THE PERFORMANCE OF TRISTAN AND ACCELERATOR DEVELOPMENT AT KEK

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Abstract

The performance of TRISTAN, a high energy electron-positron colliding beam accelerator in Japan, is described with an emphasis on the long term operation of the superconducting RF cavity system and a luminosity upgrade plan by use of superconducting mini-beta quadrupole magnets. Also presented are accelerator development works for two principal post-TRISTAN accelerator projects for high energy physics, a linear electron-positron collider project and an asymmetric B-factory project.

Introduction

The TRISTAN electron-positron colliding beam accelerator was commissioned in November 1986. Since then the first phase colliding beam experiments had been carried out till the end of 1989, in which observation of new elementary particle phenomena had been pursued with increasing the colliding beam energy from 25 GeV to 32 GeV.[1] This year we have begun the second phase TRISTAN operation which aims at accumulating a few hundreds of inverse pico-barns in integrated luminosity at several collision energies covered by the first phase operation for precise measurements of electron-positron interactions.

Following the completion of TRISTAN, post-TRISTAN accelerator projects have been under discussion in the Japanese high energy physics community. The High Energy Committee, an organization of the high energy physicists, has been proposing, as a first priority item, to make intensive R&D efforts on a TeV-class linear electron-positron collider as a possible home based facility, and also to make feasibility studies of an asymmetric B-factory with a peak luminosity well above 10^{33} cm^{-2}·sec^{-1}.

TRISTAN

Accelerator Performance

The TRISTAN accelerator complex consists of four separate accelerator systems as illustrated in Fig. 1. A 400 m long main linac accelerates electrons and positrons to 2.5 GeV. Positrons are produced by bombardment of a tantalum target with high-current electron beam of 200 MeV from a linac constructed at the upstream end of the main linac and, then, accelerated to 250 MeV by another linac located downstream of the conversion target prior to the transfer to the main linac.

Electrons and positrons accelerated in the linac are injected and accumulated in the TRISTAN accumulation ring. The accumulation ring is a storage accelerator, 377 m in circumference, and accelerates the accumulated beam to 8 GeV for the transfer to the main colliding beam ring.

The TRISTAN main collider has a circumference of 3018 m and such a shape that four quadrant arcs of 347 m in the mean curvature radius are connected together by four 194 m long straight sections. Two electron and two positron bunches circulating in opposite directions collide with each other at the midpoints of the straight sections, where the colliding beam detectors are located. RF cavities to accelerate beams are aligned on the both sides of the detector regions in the straight sections.

As stated above, in the past three years we had concentrated our efforts on upgrading the TRISTAN beam energy by use of superconducting RF cavities. Table 1 summarizes the first phase TRISTAN operation at the beam energies ranging from 25 GeV to 32 GeV. Listed in Table 2 are the TRISTAN main collider parameters achieved so far.

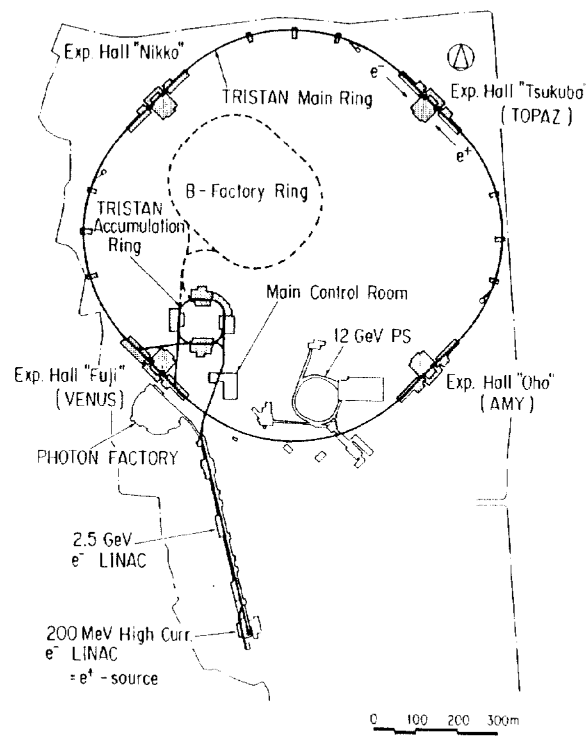

Fig. 1 Site layout of the TRISTAN accelerator complex and an asymmetric B-factory planned.

Table 1 Summary of the first phase TRISTAN operation

Beam Energy (GeV)	Total	Operation Time (hours) Exp. runs	Acc. R&D	Beam stop
25.0	1459	733	500	226
26.0	763	556	119	88
27.5	1311	725	410	176
28.0	914	476	365	73
28.25	462	243	191	28
28.5	593	482	64	47
30.0	441	364	43	34
28.62–30.4	1504	1194	149	161
30.7	1023	642	134	247
31.8, 32	955	460	440	55
Total	9425	5875	2415	1135

The maximum beam energy of 32 GeV was obtained with the RF accelerating system consisting of 104 units of the nine-cell APS-type room temperature cavities and 32 units of the five-cell superconducting cavities. Total accelerating voltage required at 32 GeV was 500 MV, of which 310 MV was provided by the room temperature cavity system and 190 MV by the superconducting cavity system.

Table 2 TRISTAN main collider performance parameters achieved

Maximum beam energy	32 GeV
Injection beam energy	8 GeV
Nominal RF frequency	508.58 MHz
Frequency shift to lower emittance	(+) 2 – 2.5 kHz
Maximum accelerating voltage	
APS system (936 cells)	310 MV
SCC system (160 cells)	190 MV
Maximum single bunch current	5 mA
Total beam current ($2e^{+}+2e^{-}$)	14 mA
Filling time	20 – 30 min.
Beam life time	5 – 6 hr.
Emittance ratio ($\varepsilon_V/\varepsilon_H$)	1 – 2 %
Beta functions at collision point (β^*_V/β^*_H)	0.1m/2.2m
Peak luminosity	1.4×10^{31} $cm^{-2}\cdot sec^{-1}$

The TRISTAN peak luminosity exceeded its design goal of 1×10^{31} $cm^{-2}\cdot sec^{-1}$ and reached 1.4×10^{31} $cm^{-2}\cdot sec^{-1}$. At the highest luminosity the beam-beam tune shift has been measured to be about 0.03 and not been saturated yet. Therefore we have been making straightforward efforts to increase the luminosity further. The measures taken for that are to increase the bunch current and to lower the natural emittance by shifting the accelerating RF frequency and to reduce the vertical-horizontal emittance ratio by carefully adjusting the closed beam orbit.[2]

The highest bunch current attained in the TRISTAN main collider was about 4 – 5 mA and determined at the 8 GeV injection stage. What limits the bunch current is speculated to be a synchro-betatron resonance effect arising from the closed orbit distortions and residual dispersions at the locations of the RF cavities. The horizontal and vertical residual dispersions at the RF cavity sections have been measured to be about 5 cm and 1 cm on average, respectively. We surmise there are two major sources for the vertical residual dispersion, one is the orbit errors in the strong insertion quadrupole magnets for low-beta and the other is those in the sextupole magnets which give rise to a horizontal to vertical dispersion coupling. To avoid this instability, the optimum closed beam orbit is looked for by carefully adjusting the orbit so that the residual dispersions are cancelled out by those manually generated.

The beam tuning at the collision energy is mainly to reduce the vertical to horizontal emittance ratio. The measure taken for this purpose is also adjustment of the vertical closed beam orbit to make the coherent beam-beam tune shift as large as possible, which is monitored continuously during the beam collision.

The vertical coherent beam-beam tune shift has been measured with shifting the electron and positron orbits at the collision point by use of electrostatic beam separators. This gives informations on the vertical beam spread and deviation from the head-on condition at the collision point. The results have shown there exist a difference of the beam spread amounting to as much as 30 % between the four collisions poins and also a deviation from the head-on of a few micron meters. We investigate those observations also to be caused by the orbit errors in the sextupole magnets which give rise to a residual dispersion and differences in emittances and beta-functions at the collision points through the horizontal to vertical dispersion coupling as well as the coupled betatron motions.

Superconducting RF Cavity

The superconducting RF accelerating system consisting of 32 units of 508 MHz niobium cavities has been in operation in the TRISTAN collider (Fig. 2).[3] The cavity unit is a 1.473 m long five-cell structure and equipped with a coaxial-line input coupler on the beam pipe at the one cavity end and two higher-order mode couplers on the beam pipe at the other end. Two cavity units joined only mechanically are assembled in a horizontal cryostat.

The 16 cavities were first installed in the ring in the summer of 1988 and the remainings were installed in the last summer. Operation time of the cavities at 4.4°K accumulated so far amounts to about 9000 hours for the group installed first and about 4000 hours for those installed later. To see changes of the cavity performance in the long-term operation, we plot in Fig. 3 the maximum accelerating field measured for the first installed 16 cavities on every occasion of the thermal cycle, after cool-down and before warm-up. Generally

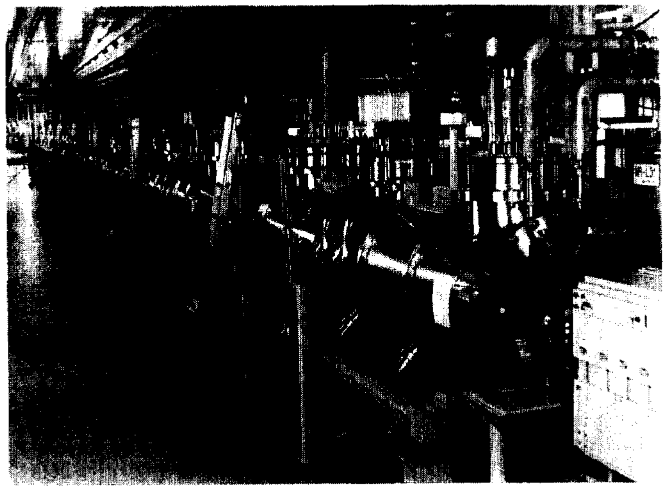

Fig. 2 Sixteen superconducting cavities installed in one of the two superconducting RF sections in the TRISTAN collider.

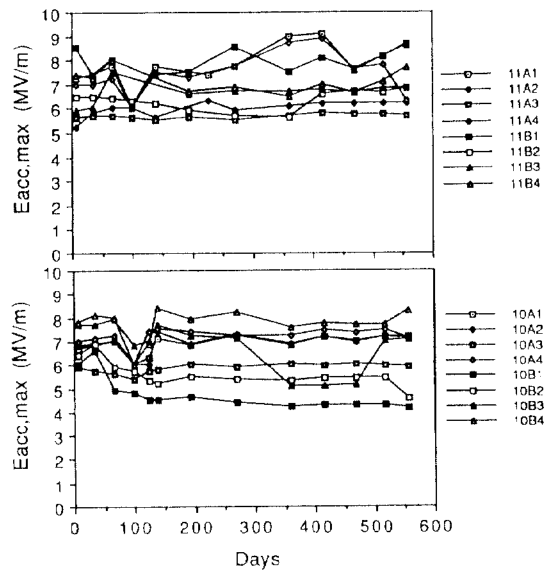

Fig. 3 Time variation of the maximum accelerating field for the 16 cavities installed in 1988 and operated for about 9000 hours.

speaking, no serious degradation of the maximum field gradient sustained in the cavities has been observed in the past two years. Two cavities showed a considerable decrease of the field gradient shortly after the initial cool-down, but have been holding almost the same gradient after the initial degradation.

In the present superconducting cavity system, we have been encountering two problems as follows. One is the heating-up of the N-type ceramic connectors used for extracting a higher-order-mode RF power generated by the circulating beams. This is caused by a bad RF contact at the pin of the N-type connectors and limits the maximum allowable circulating beam current to less than about 13 mA. All the connectors and coaxial cables used in the higher-order-mode couplers are, therefore, to be replaced in this summer shut-down with newly developed ones which are designed to stand the beam current as high as 20 mA.

The other problem is a fast quenching phenomenon frequently observed in the cavities located in the far-end of the straight sections, i.e. close to the arc-end of the ring. This occurs always in association with the circulating beam and has empirically been known to be dependent upon the closed beam orbit. At the quenching the cavity voltage drops to almost zero within about 20 μsec which is much faster than the cavity time constant of about 600 μsec. We think this to be attributable to a spark discharge in the cavity caused by the synchrotron radiation generated at the arc-end of the ring.

Superconducting Mini-beta Quadrupole Magnet

A straightforward way to improve the beam collider luminosity is to reduce the beta-functions or beam sizes at the collision point. For this purpose, we are going to install a so-called mini-beta system in the TRISTAN main collider.[4] It consists of a pair of superconducting quadrupole magnets, QCS, located inside the present low-beta insertion as illustrated in Fig. 4. The lowest beta-functions achievable with this mini-beta system is determined by the quadrupole location, which is brought closest to the collision point avoiding the interference with the experimental detector. Optics parameters of the mini-beta system thus designed are given in Table 3, and a doubling of the luminosity is foreseen after installation of the system.

Four pairs of the superconducting quadrupole magnets for the mini-beta system are under construction and to be mounted in the four experimental insertions of the TRISTAN main collider in this summer shut-down. The magnets are an iron free type to avoid the magnetic interaction with the detector solenoid. Figure 5 illustrates a cross-section of the magnet assembled in a horizontal cryostat. The inner diameter of the warm bore is 104 mm and the outer diameter of the vacuum vessel is 400 mm. The coil is a four-layer two-wedge structure with an inner and outer diameter of 140 mm and 217.7 mm, respectively. The magnet is designed to be operated at a maximum field gradient of 70 T/m in 4.4°K single-phase liquid helium. The effective magnet length is 1.17 m. Principal magnet parameters are listed in Table 3. Three features special to the present coil fabrication have to be noted, i.e. (1) use of precisely machined FRP end spacers to make the end tight and reduce the training, (2) adoption of a double pancake winding method to reduce the number of electrical joints between the coils, and (3) winding with two kinds of cables with different cable-lay-direction each other to avoid twisting of the assembled coil.

The eight quadrupole magnets have been completed and tested in a vertical cryostat. Figure 6 shows a training behavior of the eight magnets. All the magnets exceeded the design current of 3405 A within two training quenches. We have measured the magnetic field inserting a 1.5 m long room temperature rotating coil of 39.4 mm in radius in the magnet bore. Figure 7 shows the measured integrated harmonic contents which are expressed as a ratio to the quadrupole component at the radius of the rotating coil.

Table 3 Design parameters of the TRISTAN superconducting mini-beta system

<u>Optics parameters</u>	
QCS location (magnet front end to the collision point)	2.5 m
Beta-functions at the collision point (horizontal/vertical)	1.25m/0.05 m
Luminosity enhancement $(\sqrt{(\beta^*_V\beta^*_H)}_{present}/\sqrt{(\beta^*_V\beta^*_H)}_{mini\text{-}beta}$	1.9
<u>QCS parameters</u>	
Magnet length (magnetic length)	1.45 m (1.17 m)
Inner warm-bore radius	50 mm
Field gradient	70 T/m
Coil current	3405 A
Inductance	58 mH
Diameters of strands/filaments	0.68mm/8.7μm
Field uniformity (B_n/B_2)	$\leq 5 \times 10^{-4}$

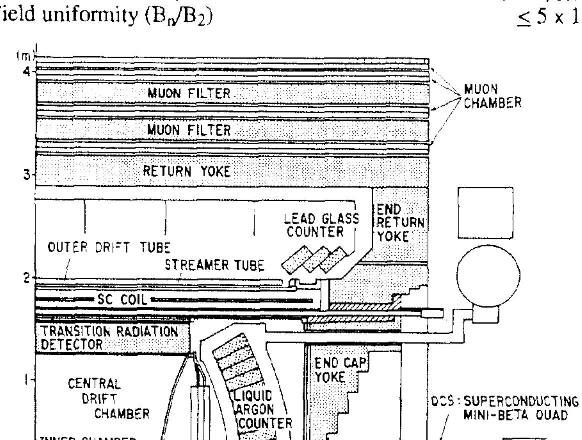

Fig. 4 Configuration of one of the four TRISTAN experimental insertions equipped with the superconducting mini-beta quadrupole magnets, QCS.

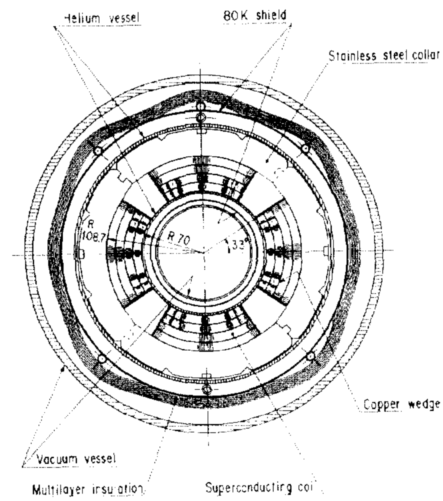

Fig. 5 Cross-section of the superconducting quadrupole magnet assembled in a horizontal cryostat.

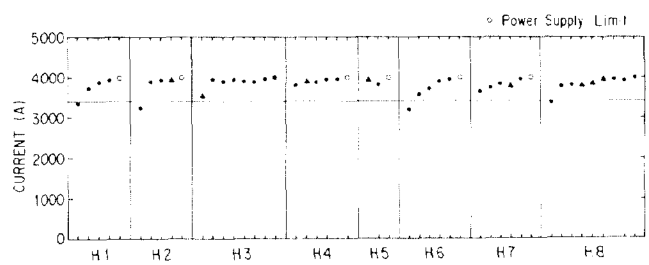

Fig. 6 Training behavior of the eight superconducting quadrupole magnets fabricated. Black circles and triangles indicate inner and outer coil quenches, respectively. White circles indicate the maximum currents of the power supply, and have been reached without quench.

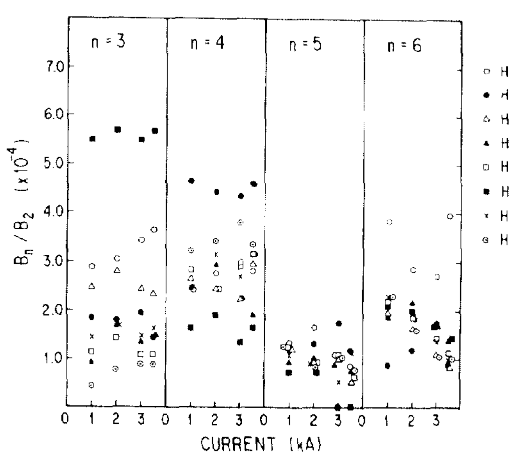

Fig. 7 Integrated harmonic contents measured for the eight superconducting quadrupole magnets fabricated.

Linear Electron-Positron Collider

Since 1987 we have been making coherent accelerator R&D on TeV-class linear electron-positron colliders, which the Japanese high energy physics community proposed to be a first priority post-TRISTAN energy frontier project.[5] Through extensive parameter studies, the R&D group obtained a preliminary design of the collider with a center-of-mass energy of 1 TeV, JLC, as given in Table 4. Figure 8 illustrates a configuration of the JLC complex. As seen from the design proposed, many JLC parameters are far beyond the limit conventionally obtainable with the present accelerator technology. Then, pursuing the present R&D, we have laid down the R&D targets as listed in Table 5, and are going to hit them through the construction of a JLC accelerator test facility, ATF. The ATF is to be built in the TRISTAN warehouse and accommodated with proto-type accelerators and stations to make critical tests of the developed components. The proto-type accelerators consist of a 1.54 GeV S-band injector linac, 1.54 GeV damping ring. 1.0 GeV X-band linac, and final focus test beam line.

Development works of the accelerator components are underway for and with the ATF. We briefly describe those for RF power sources, accelerating structures with damped Q's for the higher-order-modes, and high gradient acceleration.

A high power S-band klystron, E3712, has been developed by using a new simulation code FCI for tube design. The first tube fabricated was successfully tested up to 100 MW with an efficiency of about 40 %. As a high power RF source for the X-band linac, we are also developing new klystron tubes. To investigate beam behavior in the tube first, a diode with a cathode of 50 mm in diameter was fabricated and tested. It showed a designed micro-perveance of 0.6 up to the cathode voltage of 450 kV. Based on this result, a klystron with an output power of 30 MW, XB-50 K, has been designed and will be tested shortly, and a larger cathode one, XB-72 K, is to follow XB-50 K aiming at an output power of 150 MW.

Accelerating structures with damped Q's for the higher-order-modes are highly desirable for the JLC linac, which will be operated with multi-bunches, to avoid beam breakup effects due to wake fields excited by preceding bunches. Several types of the damped structures have been studied by using a 3 D computer code, MAFIA. Figure 9 shows a one of the structures thus obtained. The structure is calculated to have damped higher-order-mode external Q's as expected, e.g. as low as 13 for the most dangerous TM_{110} π-mode, and its fabrication is underway for RF tests.

In order to investigate high gradient acceleration in the disc loaded copper structure, we have been carrying out an experiment to accelerate a beam at a gradient as high as 100 MV/m in a 60 cm long S-band $2\pi/3$ mode structure. An input RF power of 200 MW is generated by combining the output of the two klystron tubes, Toshiba-E3712 and SLAC-5045. Up to now we have attained the beam acceleration at the highest gradient of 85 MV/m with an input RF power of 145 MW. To reach this gradient RF-pulse-conditioning of the structure for about 900 hours with 1 μsec RF pulses (50 pps) was required. This experiment has provided invaluable informations to understand the RF breakdown phenomena at high gradients in the linac structure through measurements of such effects as dark current multiplication and surface field enhancement.

Table 4 Parameters of JLC

Beam energy	500 GeV
Luminosity	6.2×10^{33}/cm^{2}sec
Accelerating frequency	11.424 GHz
Accelerating gradient	
In a structure	100 MeV/m
Averaged in linac	70 MeV/m
Total length (e^+ linac + e^- linac)	14.3 km
Number of particles/bunch	1.0×10^{10}
Number of bunches/RF pulse	10/14 ns
Repetition frequency	200 Hz
Normalized emittance ($\varepsilon_{Vn}/\varepsilon_{Hn}$)	3×10^{-8}-$8/3\times10^{-6}$ rad·m
R.m.s. beam size at IP ($\sigma^*_V/\sigma^*_H/\sigma_Z$)	1.4/230nm/76μm
Crossing angle	6.0 mrad
Beta functions at IP (β^*_y/β^*_x)	0.05/14 mm
Total length of FF/beam	365 m
Distance between last e^+ quad and e^- quad	2.0 m

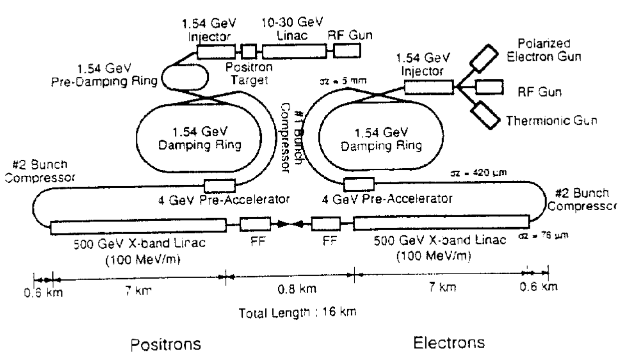

Fig. 8 Configuration of the JLC complex preliminarily designed.

Table 5 Targets of the JLC R&D

1. Electron Source
   - Thermionic gun:
     - 10 bunches/14 ns, 1×10^{10} e^-/bunch, $\gamma\varepsilon = 1.0 \times 10^{-3}$ m·r
   - Low emittance RF gun:
     - $\gamma\varepsilon = 1 \times 10^{-6}$ m·r, 10 bunches/14 ns, 1×10^{10} e^-/bunch
   - Polarized gun (super lattice):
     - Polarization > 70 %
2. Positron production
   - Normalized yield > 0.15 N^+/N^-/GeV
   - Pulse intensity = 210 J/pulse
3. S-band injector
   - High gradient acceleration, 50 MeV/m
4. Damping ring
   - Damping time = 4.8 ms
   - Normalized emittance: $\gamma\varepsilon_x = 3 \times 10^{-6}$ m·r, $\gamma\varepsilon_y = 3 \times 10^{-8}$ m·r
5. X-band main linac
   - High gradient acceleration, 100 MeV/m
6. Final focusing
   - Achromatic focusing with demagnification factor of 1/300
   - Beam position and profile monitors for beams focused to < 30 nm

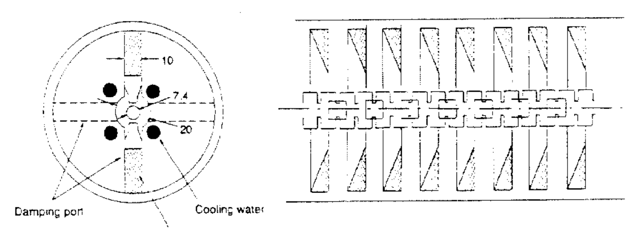

Fig. 9 Schematic drawing of an X-band structure with damped higher-order-mode Q's designed by use of a 3D computer code, MAFIA.

Asymmetric B-Factory

There is growing interest in KEK in looking for new physics beyond the Standard Model with a B-factory, a high luminosity electron-positron collider with a center-of-mass energy of about m (Υ_{4s}) = 10.6 GeV. Great concern of the experimental physicists is in the measurement of rare and CP-violating B-meson decays, and it requires an asymmetric collider with a luminosity well above 10^{33} $cm^{-2} \cdot s^{-1}$, in which an electron and positron beams collide with unequal energies so that the moving center-of-mass system enables a separation of a B-meson from its anti-particle produced.

We have been making extensive design efforts on the asymmetric B-factory since 1988.[6] The following are guidelines given for the accelerator design. (1) The nominal electron and positron beam energies are 8 GeV and 3.5 GeV, respectively. (2) The collision luminosity has to be 2 ~ 3 x 10^{33} $cm^{-2} \cdot s^{-1}$ shortly after the turn-on of the machine and be upgraded to 10^{34} $cm^{-2} \cdot s^{-1}$ afterwards. (3) The two rings of equal circumference will be build in a new tunnel to leave a maximum amount of flexibility in the design for a highest luminosity. (4) One experimental collision region will be allocated in the tunnel. (5) The present injector system for the TRISTAN electron-positron collider will be used for the B-factory with some modifications to increase the beam currents in the injector linac and accumulation ring.

General parameters of the B-factory accelerator preliminarily designed are given in Table 6. The two rings, a high energy ring (HER) and a low energy ring (LER), are of a racetrack shape as shown in Fig. 1 and housed vertically separated in the tunnel. Two 140 m long straight sections are prepared, one for a collision insertion and the other for RF cavities and injection systems. In the middle of the arcs two 30 m long straight section are inserted to accommodate wiggler magnets to control the beam emittance and radiation damping time. Figure 10 shows a configuration of the magnet lattice and optics parameters of the ring for a case of the beam crossing at an angle. Design of the collision insertion is of critical importance in the present accelerator. An insertion configuration for more elaborate head-on collision case is illustrated in Fig. 11, in which the two rings cross horizontally at the interaction region taking the S-shape orbits.

Although the present B-factory is thought to be a "state of the art" machine, several parameters are near or even beyond the limit straightforwardly achievable with existing knowledge and technology. Therefore, before making a decision of the B-factory construction, we will need further accelerator R&D to refine the design, especially, in such areas as RF cavities with low Q's for the higher-order-modes causing the coupled bunch instability, vacuum beam pipes which stand a high density synchrotron radiation power, more than 5 kW/m, and a comfortable integration of the collision insertion and particle detector which fulfills requirements both from the beam stability and mask configuration against the synchrotron radiation background.

Table 6 Design parameters of the asymmetric B-factory

	HER		LER	
Beam energy	8.0		3.5	GeV
Circumference		1180		m
Luminosity		2x10^{33}		$cm^{-2} \cdot s^{-1}$
Number of bunches		400		
Harmonic number		2000		
Tune shift (ξ_V/ξ_H)		0.05/0.05		
Beta functions at IP (β^*_V/β^*_H)		0.01/1.0		m
Beam current	0.22		0.5	A
Bunch length		5		mm
Emittance ($\varepsilon_V/\varepsilon_H$)		0.2/20		nm
Energy spread	7.0x10^{-4}		8.7x10^{-4}	
Energy loss/turn	3.8		1.1	MeV
RF voltage	38		20	MV
RF frequency		508		MHz
Bending radius	95.4		12.1	m

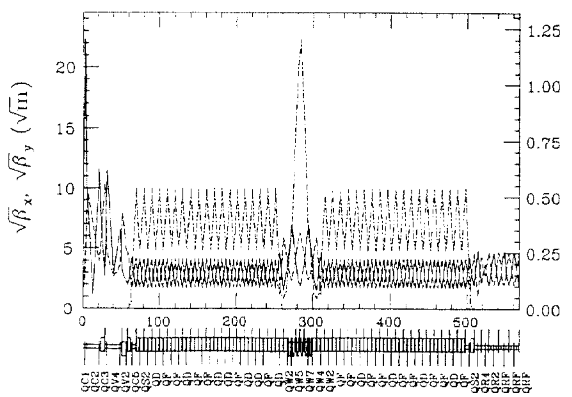

Fig. 10 Magnet lattice and optics parameters of the high energy ring preliminarily designed for the asymmetric B-factory.

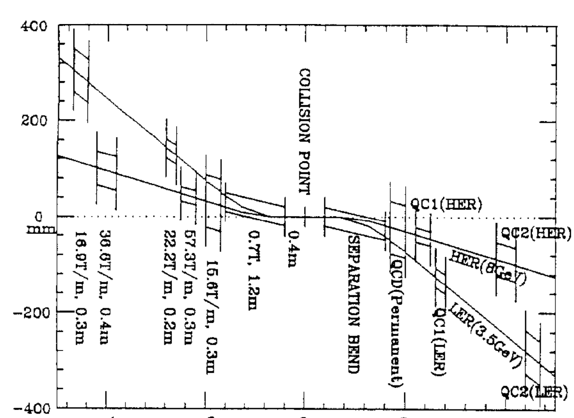

Fig. 11 A collision insertion of the asymmetric B-factory designed for a case of the head-on beam crossing.

Acknowledgement

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