Future Accelerators in Japan*

Nobu Toge
National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi, Ibaraki 305, Japan

Abstract

This paper presents a brief report on the present status of future accelerator projects at the National Laboratory for High Energy Physics (KEK), Japan.

I. INTRODUCTION

The KEK laboratory has been successfully operating the TRISTAN accelerator complex since 1986. It consists of a 2.5 GeV electron / positron linac, an 8 GeV Accumulation Ring (AR) and a 29 GeV Main Ring (MR). Concurrently with this operation, in response to recommendations by the Japanese High Energy Physics Committee, survey studies have been continued on new accelerator facilities at KEK. We have two major future projects, namely, the asymmetric e^+e^- B-factory based on TRISTAN (TRISTAN-II) and the Japan Linear Collider (JLC). The purpose of this paper is to outline those research activities and to present an update on their status.

II. TRISTAN-II (B-Factory)

A. Overview

The eventual goal of a B-factory is to allow studies of CP violation interactions in weak decays of b-mesons. The KEK version of a B-factory aims to serve this purpose by providing e^+e^- collisions at the $\Upsilon(4S)$ resonance with asymmetric energies of 8 GeV (e^-) and 3.5 GeV (e^+) [1, 2].

After considerable discussions on the ring parameters, our present working assumption has converged to build two new rings within the existing TRISTAN tunnel. Best efforts will be made to use existing infrastructures and facilities.

Table 1 summarizes pertinent parameters of TRISTAN-II for its low energy ring (LER) and high energy ring (HER). The numbers shown are for the Phase-I operation where every fifth RF bucket is filled. We aim to deliver a peak luminosity of 2×10^{33} cm^{-2}s^{-1}. Later in the Phase-II operation, by filling all buckets, while maintaining the same particle intensity per bunch, the final peak luminosity may reach 10^{34} cm^{-2}s^{-1}. Experiences to accumulate during the Phase-I will be essential in reaching the Phase-II goal.

	LER	HER	unit
Energy	3.5	8.0	GeV
Circumference	3018	3018	m
Tune shifts (x/y)	0.05 / 0.05	0.05 / 0.05	
Beta at IP (x/y)	1.0 / 0.01	1.0 / 0.01	m
Beam current	0.52	0.22	A
Energy spread	0.078	0.073	%
Bunch length (1σ)	5	5	mm
Bunch spacing	3.0	3.0	m
Bunch population	3.3	1.4	10^{10}
Emittance (x/y)	19 / 0.19	19 / 0.19	nm.rad
Synchrotron tune	0.014	0.070	
Betatron tune	~ 43	~ 39	
Energy loss / turn	0.84	4.1	MeV
Momentum compaction	2.0×10^{-4}	1.0×10^{-3}	
RF voltage	4.4	47	MV
RF frequency	508	508	MHz
Energy damping decrement	2.4×10^{-4}	5.1×10^{-4}	
Bending radius	16.2	91.3	m
Length of bend magnet	0.85	2.56	m

Table 1. Parameters of TRISTAN-II B factory

B. Injector

The present KEK linac (S-band, 400 m long) produces 2.5 GeV electron and positron beams at 25 Hz (maximum 50 Hz). It is currently used as the injector for the TRISTAN accelerator complex and for the Photon Factory (PF) ring. To eliminate the need for accelerating beams in the TRISTAN-II rings, the linac will undergo an energy upgrade [3], starting 1994 .

The upgrade involves replacement of existing 30 MW klystrons with 60 MW types and installation of SLAC-style pulse compression systems (SLED) which will amplify the accelerating power. It will increase the accelerating gradient from 9 MeV/m to 25 MeV/m. With a modest extension of accelerating structures, the total energy of 8 GeV for electrons will be achieved. The positron target will be relocated so that the positrons will be produced by 4 GeV electrons, resulting in a factor 20 increase of positron intensity to 3.2×10^9 / pulse.

To provide beams to the TRISTAN-II with improved stability and good optical matching, enhanced beam diagnostic tools and improved timing control systems will be built and implemented.

C. Ring Lattice

An important consideration in the lattice design is to maintain a sufficiently large dynamic aperture. This is to eliminate the need to alter the optics during injection, and to obtain a long beam lifetime during collisions. The very small β^* would create a large chromaticity which needs to be compensated without much compromising the operability of the ring. Our choice is a non-interleaved sextupole scheme [4], where each pair of sextupole magnets is placed π apart. The cancellation of geometric aberrations helps maintain a dynamic aperture with a good margin for the injection time .

Another ingredient in our lattice design is the use of a low momentum compaction of ~ 2.4×10^{-4} at LER (factor

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1/4 reduction), and possibly, at HER. This allows to lower the RF voltage V_c, without increasing the bunch length. It helps to reduce coupled-bunch instabilities, particularly the ones due to the fundamental mode of the accelerating cavities.

Very detailed simulation work is under way to evaluate the ring characteristics in the presence of various construction errors. Specification on beam position monitors for closed orbit corrections, optics studies and beam-based magnet alignment is examined. Our estimations of dynamic apertures mainly rely on the SAD code which has been developed at KEK [5]. Tests to explore its validity have been repeated in the machine study time at TRISTAN [6] and will continue.

The non-interleaved sextupole lattice will be tested at the TRISTAN MR in the fall of 1993. This will be done by temporarily rewiring power-supply connections of the existing sextupoles.

D. RF System

The RF system at TRISTAN-II must be carefully built to reduce the growth rate of transverse and longitudinal coupled-bunch instabilities, where there are two types: (1) higher-order-mode (HOM) coupling (transverse and longitudinal) and (2) fundamental / accelerating mode coupling (longitudinal).

Superconducting cavities theoretically offer a good solution to both of these. Up to 28 cavities have been operated at maximum fields of 7 MeV/m for 12 mA beams at TRISTAN MR. For TRISTAN-II a new aluminum test model has been designed and built [7]. The cold test has shown good results. A full-size Nb model has been recently completed. In the initial cooling test an accelerating gradient of 10 MV/m was obtained with Q ~ 10^9. The studies on HOM absorbing materials are also on-going. The IB-400 ferrite made by TDK Co. Ltd. is currently tested in various aspects such as outgassing rates, mechanical characteristics and capabilities to handle high RF powers.

To acquire full confidence over the superconducting cavity technology, we feel it is important to exercise them in actual beam environments. While we plan some beam experiments at the present TRISTAN rings in the near future, the complete final design may have to wait for experiences at real-life TRISTAN-II. Therefore, our strategy is to support the initial runs of TRISTAN-II with normal conducting RF cavities. A candidate design is based on the damped cavity idea [8], which was originally proposed by Palmer [9]. The first 2-cell prototype cavity has been completed and a low-power test is under way with and without RF absorbers. Measured damping of TM110 and TM011 modes agrees with expectations. High power testing is planned later this year.

Another idea of HOM damping (Choke-mode cavity) came out through efforts on the linear collider R & D, which also need to deal with multi-bunches [10]. It is equipped with a "choke" structure which traps the RF fundamental mode, while the HOM components are allowed to escape radially towards outside the accelerating region. A cold test has shown good HOM damping characteristics.

Beam tests of those cavities (both normal- and superconducting) are scheduled for 1995 at the TRISTAN AR. Existing hardware in the RF section will be replaced by test modules. A high beam current of 500 mA will be stored in the ring by filling 128 bunches at 3.5 GeV. It is anticipated that normal-conducting cavities allow to bring the growth rates of HOM instabilities in the range that can be controlled by using bunch feedback systems in the Phase-I operation. Our plan is to encourage efforts on different cavity ideas simultaneously and to make the final decision on the normal conducting type cavity within two years. Component testing of the bunch-to-bunch feedback is also presently under way [13]. The full system will be exercised during the high-current AR run.

When the commissioning and operation of the TRISTAN-II progresses, the beam intensity will be continually increased. Eventually the fundamental mode instabilities will become intolerable. At that time a transition to the superconducting cavities will be made. Yet another new idea which came out recently is to build a large energy storage cavity and attach it to the accelerating (normal conducting) cavity [11]. It will increase the Q value and reduce the cavity de-tuning frequency. The overall system can act like a superconducting cavity. Pilot studies on this possibility are also beginning [12].

E. Interaction Region

During the injection time, because of the large beam emittance, it is preferred to introduce a finite crossing angle to reduce parasitic crossing beam-beam effects. However, a large crossing angle could lead to excitations of synchro-beta resonance during the collision time [14].

Our present choice is driven by the desire to satisfy those conflicting requirements, with emphasis on the initial-stage runs where the bunch spacing is relatively large (3 m). We have adopted a beam separation scheme based on a combination of a small crossing angle (half crossing angle θc = 2.8 mrad) at the collision point and a pair of separation bend magnets which are superconducting [15]. The final focusing is obtained with superconducting final quadrupole magnets which are housed in the same cryostat enclosure as the separation bends [16].

This design allows certain flexibility to alter the crossing angle up to 6 - 7 mrad without a major beam-line reconstruction, when the bunch spacing is made smaller in the future. At that time, a Crab crossing scheme may be required. The beam line space for Crab RF cavities will be set aside and the Crab R&D efforts will be continued [17].

Our current discussions are centered on detailed planning of the mechanical construction and evaluations of interface and interference with the experimental facility.

F. Other Activities

The vacuum system to achieve 10^{-9} Torr throughout the ring under the strong synchrotron radiation power up to 10 kW/m will use copper as the chamber material [18]. The time profile of vacuum baking process has been estimated and the predictions appear promising. Assuming the presence of 100 *l*/s NEG vacuum pump, the vacuum pressure distribution has been simulated for a proposed beam-line layout. A trial model (3.7 m long) of the full-size OFC vacuum chamber (although straight) has been built. Studies to improve the surface treatment process are under way.

Ground motions over short (10 ms) and long time (days) period have been monitored in the TRISTAN tunnel [19]. It appears that the seismic vibrations in the 10 - 100 Hz range is sufficiently small (the vibration amplitude is about 1 μm at 1 Hz) so that their effects on the beam tuning is manageable. However a mid-term(hours) to long term (weeks) ground motion of an order of 100 ~ 200 μm has been observed. It is likely due to the tidal wave, but it is also mildly correlated with the weather. This could cause a problem for the tuning stability of the ring. Some kind of feedback may need to be developed using signals from hydrostatic leveling systems.

G. Outlook

We are hoping to obtain a government grant of the TRISTAN-II this year, which would allow us to begin construction in the Japanese fiscal year of 1994 (to start April 1994). If this turns out to be the case, the accelerator will be commissioned sometime in 1998. Detailed schedules on the transition from the present TRISTAN configuration to the TRISTAN-II, machine study programs, and the detector de-commissioning / commissioning are being worked out.

III. JAPAN LINEAR COLLIDER (JLC)

A. Overview

Our motivation stems from the notion that it is a sensible thing to start the next-generation electron - positron linear collider from the energy range near E_{CM} = 500 GeV with the luminosity $10^{33} \sim 10^{34}$ $cm^{-2}s^{-1}$ [20]. The first primary physics target is a detailed study on productions and decays of the (yet to be discovered) top quark. A search for light Higgs mesons, which are strongly suggested by SUSY-based Grand Unified Theories (GUT), is another important menu. We also believe that the construction of a linear collider of this energy range will give us important experiences to help develop even higher energy linear colliders in the distant future.

Pioneering work has been done on the nature of beam interactions to occur at the collision point [21]. Theoretical studies on the final focusing optics [22], beam dynamics in the linear accelerator [23], and simulations of backgrounds to the experimental facility [24] followed.

Extensive work has been done to search for good machine parameters to use for the JLC [20]. The parameter set for the X-band (11.424 GHz) linac case is shown in Table 2.

The current major R&D activities at KEK include construction efforts of the Accelerator Test Facility (ATF), participation in the Final Focus Test Beam at SLAC, R & D on the RF power source, accelerating structures and others

Parameter				unit
Beam energy	E	150	250	GeV
Particles/ bunch	N	0.7	0.7	10^{10}
Bunches / pulse	N_b	90	90	
Rep. frequency	f_{rep}	150	150	Hz
Bunch length	σ_z	85	67	μm
Accel. gradient	G_0	40	40	MeV/m
Active linac length	L_{ac}	5.0	8.5	km
Iris radius/wavelength	a/λ	0.18	0.18	
Filling time	T_f	75	75	ns
Total average power into cavities		11	20	MW
Total wall-plug power		75	135	MW
Peak power / cavity		50	50	MW
Normalized damping ring emittance	$\gamma\varepsilon_x$	3000	3000	nm.rad
	$\gamma\varepsilon_y$	30	30	nm.rad
Beta* at IP	β_x	10	10	mm
	β_y	100	100	μm
Beam size at IP	σ_x	335	260	nm
	σ_y	3.92	3.04	nm
Crossing angle		9.0	7.2	mrad
Beam diagonal angle	σ_x/σ_z	4.0	3.9	mrad
Disruption parameter	D_x	0.09	0.007	
	D_y	7.7	6.0	
# of beamstrahlung (BSM) photons	n_γ	0.8	0.95	
Maximum upsilon		0.15	0.39	
Energy loss by BSM	δ_{BS}	1.8	4.5	%
Geometrical luminosity reduction factor		0.63	0.70	
Pinch enhancement	H_D	1.71	1.72	
Luminosity	L	3.5	6.3	10^{33} /cm^2/s

Table 2. The parameter set for the JLC-I, based on X-band linear accelerators (Parameters with S- and C-band cases also exist [20]).

B. Accelerator Test Facility (ATF)

The eventual goal of KEK ATF is to demonstrate ultra-low emittance (flat beam, $\gamma\varepsilon_y/\gamma\varepsilon_x \sim 5\times10^{-8}/5\times10^{-6}$ rad.m), required for future linear colliders, for a train of bunches (up to 20 bunches per train) at 1.54 GeV [25]. The beam energy is somewhat smaller than what we anticipate for the real-life JLC, due to the constraints of the size of the available experimental hall. However, many parameters have been chosen so as to follow the JLC configuration.

The planned ATF consists of multi-bunch electron guns, a buncher system, the beam transport line, a 1.54 GeV test damping ring, a bunch compressor and the emittance measurement section.

Creation of multi-bunches is the very first step in building the basis of the next linear collider. As the most orthodox approach a thermionic gun driven by a grid pulsar for multi-bunch beam generation has been developed [26]. The second approach, which may eventually take over for the real-life JLC, is the RF-gun technology. By flashing the Sb-Cs target with a YAG laser light (0.15 mJ, 532 nm), synchronized to a S-band RF, electron population of 2.3×10^{10} has been obtained [27]. Also polarized electron guns have been developed in collaboration with a group from Nagoya University [28]

The 1.54 GeV injector linac at ATF will use S-band RF. New S-band klystrons have been developed which outputs 85 MW peak power for 4.5 μs long pulses (100 MW for 1 μs). To deliver the required accelerating field of 33 MeV/m (this comes from the site constraint), a dual-iris SLED cavity has been developed. A stable peak SLED output of 380 MW has been achieved for an input power of 80 MW with 4.5 μs pulse width [29]. An R&D on RF windows has been carried out with a resonant ring, which has been specifically built for this purpose. By a careful selection of raw alumina, sintering binders and by using the hot isostatic pressing method, it has been shown that alumina windows could be built to survive up to 310 MW of S-band RF power [30]. The entire 1.54 GeV linac will be completed early 1994.

Parameters for the ATF test damping ring are summarized in the table below.

Parameter		Unit
Beam energy	1.54	GeV
Repetition rate	25	Hz
Circumference	138.6	m
Harmonic number	330	
# of bunch trains	5	
# of bunches / train	20	
# of particles / bunch	$(1 \sim 3) \times 10^{10}$	
Energy loss / turn	0.173	MeV
# of FoBo cells	36	
Longitudinal Impedance threshold	0.30	Ω
Bending field strength	0.896	T
Momentum compaction	1.97×10^{-3}	
Natural emittance	1.34×10^{-9}	rad.m
Wiggler pitch	40	cm
Damping time (x / y / s)	6.32 / 8.26 / 4.88	ms
Tune (x / y)	16.2 / 8.3	
Wiggler field strength	1.88	T
RF frequency	714	MHz
# of cavity cells	4 + 1	
Bunch length	4.73	mm
RF voltage	0.77	MV
Energy spread	0.0773	%
Touchek lifetime	89	s
Emittance with intra-beam (x / y)	4.47×10^{-6} 4.47×10^{-8}	rad.m rad.m
Phase advance/cell (x / y)	140 / 52	deg.
Damping partition number (x / y / s)	1.3068 / 1.000 / 1.6932	

Table 3. Parameters of the ATF test damping ring.

The optics of the ATF damping ring uses an FoBo lattice where the horizontal defocusing is provided by combined function bend magnets. This lattice creates a low dispersion with relatively weak bend fields, and it helps to reach a low beam emittance. To control the damping time, wiggler magnets (21 m long) are introduced in the straight section where dispersion is absent. Allowed magnet construction errors and alignment errors have been evaluated. The magnet support system with 5 μm accuracy with five degrees of freedom has been developed, and it is currently tested.

The vacuum chamber design has been refined to reduce the impedance of the entire vacuum system, including the beam diagnostic devices. Synchrotron photon absorbers are arranged so that they are not directly seen by the beam. The design value of longitudinal impedance of ~ 0.1 Ω appears possible [31].

Beam extraction from the damping ring will be done with a pair of two kicker magnets that are placed 180 degrees apart in phase advance [32]. This should reduce extraction orbit errors significantly. A detailed simulation work on the bunch compressor is in progress, taking into account the effects of the beam loading due to the multi-bunch nature of the beam [33]. The present design will occupy about 40 m of length. It is expected to compress the bunch length by a factor 1/10.

Development efforts are being made on beam instrumentation devices such as wire scanners, beam profile monitors, fast signal processing electronics, beam position monitors [34]. The wire scanner and a few other new instruments have been tested earlier this year in collaboration with a group from Tohoku University, using their electron linac facility. Synchrotron radiation monitor to use at the damping ring will be developed with a group at Institute for Nuclear Study, University of Tokyo.

Detailed EGS simulations and heat calculations on the positron production target has been on-going [35]. A prototype is planned to use 1.54 GeV electrons from the ATF linac.

C. Participation in Final Focus Test Beam (FFTB) at SLAC

As part of the U.S.-Japan collaboration program in High Energy Physics, KEK has been part of the Final Focus Test Beam (FFTB) collaboration based at SLAC. The goal of FFTB is to exploit the high energy (47 GeV) low emittance beam available at SLC, and explore the feasibility of extremely tight focusing at the interaction point required at future linear colliders. The beam commissioning has recently started. A bulk of beam time is scheduled for summer this year.

At the early stage of the project, physicists from KEK participated in the optical design and error analyses in the FFTB beam line [36]. Later, KEK has taken the responsibility for fabricating the doublet of small-bore (13 ~ 20 mm diameter) normal conducting final quadrupole magnets [37]. While those magnets have to create 140 ~ 180 T/m field gradient over up to 1.1 m of length, the higher-pole field components must be less than 0.01 % for sextupoles and below 0.1 % for octupoles. The fabrication accuracy, presently possible at 2 ~ 3 μm, allows to satisfy the octupole requirement, but it is not sufficient for the sextupole errors. Remaining errors will be corrected by using trim windings.

The support system of the magnets has an adjustable table which is driven by high-power stepping motors and Piezo-electric devices. Position controls with the full six degrees of freedom are featured. The magnet position will be monitored with a laser interferometer and micro-sensors. The fabrication of magnets has been finished earlier this year, with complete magnet measurements. They have been delivered to SLAC and the installation in the beam line has been recently completed.

A novel idea on measuring the small beam spot parameters at the beam focal point has been proposed by a physicist at KEK [38]. It utilizes an interference pattern of two laser beams as a fine strip target to place at the beam focal point. The laser photons interact with the beam through Compton scattering process. Beam spot size parameters are deduced by knowing the width of the laser interference pattern and by measuring the modulation of the rate of Compton-scattered photons. The monitor based on this concept is presently under construction. Creation of laser interference pattern has been confirmed. It will be installed at the FFTB early summer this year, and will be tested.

D. RF Power Source Research and Development

The linear accelerator at JLC will be based on some sort of disk-loaded accelerating structure driven by high power RF klystrons. From the wall-plug power efficiency point of view, it is advantageous to use a higher RF frequency such as X-band (11.424 GHz).

In early days of JLC efforts, a new simulation code FCI was developed to study behaviors of electrons in klystrons [39]. The first X-band klystrons built were 30 MW class XB-50K series tubes. Studies were made on high-voltage behaviors of electron guns and klystron windows. After achieving up to 26 MW output power, efforts were shifted to the XB-72K series klystrons (100MW class). The maximum output power of 79 MW has been achieved for 50 ns pulses. The peak electron voltage is 600 kV [40]. With improved high voltage performance of the output window, we hope to raise the output power to 100 MW or more. Possible use of superconducting coils for the beam focusing in the klystrons is contemplated.

The first high gradient tests of accelerating structures were conducted at S-band by combining the RF power from two klystrons (total 160 MW) on a 60 cm structure. An average accelerating field of 91 MV/m was achieved [41]. Subsequent studies have been made on 20 cm traveling wave structures at X-band with 100 ns pulses from an XB50K klystron. Dark currents and conditioning characteristics were studied. The average accelerating gradient reached 68 MV/m in runs over 600 hours for one structure sample, and 85 MV/m (limited by the klystron) within 50 hours for another. Efforts are being made to improve the fabrication process such as machining accuracy and brazing [42].

At JLC where multi-bunch trains are accelerated, it is essential to reduce the effects due to higher order mode fields within the accelerating structure. Studies on the damped mode cavity, choke-mode cavity and a detuned structure are in progress [43, 10]. Fine fabrication of X-band structures is being studied to achieve alignment of cells within a few microns, and to eliminate need for tuning after the brazing. A multi-cell choke mode cavity is being designed to prove the high power operation at S-band.

Review work of the JLC parameters in the past year has shown that a linear collider at 300 ~ 500 GeV E_{CM} could be also designed using C-band (5.712 GHz) and S-band (2.856 GHz) linacs [20]. It appears possible to expand them in a higher energy range. At the present stage we defer final decision on the RF frequency, and we will let development efforts on those possibilities cross-fertilize.

E. Outlook

The immediate goal of the JLC development group is to construct the ATF and demonstrate the feasibility of multi-bunch flat beam with adequately low emittance. Development efforts on the RF power source and accelerating structure, studies on beam dynamics and collimation, refinement of the final focus optics and overall system design will continue. During this process various technical possibilities will be sorted out. We hope to submit a technical design proposal of the JLC in 1996 - 97.

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