horizontal beam size, however, situation is different from the vertical case, because the synchrotron radiation corn sweeps the SR-interferometer. Mitsuhashi has shown that, even in the horizontal case, one can obtain the beam size if one assumes bunch shape. The reliability of horizontal measurements is limited at 20 μm for some reasons. The recent results of the development on the SR-interferometer will be reported elsewhere in these Proceedings [16].

The wire scanner method is to measure the beam size at the extraction line. This method is, in practice, rather difficult compared with the SR-interferometer, but the development of the measuring system for the extracted beam is quite important as a front-end technology. We have applied two different methods; the four-scanner method and the quad-scan method. In either case, special precautions have been taken to compensate effects of field jitter in the extraction kicker magnets, when measuring horizontal beam sizes, in particular. Considering that the beam is very thin in the vertical direction, any coupling between the horizontal and vertical planes is harmful. In this respect, the system is still to be upgraded in the vertical measurement. Results will be reported elsewhere in These Proceedings [17].

The typical r.m.s. beam size measured with the SR interferometer is 39 µm and 15 µm in the horizontal and vertical directions, respectively. The vertical emittance can be estimated to be around 0.05 nm-rad, almost 5 % of the natural emittance. Note that the effect of the spurious vertical dispersion is negligible for the present conclusion. In the horizontal case, however, the contribution to the beam size from the energy spread is bigger than that from the emittance, so that the deduced emittance value is affected by measurement errors of related quantities. The estimated value now is 0.8 nm-rad, and we conclude the design emittance is almost attained. Measurements at the extraction line has been successful in the horizontal plane, and confirmed this conclusion.

The eventual goal of 1998 at the ATF is to achieve a very low emittance, or a coupling of 1 %, in the vertical plane, by improving the instrumentation systems and the correction algorithm.

3 X-BAND LINAC RF SYSTEM

3. 1 X-band klystron

Demonstration of truly usable 80-MW class, 2-µs X-band klystrons is the eventual goal. In 1997 and early 1998, we have attained promising results on the X-band klystrons.

Since 1997 we have been developing X-band klystrons employing a traveling-wave output structure, aiming at reducing electric field strengths. Although the first model (XB-72k#7), which was designed in collaboration with BINP, exhibited beam instabilities in the output structure, the second model (#8), with some modifications, succeeded in achieving 55 MW. Further modifications were made on the output structure to improve efficiency in the third model (#9), and we have achieved 70 MW with an efficiency of 30 %. Table 2 summarizes the principal parameters of x-band klystrons tested so far as well as that in design.

Table 2: X-band klystron status.

		XB-72k #8	XB-72k #9	XB-72k #10	Russian PPM tube
Perveance		1.23	1.25	1.2	0.95
RF power	MW	55	72(65)	[123]	73,50
Voltage	kV	530	524	[550]	550
Pulse length	µs	0.5	0.27 (1.5)	[1.5]	0.1, 0.4
Efficiency	%	20	30	[47]	30
Rep. rate	Hz	5	5(50)	[50]	5

( ) : Values to be tested in future
[ ] : Design values (maximum)

A remarkable event in 1997 is the set-up of the klystron modeling group at KEK. We have introduced a simulation code MAGIC, 2D and 3D particle-in-cell simulation codes, for the design of klystrons. To check code performance, we have compared the experimental results on XB-72k#8 and a XL-4 klystron made by SLAC, with the MAGIC simulation results. Agreement was quite good. (We greatly appreciate that technical data and operational results of XL-4 have been provided by courtesy of SLAC.)

We have been proceeding to the next model (#10), which will be finished in November, 1998. In the computer simulation, we can achieve an output power of more than 120 MW at a low maximum electric field in the output cavity of 85 MV/m and an efficiency as high as 47 %, which can be compared with 75 MW at 105 MV/m and 47 % of XL-4. If we succeed in a power of 120 MW at a pulse length of 1.5 µs (modulator limited), it would be promising to operate it at a reduced power such as 80 MW at a longer pulse length of more than 2 µs, which is an eventual goal. Therefore, this model would be a milestone toward our eventual goal. It should also be noted that this is the first one designed with the MAGIC code.

The activities on the developments of the X-band klystrons was published recently in [18], and will be reported elsewhere in these Proceedings as well [19].

Regarding klystrons employing periodic permanent magnet (PPM) focusing, we have collaborated with BINP in design and fabrication. A PPM tube was delivered from BINP to KEK last May, and has been tested. The results are also shown in Table 4. We are now planning to go on to the next stage; design of a PPM tube, approaching our eventual goal with an output power of 80 MW, a pulse length of 2 µs, an efficiency of 60 % and a repetition rate of 120 or 150 Hz.

We have started the development of an 100-MW class rf window for klystrons. It is of the mixed mode TW type (TE_{11} + TE_{12}). A cold model will be delivered by the end of June, and a high-power model will be tested in December.

Regarding the DLDS, the idea of multi-mode DLDS has been proposed by SLAC, a more sophisticated one than the original single-mode DLDS by Mizuno. With SLAC, we are fabricating a cold model of a mode launcher/extractor, and are planning a microwave polarization stability experiment in waveguides.

3. 2 X-band accelerating structure

(a) One-shot diffusion bonding [20]

Among accelerating structures proposed for eliminating the effect of induced wakefields; detuned structure (DS), damped detuned structure (DDS) and heavily damped structure, the JLC has proposed a structure based on the DS principle. The accelerating unit is 1.3 m in length and 80 mm in outer diameter.

For the DS scheme to work, precise frequency control of each cell as well as precise cell alignment are necessary; frequency errors better than 10^{-4}, and lateral cell misalignments smaller than 5 μm.

Conventional brazing technique is not applicable because of large frequency shifts during brazing. We have been developing a new approach; one-shot diffusion bonding. In this method, cells, machined in ultra-high precision, are stacked along a precise V-block and bonded at 850–900°C under compression in a vacuum furnace.

In tests with 30 cm long structures, aiming at verifying the feasibility of the diffusion bonding, we have confirmed that cells are machined in high precision; flatness better than 0.3 μm, surface roughness better than 50 nm and scattering of outer diameter within ±0.5 μm. The cell-to-cell frequency deviation was well within 1 MHz before bonding, and the change during bonding was small.

We have so far fabricated several prototype models of the DS of 1.3 m in length. Findings obtained in these tests are summarized as follows:

(1) Cells were aligned within 5 μm with respect to the V-block, and the cell-to-cell misalignment was less than 1 μm.

(2) Cell alignment was deteriorated by 20 μm during rotation of the stacked cells from the stacking position to the upright position for bonding.

(3) A smooth bend of the order of 30 μm remained after bonding. Note, however, that this can be corrected afterward, because it is smooth. The lateral slip between neighboring cells was less than 2 μm.

(4) A shrinkage in the axial direction occurred during the bonding process; about 1 μm/cell. The mechanism of shrinkage is not clear, but it could be related to the rather long bonding period of the order of one hour at high temperature and compression.

(5) To inspect the quality of the bonding interface, we cut a finished structure, and found defects at interfaces. The size was unbelievably large; of the order of 100 μm, while there was no problem in mechanical and vacuum properties. We have not understood the reasons yet.

Meanwhile, we have fabricated a structure of 1.8 m in length and 60 mm in outer diameter, which is the same as the DDS structure proposed by SLAC. This is longer and thinner than the JLC structure, and precautions were taken to prevent deformation during the fabrication process. A remedy we took in the first trial was the introduction of pre-bonding, i.e. bonding at a lower temperature of 150°C, but under a big load of 600 kg with stacked cells on the V-block, prior to the final bonding. The result was promising.

Recently, a real structure based on the DDS principle proposed by SLAC, is being fabricated in the inter-laboratory collaboration by SLAC, LLNL and KEK. KEK has taken part in diffusion bonding of machined cells. The first trial was unfortunately a failure. The cause of the failure has been analyzed, and we are now fabricating a new one.

Regarding the fabrication of accelerating structures, we will continue R&D in a couple of years, to establish the basics of fabrication process and to develop techniques appropriate to mass production.

(b) Wake field measurements

To confirm the performance of the DS structure, we have measured the wake field characteristics at the Accelerator Structure SETup, or ASSET of SLAC [21]. It was confirmed that cancellation of dipole wake field effects by two orders of magnitude was obtained with the detuned structure. This is consistent with a simulation made with the open-mode expansion code, a wake field evaluation code, which was developed by M. Yamamoto.

(c) High Field Test

We have attained an accelerating gradient of 50 MV/m with a short model of 30 cm in length. We have just started high field tests with a 1.3 m long DS, to verify the high-power performance with a full-scale model, since dark currents usually increase with structure length [22].

4. C-BAND LINAC RF SYSTEM

The design study of a linear collider based on C-band linacs has been pursued for many years. We started hardware R&D on the C-band linac rf system in 1996. The goal is to set up one unit of the C-band linac operating at high powers, and to make system reliability check. Technology jump from the S-band linac is modest in C-band linacs. In these R&Ds, however, all components have been designed looking for high reliability and good efficiency, which are essential requirements for linear colliders.

We have already developed 50-MW class C-band klystrons, and a 110-MW pulse modulator, a pulse compressor, a accelerating structure and other microwave components. All of these, except for the pulse compressor, are prototype models, which are capable of high power operations at the design ratings.

The results of the R&D on the C-band linac rf system are reported in [3] together with a comprehensive list of the published reports.

4. 1 C-band klystron

We have developed the E3746 klystrons in collaboration with Toshiba Corp.. The first model incorporated a single-gap output structure, but we adopted the 3-cell traveling-wave output structure to improve efficiency in the second model. Table 3 lists the performance obtained so far as well as the design goal. An analysis has shown a possibility of an efficiency of 47 % with a slight modification to the second model. In 1998, we will proceed toward design and fabrication of the third model, incorporating periodic permanent magnet focusing.

Table 3: E3746-klystron performance; achieved vs goal

		#1	#2	Goal
Peak power	MW	46.4	53	50
Efficiency	%	41.5	44	45
Pulse width	μs	2.5	2.5	2.5
Repetition rate	Hz	50	50	100
Gun Voltage	kV	351.2	367	350
Focusing		Solenoid	Solenoid	PPM
First test		Aug. 97	May 98	

4. 2 C-band accelerating structure

The proposed C-band linac assumes the accelerating structure using the choke-mode cavity invented by Shintake [23]. This is a heavily damped structure which strongly damps higher-order modes.

Some years ago, we fabricated an S-band test model of the choke-mode cavity structure, of 55 cm in length, and verified performance of this structure through high-power tests, beam acceleration tests and wakefield measurements [24]. An accelerating gradient of 50 MV/m was achieved with this S-band model.

We are now fabricating a prototype C-band accelerating structure of 1.8 m in length, which is capable of high power operations. We are planning an induced wakefield measurement using the ASSET at SLAC in 1998.

5 FUTURE PROSPECTS

The ATF is a good playground for developing the instrumentation systems and the control processes, actually using beams. While doing the first-order optics study at the DR, we will improve the Linac toward reliable operation in the multi-bunch scheme, eventually aiming at the operation of the DR with multi-bunch beams. Regarding long-term plan of the ATF, bunch compression experiment would be a challenging task we should tackle as a future program.

We will continue the development of X-band linac technologies in coordination of ISG. Most crucial are developments of truly usable klystrons as well as the fabrication technique of structures, compatible with mass production, in particular.

We have thought it quite important to assemble and test for an extended period at high powers, a complete set for either X-band or C-band linac rf system, the schedule vague, though.

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