The TRISTAN and KEKB Colliders

Takahiko Kondo (KEK) —– version 0 (2026.6.30) —–

KEK (High Energy Accelerator Research Organization) is a laboratory in Tsukuba Science City, 55 km northeast of Tokyo, Japan. KEK was founded in 1971 to boost Japan's high-energy physics that has been lagging behind the world frontier since the World War II. However due to budget constraints, the planned 40 GeV proton synchrotron was significantly reduced down to 12 GeV far from the energy frontier of the world [1], An e^+e^- collider TRISTAN construction started in 1981 and its operation continued from 1986 till 1995. Using the same accelerator tunnel, another e^+e^- collider project KEKB started in 1994. Its operation ended in 2010. Table 1 lists major parameters of two projects.

1 TRISTAN

When KEK was founded, under the strong leadership of Tetsuji Nishikawa, KEK began a preparation for the KEK future plans. TRISTAN [1] is

[1]Tristan is the name of the protagonist of Wagner's famous opera, and Gell-Mann took the name "Quark" from a poem inspired by James Joyce's Tristan and Isolde. Thus, the project name "Tristan" also included the meaning of becoming a Japanese knight who takes on the unknown challenges of particle physics.

Table 1: Major parameters of TRISTAN and KEKB B-factory projects.

	TRISTAN	KEKB
Operation years	1986 - 1995	1999 - 2010
Beam energy	(e^-, e^+) 32 GeV	(e^-) 8.0 (e^+) 3.5 GeV
Beam current	(e^-, e^+) 4 mA	(e^-) 1.45 (e^+) 1.8 A
Peak Luminosity	4.5×10^{31} cm^{-2}s^{-1}	2.1×10^{34} cm^{-2}s^{-1}
Circumference	3.016 km	
Experiments	AMY, TOPAZ, VENUS	Belle
Physics goals	top search, QCD, 2γ	B physics, CP violation

standing for ”Tri Ring Intersecting STorage Accelerators in Nippon” consisting of tri-ring intersecting storage rings for various types of colliding beam experiments such as ep, pp, e^+e^- etc.

The original design proposed in 1973 was three accelerator rings with total circumference of 2035 m. The phase 1 was an electron proton collider in the energy range of 16 GeV$\times$70 GeV. Then a superconducting magnet ring would be added in the same tunnel to push up the proton energy to 180 GeV for pp and ep collider physics [2].

In late 1970s, the TRISTAN ep collider plan was revised for higher energies to achieve momentum transfer larger than 100 GeV/c which was highly desirable to investigate strong and weak interactions [3]. The new version was designed so as to have the largest size that could be accommodated on the KEK site. The total circumference was raised to 3016 m, making it possible to accelerate electrons up to 25$\sim$30 GeV and protons more than 300 GeV with superconducting magnet rings of 4.5 Tesla.

Proton and electron beams were planned to be injected from the existing 12 GeV KEK proton synchrotron and the 2.5 GeV electron linac for the synchrotron radiation facility (Photon Factory) to be completed by the end of 1981, respectively.

The machine had a fourfold symmetry with four long straight sections of 230 m. The length of the straight section is determined in such a way that enough space be provided to rotate the polarization of electrons to realize polarized ep collisions. The accelerator tunnel was designed to be wide enough to allow three accelerator rings.

The revised TRISTAN project was divided into two phases. In the first phase, while constructing the accelerator tunnel and experimental halls according to the full TRISTAN plan, only one electron ring was built to carry out electron-positron collisions as shown in Figure 2. The center of mass energy was expected to be 50$\sim$60 GeV, exceeding PEP (29GeV) at SLAC and PETRA (46GeV) at DESY. Therefore, in e^+e^- colliders, TRISTAN was to achieve the world's highest energy during the period until the LEP at CERN took over.

The most important target of the phase-1 TRISTAN e^+e^- collider was to discover the top-quark, the last missing piece of the quark sector. The top-quark mass was expected to be less or around 30 GeV, as a common sense those days. For example, prominent theorists predicted like 14 GeV (Georgi), 20 GeV (Glashow), 26 GeV (Sugawara) [4]. Nobody expected top is as heavy as 170 GeV.

The phase-1 TRISATN project was approved by the Japanese Government on April 1981 as a five year project. Figure 1 shows a snapshot

Figure 1: (left) Groundbreaking Ceremony of TRISTAN on Nov. 1981, attended by S. Ozaki, T. Nishikawa, Y. Yamaguchi, P. Panofsky, Y. Nambu. (right) Accelerator tunnels and experiment halls were constructed open-cut. Mt. Tsukuba at the back.

at the Groundbreaking Ceremony of the TRISTAN ring held in November 1981. Pief Panofsky (SLAC) and Yoichiro Nambu (Chicago Univ.) came all the way for the ceremony.

Satoshi Ozaki moved from BNL to KEK as a TRISTAN project leader. Three large-scale general purpose detectors were approved. VENUS and TOPAZ teams were domestic, while AMY led by Steven Olsen (Rochester Univ.) was the first KEK-based international collaboration made up of physicists from US, Japan, China and South Korea. All detectors used superconducting solenoidal magnets. VENUS constructed a cylindrical drift chamber[2] while TOPAZ built a time-projection tracking chamber. VENUS constructed a liquid-Argon EM endcap calorimeter[3].

The construction of TRISTAN for phase-1 started in 1981 [5]. As shown in Figure 2, the civil engineering work for the accelerator tunnel was carried out on a scale that could include the phase-2 two proton rings.

On November 14, 1986, just five year since the groundbreaking ceremony, TRISTAN achieved e^+e^- collisions at the world's highest center-of-mass energy of 50 GeV [6]. TRISTAN was operated for data taking from 1987 till 1995. In 1988, five-cell superconducting RF cavities with field strength of 6$\sim$ 9MV/m were added to increase the beam energy from 30 to 32 GeV. This system was the largest system in the world until 1995. Furthermore, in 1990, four pairs of superconducting quadrupole magnets with field gradient of 70 T/m for mini-beta system were inserted into the

[2] Photo on the cover page of CERN Courier Vol. 24, No. 10, Dec. 1984 (URL) https://repository.cern/records/s2p62-21r74

[3] Its cryostat was fabricated by Kawasaki HI Ltd. Later Kawasaki HI built the cryostat of ATLAS barrel LAr calorimeter and CMS endcap structure.

four collision points. The luminosity of $4\times10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ were kept for last 4 operation years [7].

Figure 2: TRISTAN main ring tunnel was built wide to install two proton rings for phase-2.

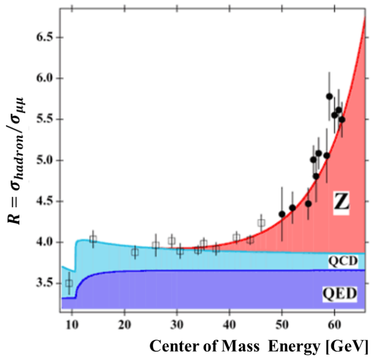

Figure 3: Ratio of σ(hadrons)/ $\sigma(\mu^+\mu^-)$ as a function of center of mass energy.

The first experimental results from three TRISTAN groups were presented in 1988 [8]. All observed processes were consistent with the standard model and no signs of the top quark. Figure 3 shows the R-ratio (total hadronic production divided by $\mu^+\mu^-$ rate) as a function of center of mass energy, If a top quark pair were produced, the R-ratio should have jumped up by about one unit. Observed gentle rise of R-ratio was explained well by the virtual γ-Z_0 interference. The energy of TRISTAN was too low to produce top-quark pairs. The next energy frontier e^+e^- machine LEP was also too low. AMY, TOPAZ and VENUS jointly verified existence of a triple-gluon self-coupling by carefully studying 4-jet production, the world's first confirmation.

2 Post-TRISTAN politics

On March 1986, the Japanese High Energy Committee chaired by Yorikiyo Nagashima (Osaka Univ.) submitted the recommendation report for the Japan's energy frontier projects as [9]

1. Start accelerator R&Ds immediately aiming at domestic construction of a TeV e^+e^- linear collider.

2. Promote international cooperative experiments at SSC.

I, the current author, was the person who pushed strongly the 2nd recommendation for SSC participation.

Late 1980s and early 1990s, KEK received quite amount of criticism, since TRISTAN could not make any breaking-news discoveries. Hirotaka Sugawara who served as the KEK director in 1989-2003, said in his memoire written 20 years later [17],

> *TRISTAN was under serious attack. All Government wanted to hear was when KEK would shut down the TRISTAN. . . . because they themselves were targeted for funding a large sum of money to TRISTAN which failed to find a top quark.*

According to Sugawara, most persuasive future plans in late 1980s were

1. TRISTAN transforms to a synchrotron radiation facility
2. KEK builds Japan Hadron Facility (JHF) a nuclear physics project
3. Japanese high energy community participate in SSC (and/or LHC) without major domestic project.

About SSC participation ohf Japan, Sugawara recalls [17]

> *US government approached the Japanese government at the highest level and asked Japan to get involved in the SSC project in a major way. Prime Minister Miyazawa told me directly that he would accept Bush's offer if the Japanese researchers were interested in it. Monbusho decided that it will support the participation of experimentalists in SSC. . . . . . the in-kind contribution was more or less decided that it will go through MITI* [4]*. .*

Taking the opportunity when the SSC issue became a problem at the highest government level, Sugawara managed to slowly re-open a dialogue with the government officials on the future of KEK. His question was whether it were a sound policy in the field of high energy physics of Japan to participate in SSC without no major domestic project. At the same time, he discussed with nuclear physics and neutron communities to get their consents on postponement of the JHF (later J-PARC) project. All he needed then was a new and attractive accelerator project for the KEK future.

[4] Ministry of International Trade and Industry

While the TRIATAN project rose and fell, notable progress was happening in the corner of particle theories, the CP violation of the weak interaction. In 1973, Makoto Kobayashi and Toshihide Maskawa proposed so-called KM-mechanism of CP violation assuming three generations of quarks [10]. Then in 1980, using the KM-mechanism, Carter, Bigi and Sanda pointed that CP violation could be as high as 20% in the B meson system [11].

In 1980, CLEO group at CESR discovered Υ_{4S} (10.58 GeV) just above the $B + \overline{B}$ open threshold. In 1987, B_0 lifetime was measured to be 1.29 psec by MAC group at PEP, long enough for decay vertex detection. Then, ARGUS group at DORIS-II identified a large $B_0\bar{B}_0$ mixing oscillation. These three values turned out to be just barely suitable in making it possible to measure the CP violations in B system experimentally. In his memoir Ichiro Sanda recalled it and expressed like [18]

> *the Mother Nature has gone out of Her way to show us CP violation.*

3 KEKB B-Factory

Now, how to experimentally find the CP violation of the B-meson system? In 1986, Pier Oddone (LBL) proposed a groundbreaking idea of an asymmetric e^+e^- double-ring collider [12]. If two beam energies are very different, the center of mass system moves in the lab frame. Then two decay vertex points of B_0 and $\overline{B}_0$ from a parent Υ_{4S} could be separately located and reconstructed with identification of CP eigenvalues.

Since the branching ratio of B_0 decay into $J/\psi K$ CP eigenstates is very small, B-factory must have the peak luminosity greater than 10^{33} cm^{-2} s^{-1}, 100 times of the luminosity that TRISTAN reached.

In 1994, two asymmetric collider projects KEKB at KEK and PEP-II at SLAC were approved for construction aiming at exactly the same physics goal. A historic accelerator race started. Table 2 shows timelines of KEKB and PEP-II.

Several key features of the KEKB accelerator design are written in the very stimulating review by Katsunobu Oide, one of leading accelerator physicists at KEK [19]. Followings are excerpts from his review;

- The TRISTAN tunnel was thought to be too long for B-factory. A new tunnel with shorter circumference of 1,400 m was once designed, but soon abandoned due to high cost. The TRISTAN arc section (for 3 rings originally) was just wide enough to install two rings with horizontal separation, minimizing the vertical beam

Table 2: Timelines of KEKB and PEP-II projects

	KEKB	PEP-II
1993		(10.22 SSC demised)
1994	Apr. Start construction	Jan. Start construction
1995	Dec. Start removing TRISTAN	
1996	ARES, SC cavity test at AR	
1997		6.16 HER beam first stored
1998	May Linac upgraded 12.13 HER beam first stored	7.16 LER beam first store 7.23 First collisions
1999	1.14 LER beam first stored May BELLE rolled in	2.8 Lpeak = $5.2\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ May BABAR rolled in
2000	Aug. LER solenoid winding started	
2001	8.14 discovery of CPV	2001.8.14 discovery of CPV

Figure 4: KEKB arc section. Two rings (HER and LER) were placed horizontally, thanks to wide TRISTAN tunnel.

Figure 5: Many large ARES cavities (cylindrical shape lined up on the left) were installed in wide and long straight sections of TRISTAN.

emittance (see Figure 4). Long straight sections with large aperture (for spin rotators originally) was adequate to install many AREA[5] and superconducting cavities (see Figure 5).

- KEKB had a horizontal beam crossing angle of 22 mrad. The merits of a finite crossing angle were obvious from the points of beam optics, detector background, etc. Historically a large crossing angle was once tried at DORIS in the 1970s but unsuccessful. PEP-II stuck the traditional head-on collision scheme. KEKB managed to avoid the synchrotron-betatron coupling by choosing good tunes. After KEKB success, the finite crossing angle scheme became a world standard for colliders.

- Long TRISTAN tunnel brought enough room and flexibility to install such as 2.5π cell structure, local chromaticity correction, a long wiggler sections etc.

- KEKB chose ARES and superconducting cavities. Both types were strong against HOM excitation, contributing beam stability significantly.

- CIM (continuous injection mode) has been used for injection starting in 2004, effectively making injection power comparable to PEP-II.

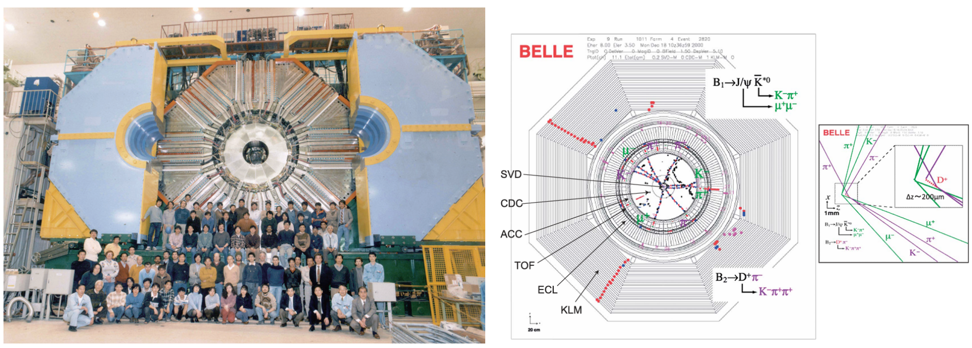

Figure 6: (right) Belle detector with high quality vertex detector and excellent particle ID capabilities using home-made Aerogel Cerenkov counters. The high-resolution electromagnetic calorimeter was built with CsI(Tl) crystals imported from Russia and China. (right) A CP event detected by Belle [13].

[5] Accelerator Resonantly-coupled Damped cavities

An international collaboration "Belle" of 360 physicists from 14 countries was formed under the leadership of Fumihiko Takasaki and Steve Olsen. Belle was designed to optimize the observation of CP violation in the B meson system [13]. Figure 6 shows the Belle detector and one of observed events with clear identification of CP eigenstates and separate vertex points.

Both detectors BELLE and BABAR were rolled in their interaction points in May 1999 and data takings started immediately after.

Half a year later on Feb. 2000, the Nature dedicated two pages to a sensational news profile along with a photo of Jonathan Dorfan (SLAC DG) and Pier Oddone inside the SLAC 2-mile linac tunnel as if they were triumphant in the accelerator race:

> *"Stanford accelerator takes lead in race to quantify CP violation" The B-factory at the SLAC is poised to win an international race to quantify a critical element in the Standard Model of particle physics.* [14]

In fact, the early operation of the KEKB accelerator ran into various difficulties. The most serious problem was a single-beam blowup of the positron beam, caused by a formation of electron-cloud from photo-emissions and secondary emissions. Such electron-cloud could possibly create a single bunch head-tail instability.

In order to reduce such electron-cloud effects, KEK started a crash program of winding solenoid coils on all field-free part (2300m) of the positron ring. Starting from September 2000, working day and night, about 3300 solenoid coils were wound in one year [15].

In 2001 April, the KEKB peak luminosity exceeded PEP-II as shown in Figure 7, Later, both accelerators exceeded each of the luminosity goals by more than factor 2.

On Aug. 14, 2001, Belle group published a discovery paper on the observation of the CP violation in the neutral B meson system [16]. Belle collected a 29.1 fb^{-1} data sample, which contains 31.3×10^6 $B\bar{B}$ pairs at the Υ_{4S} resonance. Only several hundred events were useful for the CP violation study because of complex requirements for a clear CP eigenstate identification. Figure 8 is a plot of proper time distributions of tagged events with CP eigenvalues of even or odd. Belle group got

$$\sin 2\phi_1 = 0.99 \pm 0.14(\mathrm{stat}) \pm 0.06(\mathrm{syst}). \tag{1}$$

where ϕ_1 is one of the three internal angles of the unitarity triangle, non-zero value of which is the evidence of CP violation. BABAR group

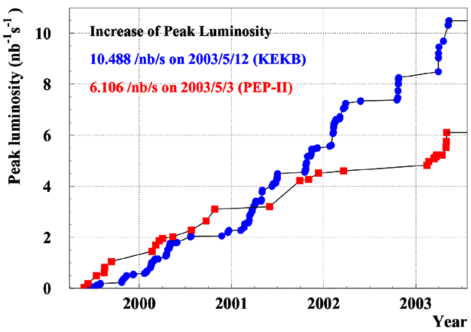

Figure 7: Peak luminosity of KEKB (blue) and PEP-II (red).

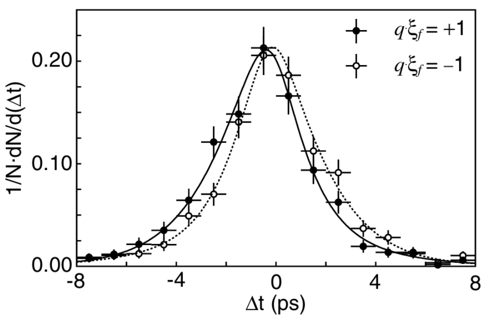

Figure 8: Discovery plot of the CP violation in the B system [16].

reached similar results using 32M $B\bar{B}$ pairs. Both papers appeared in the same issue in back-to-back. This was the first discovery of the CP violation outside the Kaon system since 1964.

The big accelerator race had been very different in terms of technology, organization and people, but both projects simultaneously succeeded in achieving the same results which were fundamental to the particle physics. There was no loser. How fair the God is!

Followings are interesting comments written by persons directly involved:

Hirotaka Sugawara wrote [17]

> *When Carlo Rubbia visited KEK around 1993, he asked me in private, "Are you seriously trying to compete with SLAC? Do you know that they have the world's best group of accelerator scientists?" I just smiled back in a Japanese way and said nothing.*
>
> *Well, I knew that SLAC people helped us a great deal in constructing our TRISTAN machine. They were, in a sense, our teacher. The best way to be a good student is to surpass the teacher. We were determined to be a good student......*

Katsunobu Oide commented [19] :

> *The competition between the two machines provided various benefits to both. It was not hostile but rather cooperative. Most information was open to each other via meetings, web,*

and visiting people. Both sides invited reviewers from the other to participate in machine review committees.

In 2008, Makoto Kobayashi and Toshihide Maskawa were awarded the Nobel Prize in Physics "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature".

4 Conclusion

In the 1980s and 1990s, KEK was able to push forward two major accelerator projects: TRISTAN and KEKB B-Factory.

TRISTAN, Japan's first collider reached the world's highest e^+e^- energy for three years, but it couldn't discover the top quark that it was aiming at. Still, the project greatly helped technologies and people jumping up to the international level.

At around 1990, KEK faced a temporarily but very difficult situation in choosing its next project. Timely, a possibility of discovering the CP violation in the B system emerged up. The KEKB with the clear and fundamental physics goal was able to gain understanding from the scientific community as well as the government.

First time in history, KEK and SLAC were in the severe project race towards the same physics goal. Under very different and distinctive accelerator designs, both labs started construction, began operation and simultaneously announced the CP violation discoveries, leading to the 2008 Nobel Prize in Physics.

KEK has been grateful, from its founding until today, for the technical advice and support provided by high-energy accelerator labs around the world, especially SLAC.

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