HEP experiments in Japan: The Next Generation

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Abstract

The HEP experiment in Japan is now stepping into next phase. J-PARC, which is a newly-built high intensity proton synchrotron facility, has started the operation recently. A new long-baseline neutrino experiment T2K is now at the commissioning stage utilizing the beam. In parallel, the upgrade of KEKB/Belle, a new generation B-factory experiment at KEK, is about to start. The accelerator will be upgraded to SuperKEKB whose luminosity is expected to be about 50 times higher. The detector is also upgraded to Belle II to keep up with the drastic increase. In this talk, a detailed review is given for these new experiments with some coverage of the readout and DAQ technologies.

I. Introduction

Japan has a long history of the accelerator based HEP experiments. The first electron synchrotron with an energy of 1.3GeV was built at Institute for Nuclear Studies of University of Tokyo (INS) from 1956. The construction of the second large accelerator, 12GeV proton synchrotron (KEK PS)[1], was started at KEK in 1970 and many early HEP experiments were performed with it. From 1999, a long baseline neutrino experiment K2K[2] had been started.

Successively, an electron-positron collider called TRISTAN[3] was constructed at KEK from 1983 and four experiments (TOPAZ, AMY, VENUS and SHIP) started data taking from 1986. In 1995, the construction of KEKB accelerator for the B-factory experiment was started by recycling the TRISTAN tunnel and the data taking by the Belle experiment has been going on since 1999.

Recently, the HEP experiment in Japan is stepping into the new generation. The operation of KEK-PS was terminated in 2005 and a new proton accelerator complex named J-PARC[4] has newly built in the Tokai campus of KEK. The beam from the accelerator is fed into the neutrino facility for T2K[5], which is the upgrade experiment of previous K2K at KEK-PS. The commissioning of the facility is just been started.

On the other hand, KEKB and Belle have been running for more than 10 years and their upgrades are about to start. This talk summarizes the preparation status of these Japanese next generation experiments, T2K and SuperKEKB/Belle II[6].

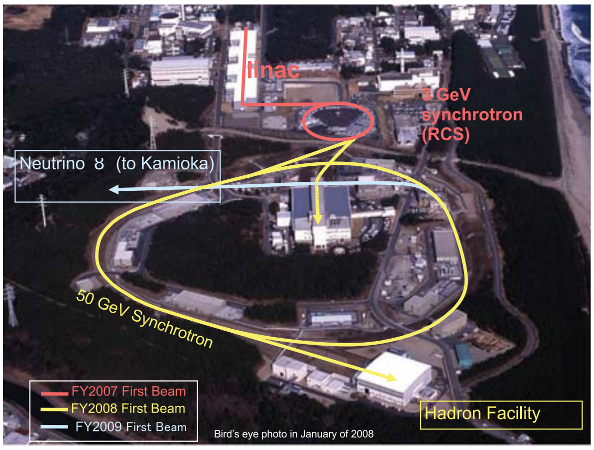


Figure 1: Aerial view of J-PARC.

II. J-PARC and T2K

A. J-PARC

J-PARC is a proton synchrotron facility built at the Tokai campus of KEK. It consists of a 400MeV injection linac, a 3GeV RCS (rapid cycle synchrotron) and a main 50GeV synchrotron. The proton beam from RCS is also used to provide both neutron and muon beams to the materials and life experimental facility(MLF). Two facilities, the hadron facility and the neutrino beam line, are constructed to feed protons from the main 50GeV synchrotron. The aerial view of J-PARC is shown in fig. 1.

The beam power of J-PARC is 10 to 100 times higher than that of KEK-PS, aiming at the MW class operation. In December, 2008, the beam acceleration up to 30 GeV succeeded with the fast extraction to the beam abort dump. Also the MLF at RCS started the operation for user runs with a power of 20kW. The slow beam extraction to the hadron experimental hall was achieved in January, 2009. There still remain some problems in the high energy/power operation in the complex and the operation at 30GeV with a power of 0.1MW is foreseen in years of 2009 and 2010.

B. T2K

T2K (Tokai to Kamioka) is a new generation long baseline neutrino experiment. It is the successor of the K2K experiment at KEK 12GeV PS. The physics goal of T2K is the measurement of the lepton mixing angle θ_{13} and is also aiming at the discovery of the CP violation in the lepton mixing matrix. T2K consists of the neutrino facility of J-PARC, the near detector complex located 280m apart from the target station, and the Super Kamiokande (SK) detector located in Kamioka which is $\sim$300km far from J-PARC as shown in Fig. 2.

The neutrino beam from J-PARC is tilted by 3 degree from the axis to SK so that the neutrino flux becomes maximum in the SK sensitive energy where the oscillation becomes maximum. The construction of the neutrino facility at J-PARC was completed on schedule and the beam commissioning has been started from April 2009.

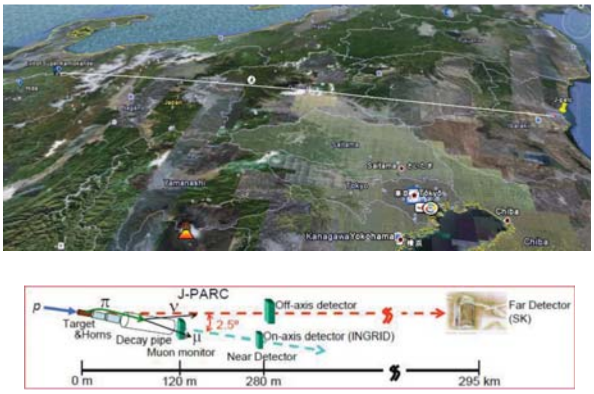


Figure 2: T2K configuration

C. Near detector : ND280

The “near” detector is the key component of T2K which is newly built at 280m downstream of the target station. The detector consists of two systems. One is the on-axis detector called INGRID placed along 0 degree axis, and its purpose is to measure the direction and intensity of the neutrino beam. The other is the off-axis detector ND280[7] placed in 2.5 degree off-axis which measures the flux and energy spectrum of neutrino beam.

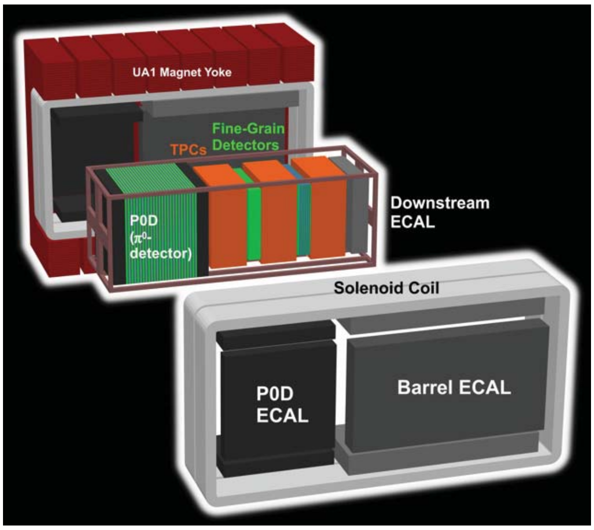


Figure 3: ND280: T2K off-axis detector system.

Fig. 3 shows the configuration of the off-axis detector. The detector is composed of lead/scintillator tracking detectors for π^0, TPCs and Fine-Grained Scintillator detectors (FGDs), and downstream electro-magnetic calorimeters. The detector complex is equipped in a solenoid coil surrounded by a magnet yoke providing a 0.2 Tesla magnetic field, which is recycled from the UA1 experiment[8]. New technologies are used in the detector. The Micromegas[9] technology is used for the gas-amplification readout of TPC. The dE/dx resolution measured in the beam test is 6.9%, which provides a $> 5\sigma$ e/μ separation for a momentum range more than 200 MeV/c, with the spacial resolution of 320(650)μm for 15(75)cm drift length. The FGD is the solid active target with the plastic (1st layer) and water (2nd layer) scintillators and the scintillation light from them is fed into Multi-Pixel Photon Counters (MPPC) array from Hamamatsu through WLS fibers. The beam test result confirms the expected performance with a pulse height of $\sim$ 30 p.e. for the minimum ionizing electrons.

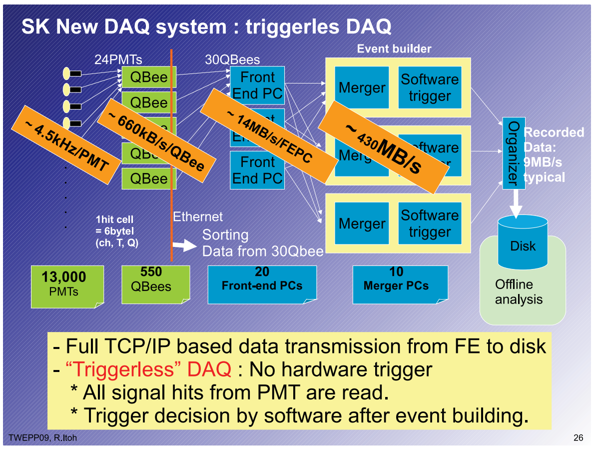
The magnet installation was already completed in 2008 and the installation of FGDs and TPCs is being in progress. The commissioning of the entire detector system is scheduled by the end of 2009.

D. SK DAQ upgrade

Super Kamiokande (SK) is a large water Cerenkov counter system consisting of 13000 PMTs in 50,000 tons of water. The detector is used as the far-side detector of T2K. Recently the data acquisition system of SK has been upgraded with the new front end electronics so that it can process all the PMT hits with no dead time[10]. The system has no central trigger and each PMT hit exceeding the threshold is sent to the event builder asynchronously where the average data flow becomes $\sim$430MB/sec. The “software trigger” processing is performed by combining the hits in the neighboring time slice and the data flow is reduced down to $\sim$9MB/sec at the storage level. Fig. 4 shows the schematic view of the upgraded SK DAQ.

E. *Physics sensitivity of T2K and schedule*

The physics sensitivity of T2K is summarized in Fig. 5. The lepton mixing angle $\sin^2\theta_{13}$ can be measured down to 0.01 which is a 10 times improvement from the current best limit set by CHOOZ[11]. The error in the mixing angle $\sin^2\theta_{23}$ is also expected to be reduced to $\sim$1/10.



SK New DAQ system : triggerles DAQ

- Full TCP/IP based data transmission from FE to disk
- “Triggerless” DAQ : No hardware trigger
  * All signal hits from PMT are read.
  * Trigger decision by software after event building.

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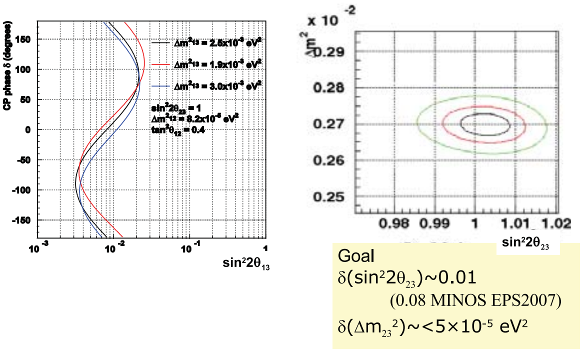
Figure 4: New data acquisition system for Super Kamiokande. No hardware trigger is used (triggerless DAQ).



Goal

$\delta(\sin^2 2\theta_{23})\sim 0.01$

(0.08 MINOS EPS2007)

$\delta(\Delta m_{23}{}^2)\sim<5\times10^{-5}$ eV^2

Figure 5: Physics sensitivity of T2K.

The commissioning of T2K has been started from April, 2009 and the first physics results are expected in 2010.

III. KEKB AND BELLE

The Belle experiment[12] is a B-factory experiment in the KEKB e^+e^- collider located at the KEK Tsukuba campus. Fig. 6 shows the KEKB accelerator and the Belle detector.

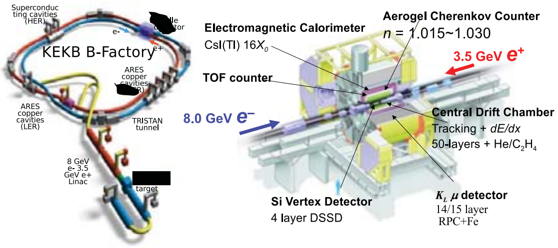


Figure 6: KEKB and Belle.

A. *Operation History*

Fig. 7 shows the operation history of the KEKB accelerator. The operation was started from July, 1999 and the luminosity of the machine gradually increased. Recently the world highest luminosity of $2.108 \times 10^{34}\text{cm}^{-1}\text{sec}^{-1}$ has been achieved. The machine is still running and Belle has accumulated an integrated luminosity of $\sim$950 fb^{-1} by now (September,2009), which provides the world's largest data sample of B meson pairs.

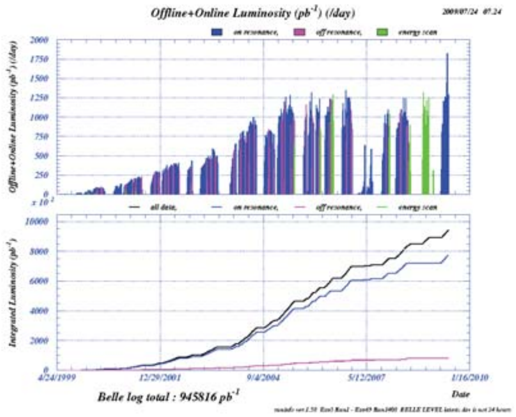


Figure 7: KEKB operation history

In order to achieve such a high luminosity, the crab crossing scheme is used in the KEKB accelerator. By rotating the electron and positron bunches before the collision so that they make the “head-on” collision as shown in Fig. 8. Crab cavities were installed in both electron and positron rings from 2007. It is confirmed that the luminosity increases by about 30% with the crab cavities compared to that without them.

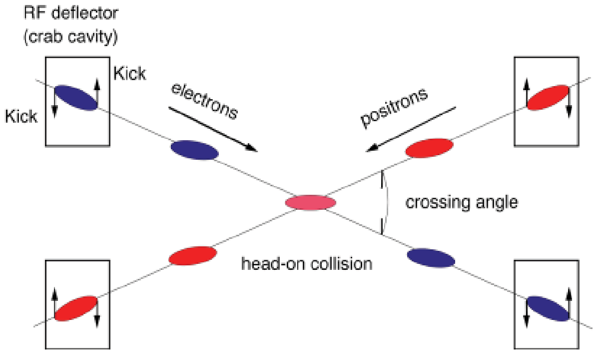


Figure 8: Principle of crab crossing

B. *Physics results by Belle*

The Belle experiment produced a number of important physics results. The most prominent result is the observation of the CP violation in B meson decays[13] as shown in Fig. 9. The CP phase $\sin 2\phi_1$ is measured to be $0.642 \pm 0.031 \pm 0.017$ and it is confirmed to be non-zero. It brought Nobel Physics Prize to Profs. Kobayashi and Maskawa in 2008.

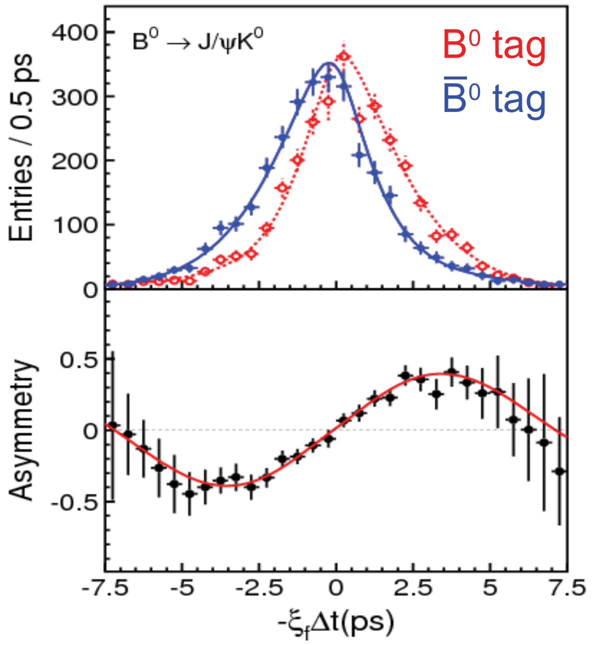


Figure 9: The observation of CP violation in B meson decays by Belle.

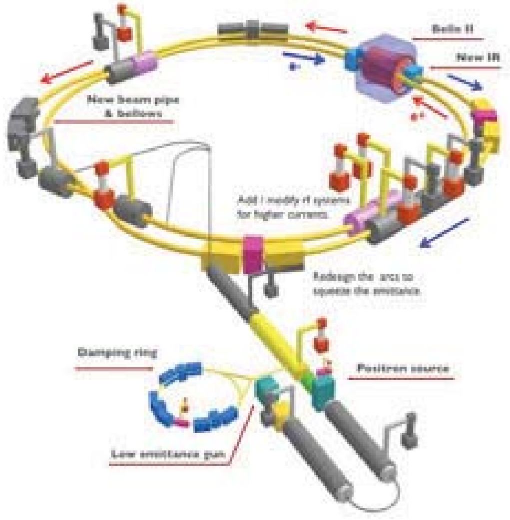


Figure 10: Upgrade to SuperKEKB.

The other important result is the discoveries of new particles X(3872), Y(3940) and Z(4430) which are considered to be particles composed of 4 quarks[14]. The evidence of $D^0 - \bar{D}^0$ mixing is also confirmed by the experiment for the first time.

However, in order to go beyond, especially to search for New Physics, an event statistics of more than 50 times higher is required. It is the reason of the upgrade to SuperKEKB and Belle II as discussed in following sections.

IV. SUPERKEKB AND BELLE II

Fig. 10 shows the upgraded SuperKEKB accelerator. The target luminosity of the machine is $L = 8 \times 10^35cm^{-2}sec^{-1}$ which is ~ 50 times higher than that of existing KEKB. In order to achieve such a high luminosity, various modifications are made to the KEKB ring. The main improvement is to have extremely small beam size of less than 50nm, which is called the "nano-beam" scheme. To realize the nano-beam, the beam emittance is required to be very small, and the dumping ring is newly added to the injection linac for the purpose.

The Belle detector is also upgraded to Belle II to keep up with the increased luminosity. The comparison of Belle and Belle II detector systems is shown in Fig. 11. Since the hit rate of each detector is expected to increase drastically, the main issue of the upgrade is to manage the detector occupancy by pixelizing the detection unit. The key changes are 1) the addition of pixel detector, and 2) the upgrade of the particle identification(PID) device. The detail of each upgrade is described in following subsections.

A. *Pixel detector*

To achieve the better vertex resolution in Belle II which is essential for the study of CP violation in B meson decays with a low background, the pixel detector is newly added. The detector is composed of 2 layers of very thin monolithic silicon pixel sensors made using the DEPFET[15] technology, which is originally developed for TESLA and ILC. The thickness of a sensor is only 50μm with a pixel size of $50\times50\mu\mathrm{m}^2$, and the sensors are placed just outside of the beam pipe of 1cm radius. Together with the 4 layers of silicon strip detectors (DSSD) which surrounds the pixel detector, the vertex resolution is expected to improve more than twice. Fig. 12 shows the current design of the DEPFET pixel detector.

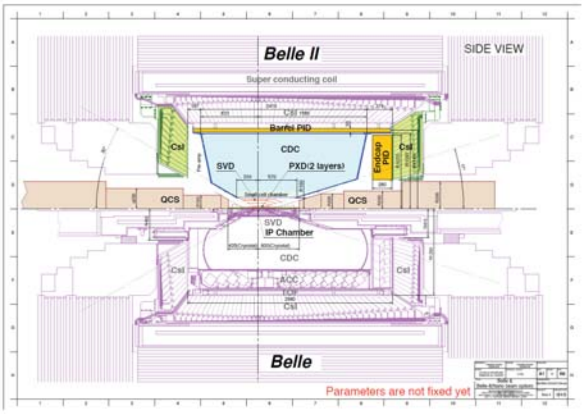


Figure 11: Comparison of Belle and Belle-II.

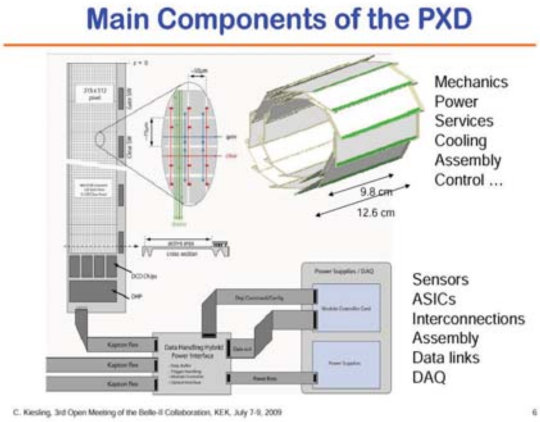


Figure 12: Design of DEPFET pixel detector

B. Particle Identification Device

The performance of the particle identification(PID) is the key issue for the search of New Physics in the rare decays of B mesons. The device used in Belle is the threshold type Cerenkov counters using the aerogel as radiators and the performance is limited. The PID upgrade consists of two different type detectors. The first is the device for the barrel region. The detector is a variant of DIRC[16] used in the BaBar detector, which detects the Cerenkov ring produced in the quartz bars surrounding the central drift chamber. There are several candidates for the upgrade. Among them, the TOP (Time Of Propagation)[17] counter is the most promising candidate which utilize the 3-D information of the Cerenkov ring by detecting the projected position of the Cerenkov light obtained by the precise measurement of the detection timing.

The other is the device for the endcap region. The proximity focusing RICH[18] is supposed to be used where the aerogel is used as the radiator. Fig. 13 shows the current design of these devices.

Since the performance of both detectors rely on the detection efficiency of Cerenkov photons, the choice of photon sensor is the key issue. The R&Ds on two different sensors are in progress. They are MCP-PMT (Micro Channel Plate PMT) and HAPD (Hybrid Avalanche Photo Diode)[19]. Two candidates of MCP-PMT, HPK SL10 and Photonis 85015, are being tested for the use in the barrel PID. HAPD (Hybrid Avalanche Photo-diode) is a good candidate for endcap PID sensors as well as MCP-PMT. The pictures of candidate sensors are shown in Fig. 14 with the preliminary test results.

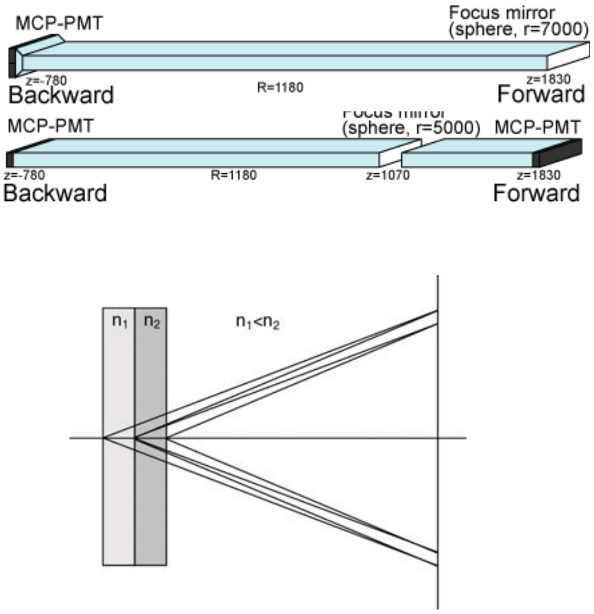


Figure 13: TOP detector used for particle identification in barrel region, and aerogel RICH in endcap region.

C. Data Acquisition System

The requirements to the data acquisition system are quite tough to manage the drastic increase of trigger rate of Belle II detector. Table 1 shows the comparison of the requirements to DAQ for Belle and Belle II. As seen, the L1 trigger rate becomes $\sim$20kHz with an event size of 300kbytes after the front end reduction in Belle II. It implies the data flow of 6Gbytes/sec before the HLT(High Level Trigger) processing. The events to be used for the actual physics analysis is estimated to be $\sim$10% of them and other background events are supposed to be discarded by HLT before the storage.

	Belle	Belle II
L1 trigger rate	0.5kHz	20kHz
Raw event size	40kB	500kB
Front end data size reduction	1	1/3
Event size at L1	40kB	300kB
HLT reduction	1/2	1/10
Data flow at storage	20MB/sec	700MB/sec

Table 1: Comparison of requirements to DAQ for Belle and Belle II. The data flow at storage includes the additional data bandwidth to store HLT processing results.

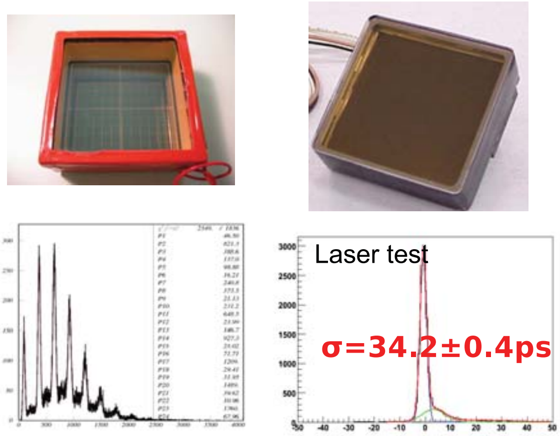


Figure 14: Candidates of photon sensors. MCP-PMT(left) and HAPD(right).

The new DAQ system is designed by inheriting the concept of existing Belle DAQ system. In the Belle DAQ system, a unified readout scheme is used for most of subdetectors, which consists of the Q-to-T converter and the pipeline TDC implemented on a common pipeline readout module (COPPER)[20]. In Belle II, the readout electronics is placed near the detector and only the digitized signals are transferred to the data acquisition system through optical fibers. We recycle the COPPERs and use them as readout modules by replacing the TDC daughter cards with the newly developed data link receiver connected to the readout electronics over the fibers. The data transmission scheme is unified and implemented using the Xilinx's Rocket IO technology. Fig. 15 shows the global design of Belle II DAQ system.

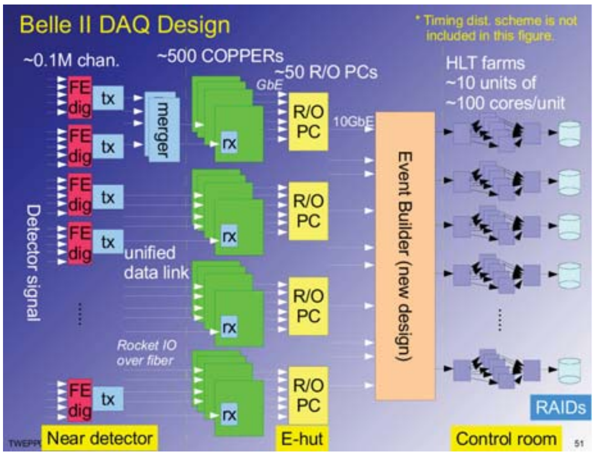


Figure 15: Belle II DAQ Design

D. *Physics reach and Plan*

The goal of the upgrade is to acquire more than 50 times higher statistics of B meson pairs. With the statistics, the measurement precision of the unitarity triangle is expected to reach order of 1%. Such a high precision enables the search for New Physics by looking at the "shifts" between various measurements as shown in Fig. 16.

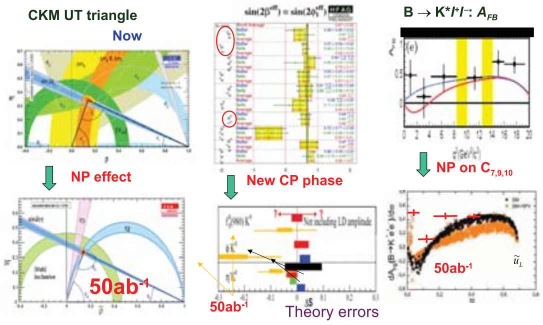


Figure 16: New physics search in various measurements by Belle II.

Although the plan of the upgrade is not yet fixed, which depends on the budget situation of Japanese government, it is quite likely that the upgrade work is started from 2010. The final decision of the detector configuration will be made by early 2010 and the construction is expected to start from 2010 spring. The commissioning of Belle II is expected in the summer of 2013. Fig. 17 shows the expected luminosity accumulation until 2020.

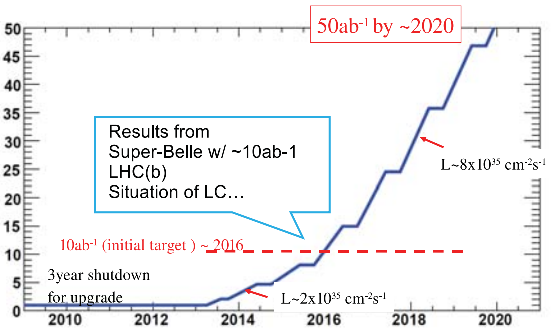


Figure 17: Expected luminosity accumulation

V. SUMMARY

1. Japan has a long tradition of accelerator-based HEP experiments.
2. A new proton facility called J-PARC just started the operation and the commissioning of the T2K experiment is now going on.
3. The Belle experiment in the KEKB e^+e^- collider has been running for more than 10 years and already produced various physics results.
4. The upgrade of Belle and KEKB, SuperKEKB, is about to start soon aiming at a luminosity of more than 50 times higher.
5. Both T2K and SuperKEKB will be the flagship experiments in Japan in coming decades.

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