ACTIVITIES ON THE LINEAR COLLIDER PROJECT AT KEK

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Abstract

This paper gives an overview of the on-going activities at KEK towards an electron-positron linear collider of a sub-TeV up to a TeV energy scale.

1 INTRODUCTION

We will review the research, development and design efforts in Japan, particularly at KEK, towards a future electron-positron collider, JLC, with the center-of-mass energies of a sub-TeV up to a TeV-scale.

A brief history and the project status is given in Section 2. Section 3 introduces the basic accelerator scheme considered for JLC. Some highlighting topics from recent R&D results are presented in Sections 4, 5 and 6.

2 JLC PROJECT HISTORY AND STATUS

In mid-1980's strong interests in pursuing electron-positron (e^+-e^-) collisions physics in a sub-TeV to a ∼TeV range emerged in the Japanese high energy physics (HEP) community. In response, systematic design work towards a linear collider, together with prototyping efforts on the RF power sources and components, began at KEK and at a number of Japanese universities. These efforts resulted in a publication titled "JLC-1 report" [1] in 1992 which gives an early systems design for the JLC.

At KEK construction of the Accelerator Test Facility (ATF)[3] began earlier in 1988 as a test bed for an upstream portion of a linear collider. It includes a multi-bunch-capable electron source, a 1.54 GeV S-band linac, a 1.54 GeV damping ring prototype and associated hardware systems. Also, participation in the FFTB program at SLAC, for demonstrating the feasibility of the beam optics design which is required to realize a nano-meter-scale spot size at the collision point, began in 1989. Physicists and engineers from KEK and other Japanese institutes and industry made numerous contributions to this program[4].

Later, to articulate the importance of an e^+-e^- linear collider as the main future project for the Japanese HEP community, and to clarify its project scope, a series of official statements were issued by the Japanese High Energy Physics Committee (HEPC) and its subcommittee[5]. In parallel to these, the design of the JLC was significantly updated, and a totally-rewritten accelerator study report which incorporate more recent results from the R&D was published in 1997[2][6].

In the past few years, extensive discussions ensued in Japan, concerning the long-term values and benefits of developing a linear collider design in the framework of an international cooperation. As a result, a Memorandum of Understanding on an "International Linear Collider Design Optimization Study Group" (ISG) was signed between the directors of KEK and SLAC in early 1998. The mission of the KEK-SLAC ISG is to produce a pre-design report within one to two years. It was agreed that joint R&D and design optimization activities are to be carried out between (but not limited to) KEK and SLAC for this purpose. As of late March, 1998 a set of base common design parameters have been tentatively arrived at[7]. Joint reviews and development of various subsystems design of a linear collider are in progress.

3 ACCELERATOR SCHEME OF JLC

Figure 1 shows a schematic diagram of JLC. The target center-of-mass energy is $250 \sim 500$ GeV in phase-I, and ~ 1 TeV or higher in phase-II. Tables 1 and 2 give the most up-to-date basic machine parameters[7] in case the main linacs are built using the X-band (11.4 GHz) technology. Table 3 gives the parameter set for an alternative, back-up case, when the C-band (5.7 GHz) RF technology is used for the the main linacs.

Item	Value	Unit
#Electrons / bunch	9.8×10^9	
#Bunches / train	87	
Bunch separation	2.8012	ns
Train length	240.9	ns
RF frequency	11.424	GHz
RF wavelength	26.242	mm
Klystron peak power	75	MW
Length / cavity unit	1.8	m
a/λ	average 0.17	
Filling time	118	ns
Shunt impedance	95	MΩ/m
E_{acc}(no-load)	77	MV/m
E_{acc}(loaded)	56.9	MV/m
Normalized emittance	3×0.03 (Linac)	10^{-6}m.rad
	3.5×0.057 (IP)	10^{-6}m.rad
Bunch length	125	μm

Table 1: Partial list of tentative JLC parameters as of late March, 1998 [7], if the main linacs are built based on the X-band technology. The repetition rate could be 150 Hz instead of 120 Hz.

The electron beam is created by a standard thermionic gun, or a laser-driven photocathode gun which can produce polarized electrons. The positron beam is produced

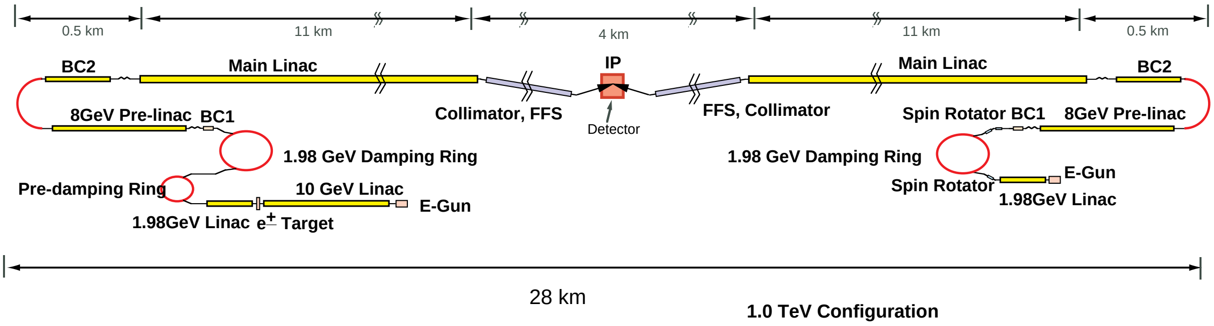

Figure 1: Schematic layout of JLC in its $E_{cm} = 1$ TeV configuration.

E_{CM}	500 GeV	1 TeV	
#cav/linac	3207	6692	
#klystrons/linac	2138	4462	
Length/linac	5.25	10.96	km
P(wall-plug)	99	200	MW
Rep. rate	150	145	Hz
$\beta_x^* \times \beta_y^*$	10×0.1	14×0.1	mm×mm
$\sigma_x^* \times \sigma_y^*$	260×3	220×2.2	nm × nm
Disruption	0.1×8.4	0.07×7.0	
$< -\Delta E/E >$ due to BSM	4.1	8.0	%
Multibunch blowup factor	1.56	1.18	
Lum. pinch enhancement	1.71	1.65	
Luminosity	8×10^{33}	12.6×10^{33}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Table 2: Tentative JLC parameters (continued), if the main linacs are built based on the X-band technology. Parameters that would vary for $E_{\mathrm{CM}} = 500$ GeV and 1.0 TeV are shown.

by a 10 GeV electron beam from an S-band linac, impinging on a positron-production target. Both electron and positron beams consist of multi-bunch trains for maximizing the luminosity for a given, 38 % linac RF system power efficiency. The electron beam is injected directly into a 1.98 GeV damping ring, whereas the positron beam, having a larger emittance, is first to be "cooled down" to an invariant emittance of $\gamma\epsilon_x \simeq 10^{-4}$ m in a pre-damping ring. The equilibrium emittances from the main damping rings are, respectively, $\gamma\epsilon_x = 3 \times 10^{-6}$ and $\gamma\epsilon_y = 3 \times 10^{-8}$ m. The $\sim$ 5 mm-long bunches from the damping rings are compressed to $\sim 100\mu$m by a two-stage bunch compressor (BC) consisting of rf sections, chicane sections and an arc.

The unloaded gradient in the main linac is set to be high in as much as realistic rf technology is considered to allow: 40 MV/m for C-band and 77 MV/m for X-band. The beam-loading is approximately 26 %. Heavily-damped (HDS), constant-gradient structures is adopted for the C-band, and damped-detuned structure (DDS) for the X-band. Pulse compression will be achieved by one of, or a combination of, three alternate schemes, namely two-port SLED, SLED with disk-loaded energy storage cavities (SLED-III) and DLDS (Delay-Line Distribution System). The transient beam-loading will be compensated by structures using frequency-shifted cavities, stagger-timed triggering klystrons, or by modulating the rf phases of a pair of klystrons whose power is combined to drive a set of accelerating structures.

The JLC design with the X-band main linacs has adopted the same accelerating gradient (after subtracting the beam-loading effects, $E_{acc} \simeq 56.8$ MV/m), independent of the target center-of-mass energy. This means that the organization of individual power units will not undergo any major conceptual changes as energy-upgrades from $E_{\mathrm{CM}} = 250$ GeV up to 1 TeV are performed. There, the length of the linacs is simply extended in proportion to the target energy, introducing additional power sources, power distribution systems, accelerating structures and associated linac beam-line components. If a land area with a sufficient length is offered as the site of JLC, in the initial stage of operation with $E_{\mathrm{CM}} = 250 \sim 500$ GeV, the simplest operational solution would be to use a bypass beam line along the main linac tunnel to deliver the relatively low-energy beams to the interaction region. This is so that the linac extension work can proceed during the machine down time.

The beam delivery system consists of so-called "big bends," collimators and the final focus system. The first two are inserted in order to reduce beam-induced background at the experiments. The "big bends" also make it possible to have two collision points, one of which may be used for collisions other than e^+e^-, such as γ-e and γ-γ. The final focus system is based on a two-family non-interleaved sextupole scheme and is designed to give a final spot size $(\sigma_x^* \times \sigma_y^*)$ as small as 260 nm × 3 nm in operation with $E_{\mathrm{CM}} = 500$ GeV.

4 ATF - ACCELERATOR TEST FACILITY

The ATF, Accelerator Test Facility, project[3] at KEK was initiated to build a work-house for conducting numerous

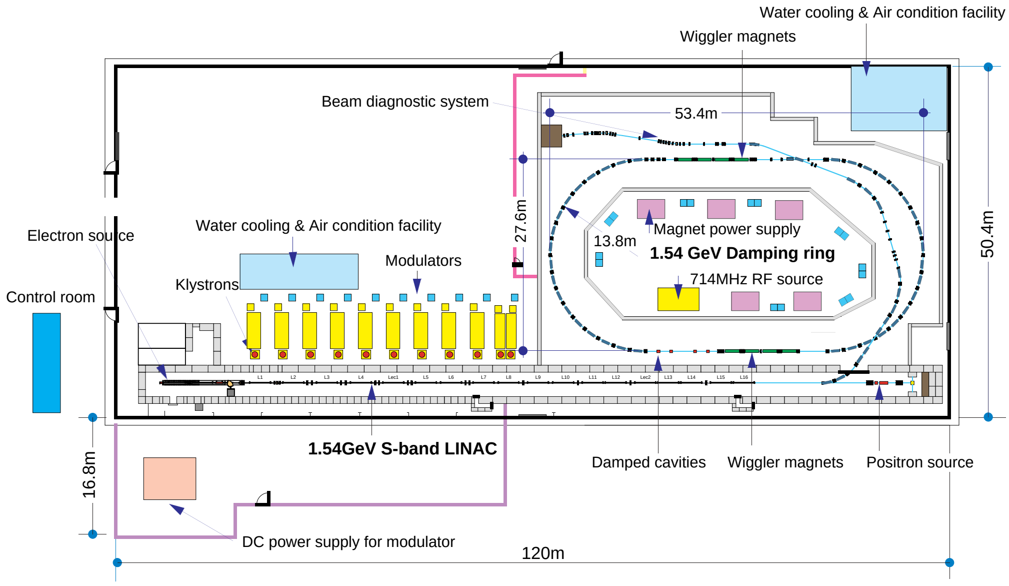

Figure 2: Plan view of the accelerator test facility (ATF) at KEK.

R&D and self-training activities concerning an upstream portion of a linear collider. As shown in Figure 2, it consists of a 1.54 GeV S-band injector, followed by a beam transport, 1.54 GeV damping ring prototype and an extraction line.

Hardware construction of the ATF injector began in 1993. A variety of studies were successfully conducted in 1994 through 1996 on multi-bunch operation (up to 12 bunches, 2.8 ns bunch separation) of the thermionic gun, bunchers and the S-band linac whose maximum accelerating gradient is 33 MeV/m [8]. A notable achievement was the demonstration of a multi-bunch beam loading compensation scheme based on the RF frequency modulation of a selected set of accelerating structures[9].

Commissioning work of the ATF damping ring began in early 1997 with a large number of participants from outside KEK[6]. The accelerator has been operated in a single-bunch mode with the stored intensity of $\sim 1 \times 10^{10}$ electron/bunch or less at a repetition rate up to 1.56 Hz.

A number of "standard" accelerator commissioning tasks, together with development of high-precision beam measurement devices[10], have been conducted. A new type of a beam profile monitor using synchrotron radiation in the damping ring has been developed and in use (see Figure 3). It implements a double-slit which creates an interference pattern whose sharpness is uniquely correlated with the size of the light source, i.e. the beam emittance. Figure 3 shows the principle of the monitor and an observed interference pattern. With this monitor in the ring and with wire scanner monitors installed in the extraction line, a series of studies on the beam emittance are being carried out. The latest measured horizontal beam emittance (unnormalized) is $1.1 \sim 1.6 \times 10^{-9}$ m.rad, which is almost compatible with the design value of 1×10^{-9} m.rad [3].

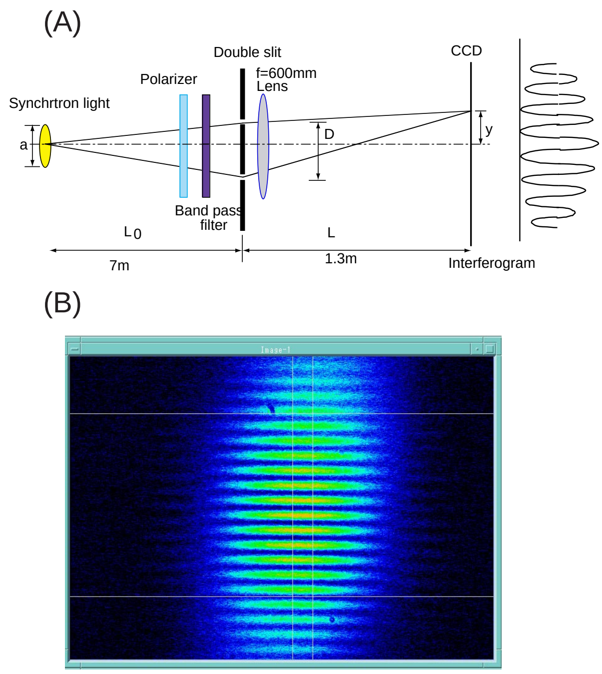

Figure 3: SR interferometry stuff.

The next step focus of the studies at ATF is to (1) confirm the horizontal emittance measurement and (2) proceed with optimizing the x-y coupling. These require continued improvements on the beam instrumentation, beam stability and beam data analysis methods, which are all vigorously

Item	Value	Unit
#Elec/bunch	1.11×10^{10}	
#Bunches/train	72	
Bunch separation	2.8	ns
Train length	198.8	ns
RF frequency	5.712	GHz
Klystron peak power	50.3	MW
Length / cavity unit	1.8	m
a/λ	$0.13 \sim 0.17$	
Shunt impedance	$67.3 \sim 53.0$	MΩ/m
E_{acc}(no-load)	45	MV/m
E_{acc}(loaded)	36	MV/m
Normalized emittance	300×3	10^{-6}m.rad
Bunch length	200	μm
#Cav/linac	3560	
#klystrons/linac	1780	
Active length/linac	6.4	km
P(total RF wall-plug)	130	MW
Rep. rate	100	Hz
$\sigma_x^* \times \sigma_y^*$	318×4.3	nm
Disruption	0.2×16.7	
$< -\Delta E/E >$ due to BSM	3.8	%
Luminosity	6.6×10^{33}	cm^{-2}s^{-1}

Table 3: Tentative JLC parameters, if the main linacs are built based on the C-band technology. Parameters are shown for the case of $E_{\rm CM} = 500$ GeV.

pursued. The study areas at ATF are expected to eventually cover multi-bunch operation of the damping ring, investigations on single-bunch instabilities, and more.

5 X-BAND MAIN LINAC R&D

The X-band main linacs are to be driven by 75 MW klystrons (pulse length $= 1.5\mu$m). Figure 4 shows recent performance of XB72K klystrons, whose output structure design is based on work at BINP, Protvino, then the entire unit manufactured in Japan. Sophisticated 2d/3d-electromagnetic code MAGIC[12] has been deployed to simulate the behavior of X-band klystrons, and the calculated results show excellent agreement with the measurements[11]. Based on this experience, a new design of an X-band klystron with optimized buncher and output cavity arrangements are being developed. In the near future, collaborative development work concerning the X-band klystrons, based on the periodic permanent magnet (PPM) focusing, is also planned to be initiated with SLAC and with BINP, Protvino.

The X-band accelerating structures are made of precisely machined OFHC copper cells (examples are shown in Figure 5), stacked and bonded using a diffusion bonding technique[13]. An important design requirement is to minimize excitation of higher-order-mode fields within the structure so as not to cause single-bunch- and multi-bunch-beam emittance dilution in the linear collider, which require ultra-high precision machining and assembly of the cells. Several prototype structures have been assembled,

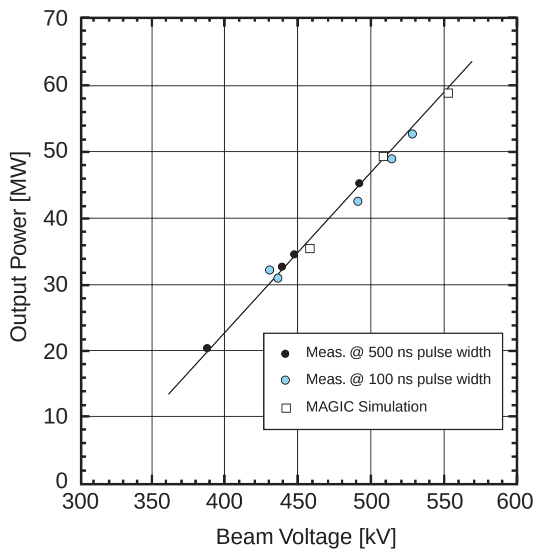

Figure 4: Performance of the XB72K X-band klystron #8 prototype. Filled circles indicate measurements. White rectangles show simulated performance using the code MAGIC.

and have been tested for their high-field characteristics and wake-field properties with promising results[14].

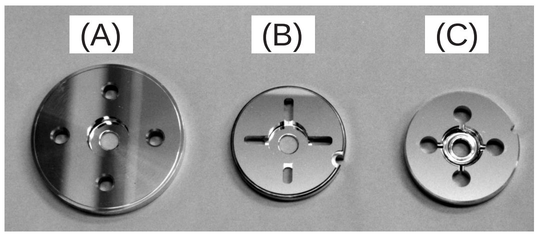

Figure 5: Variety of cells manufactured at KEK for the X-band accelerating structure. (A) Detuned Structure (outer diameter, OD = 80 mm) [2], (B) Damped Detuned Structure (OD = 60 mm)[2], (C) Rounded Damped Detuned Structure (OD = 60 mm, see text).

The current focus on the development is on designing and building a structure based on the rounded-damped-detuned concept through collaboration with SLAC, LLNL and other institutes.

The main scheme for the RF power compression and distribution considered for the main linacs is "Delay-Line Distribution System" (DLDS)[2]. Some conceptual improvements to this scheme are jointly investigated by KEK and SLAC[15]. Initial hardware component testing is planned for the second half of 1998.

Other activities on the X-band main linac development include operation and studies of Blumlein modulators, investigations on the instrumentation and precision alignment[2].

6 C-BAND MAIN LINAC R&D

Work on the hardware components for the C-band main linacs has been conducted as a development of backup technology. In this case an RF power unit would consist of a pair of 50 MW klystrons (350 kV, pulse length $= 2.5\mu$s) [17]. Their combined output is compressed into a 0.5μs, 400 MW pulse through a disk-loaded compressor cavity (SLED-III) [16]. This power is distributed onto a set of four accelerating structures based on the heavily-damped structure (HDS) scheme.

Figure 6 shows the observed high-power output signals from the first C-band klystron model build by Toshiba Co. The original design goal has been already nearly achieved with good stability in 50 Hz operation.

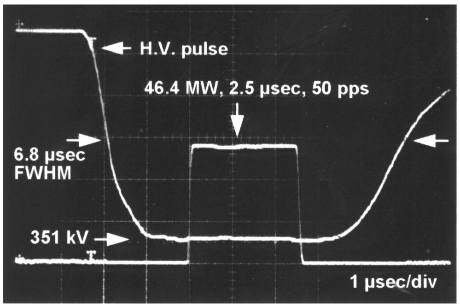

Figure 6: Observed high power output signals from a C-band klystron prototype.

Figure 7 shows a SLED-III pulse compression cavity under low-power testing. Shaping of the leading edge of the output pulse from this SLED-III cavity by means of an amplitude-phase modulation of the input pulse has been confirmed. Thus the feasibility of compensation for the beam loading effects in the multi-bunch train has been demonstrated.

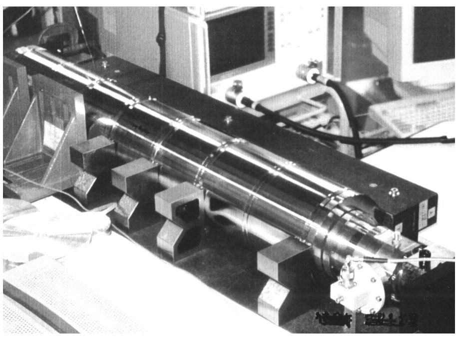

Figure 7: SLED-III pulse compression cavity (low power model) for C-band under testing.

A full-size model of the HDS structure has been also built. Measurements of its wakefield and HOM characteristics will be done at the ASSET facility in SLAC later this year.

7 CONCLUSIONS

R&D work towards an early realization of the linear collider at KEK is proceeding with collaboration with a number of Japanese universities, as well as major laboratories abroad.

Work at ATF are aiming at demonstrating production of ultra-low emittance beams in 1998. More efforts are to follow this activity, including operations in high-current, multi-bunch conditions.

We are starting joint design optimization efforts with colleagues from SLAC since early 1998. This pre-design work is scheduled to complete in approximately two years. Initial topics in the joint effort include: choice of design parameters, the basic accelerator subsystem schemes, design of key components and modeling in the main linacs, and exploratory work on the injector system design.

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[6] Collaboration in various forms are conducted with scientists from SLAC, CERN, DESY, BINP, PAL (Pohan, Korea), IHEP (Beijing, China) and Tshinghua U. (China). Japanese institutes who are working with KEK on JLC accelerator R&D include: Akita Keizaihoka Univ. Junior College, Grad. Univ. of Advanced Studies, Hiroshima Univ., Kogakuin Univ., Kyoto Univ., Nagoya Univ., Seikei Univ., Shinshu Univ., Tohoku Univ., Tohoku-Gakuin Univ., Univ. of Tokyo and Tokyo Metropolitan Univ.

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