FROM TRISTAN TO B–FACTORY

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Abstract

TRISTAN (1986–1995) is an electron-positron collider for top quark search. The center of mass collision energy was 50–64 GeV, then the highest in the world. To attain the required accelerator performance, intensive innovative R&D effort had to be made in such technologies as superconducting RF and magnet, high power RF components, vacuum, instrumentation, etc. B-factory, KEKB is an asymmetric energy (8 GeV+3.5 GeV) electron-positron collider for observation of CP violation in B-meson decays. The facility was constructed in 1998 by maximally utilizing the TRISTAN resources, and has achieved the world highest luminosity of $2.1\times10^{34}cm^{-2}s^{-1}$. In 2001, the Belle experimental group successfully observed the CP violation in B-meson decays as predicted by the Kobayashi–Maskawa theory, and this eventually led the theory to winning the Nobel Prize in physics in 2008.

OUTLINE

TRISTAN was the first Japanese electron-positron collider, and built in 1981–1986. The collision energy attained was 64 GeV, then the highest in the world.

National Laboratory for High Energy Physics (KEK) was founded in 1971 as the first national laboratory for inter-university research, and a 12-GeV proton synchrotron was built in 1971–1974 as its major research facility (KEK-PS). It must be noted that the KEK-PS energy was initially proposed to be 40 Gev and compelled to lower to 12 GeV to cope with the government's budget cut to a quarter of the initial demand (about 30 BYen). Intriguing is that the 40-GeV PS plan was realized as J-PARC after almost 40 years, whereas the machine design was considerably different than the other. Almost all of the domestic high-energy physicists then were dissatisfied with KEK-PS, and thought about higher energy world machines to be built after KEK-PS. In such circumstances Prof. T. Nishikawa, the head of the KEK Accelerator Department, proposed the TRISTAN project in 1973. The TRISTAN machine initially planned was a three-ring beam collider to facilitate various types of beam collisions: e^+e^-, e^-p, and pp.

In the 1970s, the standard theory to describe the elementary particle was steadily established by experiments, and the Kobayashi–Maskawa (K–M) theory published in 1973 was widely noticed as a basis of the standard theory. Hence the Japanese high energy physics community rightfully hoped that the new machine after KEK-PS should be the one to investigate the validity of the K–M theory and lead the theory to the Nobel Prize winning.

The K–M theory states in brief that the CP violation can be explained as the state mixing of six types of quarks. Three quarks (u, d, s) were known in 1973, and forth and fifth quarks, c and b, were discovered in 1974 and 1977, respectively. Then, to verify the K–M theory, experiments were done to find the sixth quark, t, and to show that the CP violation emerges in accordance with the K–M theory's prediction. In late 1970s, there were some theoretical predictions that $t\bar{t}$ mass plausibly ranged from 50 to 60 GeV/c^2. And after thorough discussion it was decided that TRISTAN should be an e^+e^- collider, reaching 30 GeV + 30 GeV and aim at finding t quark though the KEK site did not seem to be large enough to build a realistic machine of this energy range.

The TRISTAN construction was completed in 1986 as planned, and experiments to look for $t\bar{t}$ were carried out. But before long, it turned out that the $t\bar{t}$ mass was much heavier than expected and in the energy range beyond TRISTAN. Then some study groups were organized and investigated a possible construction of a B-factory for CP violation experiments in parallel with the TRISTAN project. What promoted this B-factory plan to a realistic one was an idea of the asymmetric energy two-ring e^+e^- collider proposed in the late 1980s. In 1993, the government accepted the KEK proposal that KEK began the construction of an asymmetric energy B-factory (e^+/e^- = 3.5 GeV/8 GeV) in 1994, provided that the TRISTAN resources could be maximally utilized, and the TRISTAN experimental program was completed by 1995.

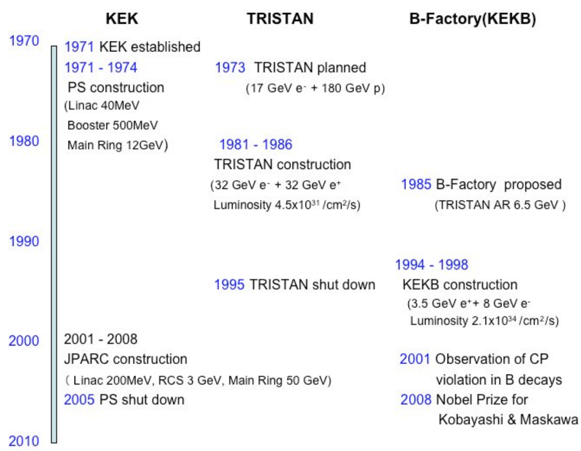

Figure 1: Progress of the accelerator construction for particle physics at KEK in 1971–2010

In order to investigate the CP violation, the KEKB collider was required to achieve the luminosity as high as 10^{34} $cm^{-2}s^{-1}$, or the stored beam currents exceeding amperes, almost two to three hundred times of those TRISTAN attained. And to reach this luminosity goal, the KEKB accelerator team had to overcome a lot of difficulties. But shortly after the completion of the machine in 1998, they could attain an unprecedentedly high luminosity of 2.1 $\times$ 10^{34} $cm^{-2}s^{-1}$ and brought the B-factory project to a great success. As a matter of fact, in 2001, the Belle experimental group succeeded in observing the CP violation in B meson decay, and this eventually led the K–M theory to winning the Nobel Prize in 2008.

Figure 1 summarizes the progress of the accelerator construction for particle physics at KEK in 1971–2010.

TRSTAN

Main parameter list of the TRISTAN e^+e^- collider is given in Table I, and the accelerator system configuration are shown in Fig. 2.

Table I: Main paramter list of the e^+e^- collider

Circumference	3018 m
Number of electron and Positron bunches	2 + 2
Beam energy	25 – 32 GeV
Initial total beam current	14 mA
Nominal RF frequency	508.58 MHz
RF voltage	180 – 500 MV (APS/936 cells/310 MV, SCC/160 cells/190 MV)
Emittance ratio ($\varepsilon_V/\varepsilon_H$)	1.5 % - 2 %
Beam life time	3–5 hr
Beta-functions at collision Point (β^*_V/β^*_H)	0.04/1.0 m
Beam sizes at collision point (σ^*_V/σ^*_H)	8/250 μm
Initial luminosity	4.5×10^{31} $cm^{-2}sec^{-1}$

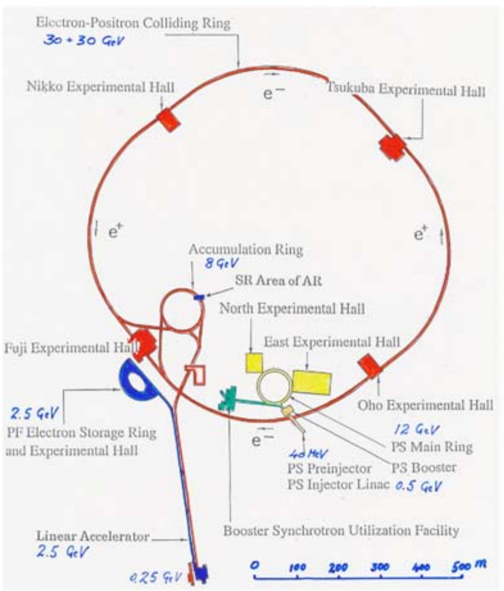

Figure 2: Configuration of TRISTAN accelerator system.

The TRISTAN accelerator system consists of a 2.5-GeV e^+,e^- injector linac with a 0.25-GeV positron generation linac, an 8-GeV accumulation ring (AR), and a main collider ring (MR). Figure 3 shows pictures of those accelerators.

Figure 3: Pictures of the TRISTAN accelerators.

It is well known that the optimally designed e^+e^- collider ring follows the rule to enlarge the diameter in proportion to the square of the beam energy. And the optimum diameter of a 30-GeV ring is given to be about 3 km. But the largest ring fit in the KEK site was estimated to be about 1 km in diameter. Therefore the TRISTAN ring had to be designed so that the huge radiation loss in the relatively small ring could be compensated with an efficient high power RF accelerating system. To cope with this requirement, the ring was designed to have unusually long straight sections (98 m $\times$ 8) for RF cavity installation, and a great deal of effort was concentrated in developing new high-power UHF accelerating components, which included APS(alternating periodic structure)-type normal conducting cavity system, world's first large-scale superconducting cavity system, klystron tubes with world's highest continuous output power, liquid He system with domestically highest cooling power, etc.

The APS cavity has an axially symmetric structure for suppression of the beam induced deflecting field, and its strong cell to cell coupling (large bandwidth > 1%) allows a long multi-cell structure to save the installation space and reduce the number of RF components as couplers, dummy loads, etc. The cavity is operated at 508.58 MHz and its main specifications are 23 MΩ/m in shunt-impedance, 300 kW in maximum input power, and 1.6 MV/m in maximum accelerating field. In the TRISTAN ring, 104 APS 9-cell cavities were installed. The cavity is illustrated in Fig. 4.

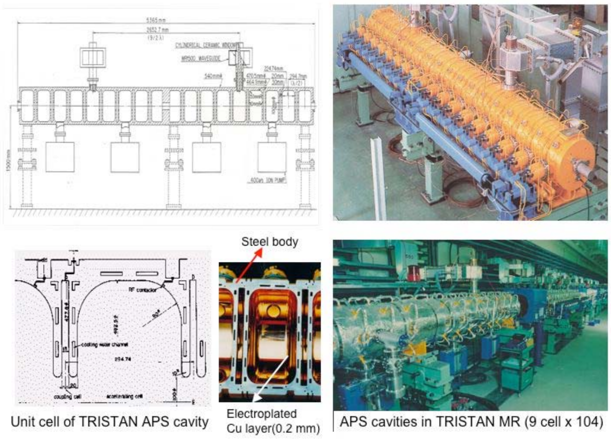

Figure 4: TRISTAN APS cavity.

The R&D of the superconducting RF cavity at KEK started as early as 1971, and made rapid progress responding to its application for TRISTAN. The cavity construction was carried out in 1981–1985. In this R&D effort, various new technologies, which became the standard ones for today's superconducting cavity fabrication, were developed such as hydro forming of Nb plates to half cavity cells, electron beam welding (EBW) to form cavity cells, electropolishing of the inner cavity surface, rinsing of cavity structure with pure H_2O and H_2O_2, etc. Figure 5 shows the TRISTAN superconducting 2 × 5cell cavity and the number of the installed cavities as a function of accelerating field.

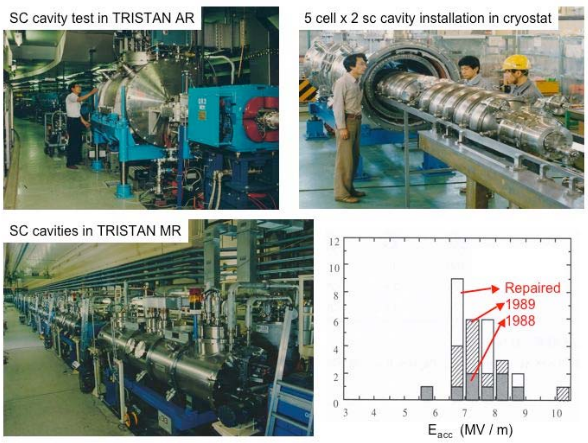

Figure 5: TRISTAN superconducting cavity.

In addition to the RF system, TRISTAN, as the first beam collider in Japan, required the development of new technologies. Typical ones are all aluminum-alloy vacuum system to achieve a vacuum pressure less than 10^{-8} Pa with radiation power deposit of 3 kW/m on the beam duct surface, superconducting quadrupole magnets for mini-beta insertion, which generated the field gradient as high as 70 T/m and enabled to make the beta-functions at the beam collision points as low as 0.04 m vertically and 1.0 m horizontally, wholly centralized computer control system, and versatile computer code SAD (Strategic Accelerator Design) for beam orbit analysis. Figure 6 shows the all aluminum-alloy beam duct, 1.2-MW klystron tube, and superconducting insertion quadrupole magnet. Also shown in the Fig. 7 are the displays of the colliding beam behavior in the MR, the accelerator control console, and one of the particle detectors installed at the four beam collision regions.

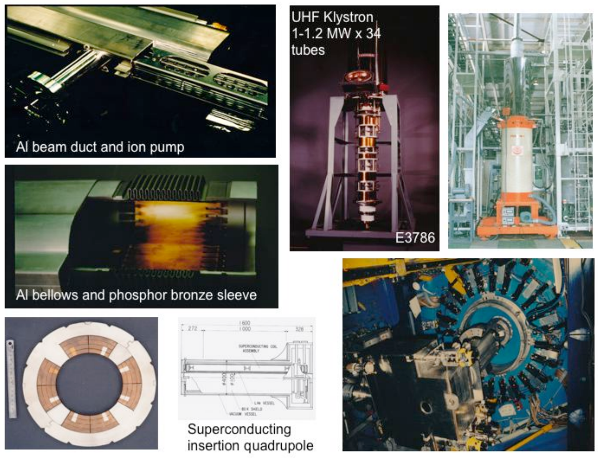

Figure 6: TRISTAN all aluminum-alloy beam duct, 1.2-MW klystron tube, and superconducting insertion quadrupole magnet.

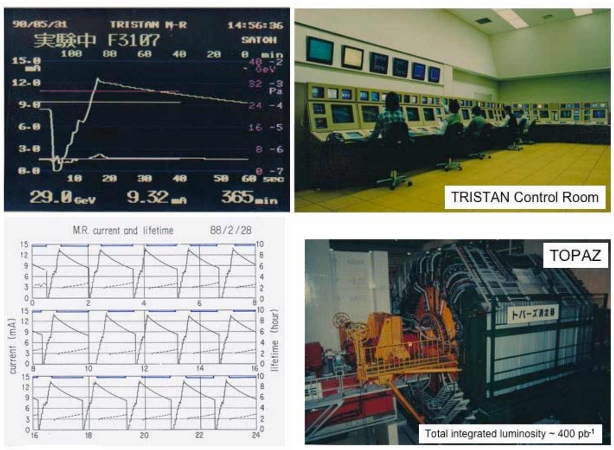

Figure 7: Displays of the colliding beam behavior in MR, the TRISTAN accelerator control console, and one of the particle detectors installed at the four beam collision regions.

B-FACTORY

The KEKB accelerator is an asymmetric energy, two-ring, e^+e^- collider, and its main parameters are listed in Table II. B-mesons to study the CP violation are produced by such reaction as $e^-(8\ \mathrm{GeV}) + e^+(3.5\ \mathrm{GeV}) \rightarrow \Upsilon_{4s}(10.58\ \mathrm{GeV/c^2}) \rightarrow B + \bar{B}$. As the branching ratio of the CP violating decay is so small, the KEKB luminosity has to be as high as $10^{34}\ \mathrm{cm^{-2}s^{-1}}$, and the stored beam currents exceeding one ampere are required. Then the injector linac was remodelled to be able to accelerate e^-

and e+ beams to 8 GeV and 3.5 GeV, respectively, and the linac beams were injected directly to the main e- and e+ colliding rings without using an accumulation ring like TRISTAN. Figure 8 shows the configurations of the KEKB accelerator system and the remodeled linac, and the pictures of those accelerators.

Table II: Main parameters of the KEKB Electron-Positron Collider

	Positron Ring	Electron Ring
Circumference (m)	3016	
Luminosity ($cm^{-2}s^{-1}$)	2.1×10^{34}	
Crossing angle (mrad)	± 11	
Integrated luminosity (fb^{-1})	1.5/day, 8.4/week, 30.2/month	
Beam energy (GeV)	3.5	8.0
Beam current (A)	1.6	1.2
Number of bunches	1584	
Harmonic number	5120	
RF frequency (MHz)	508.8	
Total RF voltage (MV)	8.0	13.0
Beta's at IP $\beta^*_H/\ \beta^*_V$ (cm)	120/0.59	120/0.59
Vertical beam size at IP σ^*_V (μm)	0.94	0.94
Beam-beam parameter $\xi_H/\ \xi_V$	0.127/0.129	0.102/0.090
Beam life time (min.@ A)	133 @ 1.6	100 @ 1.2
Injection rate (nC/s)	50	50–100

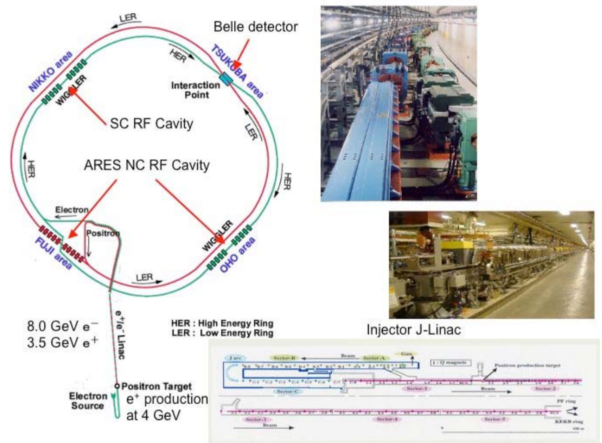

Figure 8: Configurations of the KEKB accelerator system and the remodeled linac, and the pictures of those accelerators.

In designing the KEKB rings, some measures were taken to achieve such unprecedentedly high luminosity. Several effective ones are as follows.

A special beam orbit structure is required to collide and separate two beams in the interaction region of the two-ring beam collider. In KEKB a scheme is adopted to collide the two beams at a horizontal angle of ± 11mrad. Though this finite angle crossing might cause a synchro-betatron resonance type beam instability and a slight loss of luminosity, this allows the beam separation without bending elements which become the sources of troublesome synchrotron radiation.

The magnet lattice of the KEKB rings is designed to have a 2.5π unit cell lattice with paired non-interleaved sextupoles for chromaticity correction. And local correction sextupole systems are adopted to compensate for chromaticity arising from the strong final focus normal conducting and superconducting quadrupole magnets to make the beta-functions at the collision point as low as β_H^*/β_V^*= 120 cm/5.9 mm. It is found that this lattice design makes the KEKB ring invulnerable to beam instabilities.

New types of RF accelerating cavities were also developed to eliminate serious frequency-detuning effect of the accelerating cell caused by very strong current beams. One is a normal conducting ARES (Accelerator Resonantly Coupled with Energy Storage) and the other is a single-cell large aperture superconducting cavity. Figures 9 and 10 illustrate the ARES cavity and KEKB superconducting cavity.

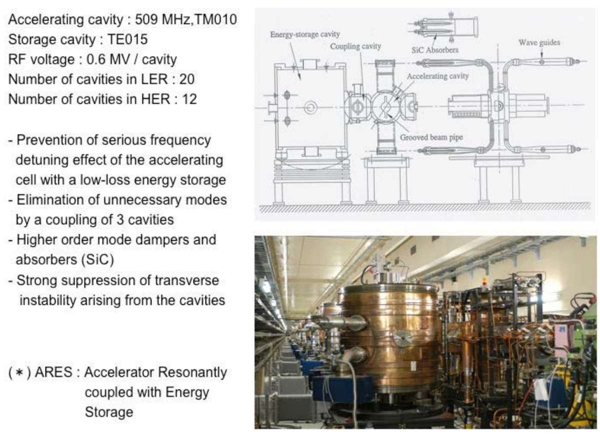

Figure 9: ARES cavity.

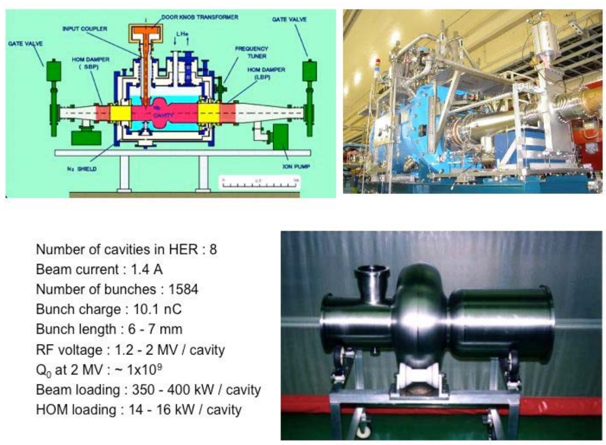

Figure 10: KEKB superconducting cavity.

The KEKB rings were completed in 1998, and long before the beam commissioning encountered very serious beam instability in the e^+ ring, which was caused by electron cloud generated by synchrotron radiation at the beam duct surface. But after a bitter struggle against this instability, it was finally found that it could be suppressed by installing solenoid coils in every empty space of the ring to generate a few tens of Gauss axial magnetic field and sweep out secondary electrons as illustrated in Fig. 11. Then the KEKB luminosity was rapidly improved and exceeded the design goal of 1×10^{34} $cm^{-2}s^{-1}$ in 2003. KEKB recorded the world's highest peak luminosity of 2.1×10^{34} $cm^{-2}s^{-1}$ in 2009. Evolution of the KEKB luminosity is shown in Fig. 12.

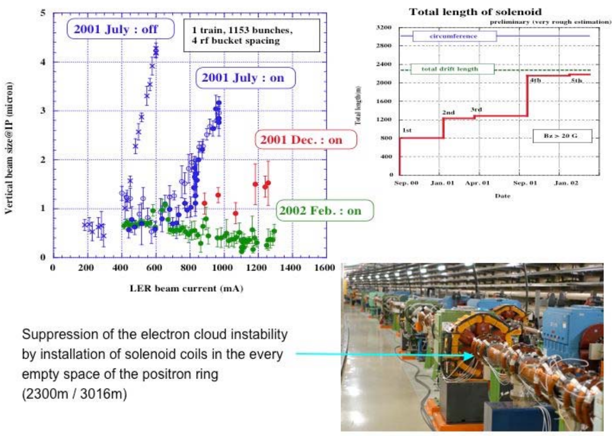

Figure 11: Suppression of the electron-cloud instability by installation of solenoid coils in the e^+ ring.

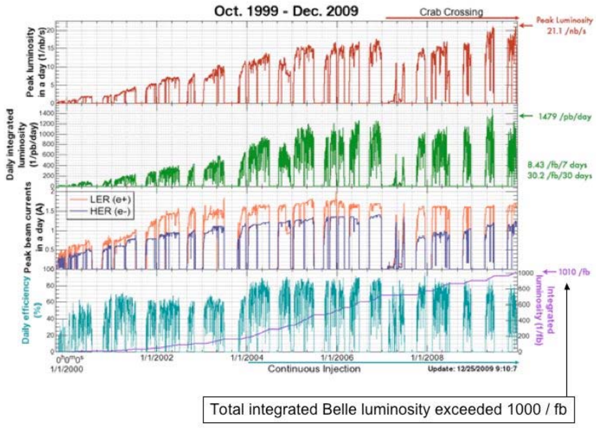

Figure 12: Evolution of the KEKB luminosity.

Now KEKB has been shut down, and is going to be remodeled to SuperKEKB of 80×10^{34} $cm^{-2}s^{-1}$ in peak luminosity for better understanding of the CP violation and looking for phenomena beyond the standard theory. SuperKEKB is envisaged to start operation in 2014.