The Eleventh KEKB Accelerator Review Committee Report

Introduction

The Eleventh KEKB Accelerator Review Committee meeting was held on March 20-21, 2006. Since John Seeman from PEP-II at SLAC was unable to attend, Yunhai Cai, an accelerator physicist at PEP-II, replaced him for this meeting. Dave Rice, Flemming Pedersen, and Shin-ichi Kurokawa were also unable to attend this meeting. Appendix A shows the present membership of the Committee.

The Eleventh Committee meeting followed the usual format of oral presentations by the KEKB staff members and discussion by the Committee members. The Agenda for the meeting is shown in Appendix B. The first day concentrated on KEKB performance and, in particular, the progress on the crab cavity, and this was continued on the second day. The Committee was again impressed by the high standard of the talks, both the technical content and the presentations themselves. The recommendations of the Committee were presented to the KEKB staff members before the close of the meeting. The Committee wrote a draft report during the meeting that was then improved and finalized by e-mail among the Committee members.

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Executive Summary

A) Foreword

KEKB continued to make excellent progress since the last Committee meeting. The peak luminosity has increased to a new world record of 1.627 x 10^{34} $cm^{-2}s^{-1}$, 62% above the design luminosity of 10^{34} $cm^{-2}s^{-1}$ (at this time last year it was 1.52 x 10^{34} $cm^{-2}s^{-1}$ and the year before it was 1.16 x 10^{34} $cm^{-2}s^{-1}$). The Committee congratulates the entire KEKB project staff on this new record. The BELLE detector has accumulated 563 fb^{-1}, another world record (365 fb^{-1} at the last meeting) and has published, or submitted for publication, a total of 163 papers in refereed journals (120 at the last meeting). KEKB was recently evaluated by the Council for Science and Technology Policy and was awarded the S-Equivalent rating – the highest possible. This rating was awarded not only for the Physics output of KEKB, but also explicitly for the machine performance. In addition, the Thomson Scientific Company has selected 6 BELLE publications among the twenty "hot papers." These are extremely impressive recognitions of the quality of the work being carried out at KEKB.

The meeting was devoted to the present status of KEKB and, in particular, the accelerator physics limitations to the luminosity and progress with the crab cavity. Unlike last year, there was little news on the plans for upgrading KEKB to a luminosity of 2-4 x 10^{35} $cm^{-2}s^{-1}$. This is due to the fact that the proposal for SuperKEKB has not been actively pursued by KEK. The Committee continues to endorse the proposal for SuperKEKB, particularly in light of the number of High Energy Facilities that are planned to close in the next two to three years (HERA, PEP-II, and Tevatron).

The KEKB machine group has done an enormous amount of excellent work, and is to be congratulated on the impressive results that have been achieved.

B) Summary

KEKB continued to make excellent progress over the last year, and holds all of the worldwide luminosity records: highest peak luminosity: 1.627 x 10^{34} $cm^{-2}s^{-1}$, highest daily integrated luminosity: 1.183 fb^{-1}, highest seven-day integrated luminosity: 7.36 fb^{-1}, and highest 30-day luminosity: 29.02 fb^{-1}. As was expected, the luminosity has continued to slowly increase during the year, but no large factors of improvement seem likely until the crab cavities can be installed. The crab cavities suffered a minor set-back during assembly, so the installation has been put off until summer 2006.

The Belle detector has now accumulated 563 fb^{-1} and of these 198 fb^{-1} were obtained since the last Review. The "Oide scenario" made several years ago was that 550 fb^{-1} would be accumulated by this time – an amazingly accurate forecast. At the present rate, 1 ab^{-1} would be accumulated by summer 2008. The crab cavities would advance this date by about a year.

Virtually all of the running has been at the Upsilon 4S state, but this year the accelerator was tuned to the Upsilon 5S and 3S states for the first time. In the three-day 5S engineering run, BELLE obtained more than four times the total integrated luminosity of CLEO, obtained during 15 days running. This is an exciting new Physics opportunity for BELLE.

The Belle detector is working well and has had only minor difficulties with the data acquisition system and the SVD detectors. Backgrounds are low, and losses during beam injection are small. Continuous injection has been acceptable to the detector but has necessitated suppressing 3.5 ms of data taking during each injection cycle. Overall, the Belle collaboration is extremely pleased with the quality and quantity of the beam being provided by the accelerator.

C) Recommendations

Last year, the Committee made many recommendations, and the KEKB staff has addressed all of them. Some of these related to the priorities of the program and are reiterated below, together with recommendations for continuing the work that has already been started.

1. The Committee strongly endorses the plan to assemble, test, install and commission one crab cavity in each ring in the summer shut down of 2006.
2. The Committee endorses the studies to design a major luminosity upgrade (SuperKEKB) aimed at a luminosity of 2-4 x 10^{35} $cm^{-2}s^{-1}$ and recommends that they be continued.
3. The Committee strongly endorses the plans for simultaneous injection in all four rings.
4. The Committee recommends continuing the studies of a movable mask which is 'electrically invisible' (rod with ceramic support) and has a much lower loss factor. A significant amount of R&D remains to demonstrate a reliable, operational movable mask with a reduced loss factor.
5. The Committee feels that HOMs is one of the limiting factors in increasing the current. Detailed studies of the vacuum components including proper damping and component cooling should be continued.

The Committee has made new recommendations throughout the different sections below. Highlights of these recommendations are summarized here.

6. The Committee supports the present approach to assembly of the coaxial coupler into the crab cavity, and recommends that continued efforts be made to improve the alignment fixtures, rather than searching for a new assembly approach.
7. The Committee recommends that the crab cavities should be installed in both rings at the earliest possible time, and commissioned, so that the benefits and limitations associated with them can be determined.
8. The Committee recommends that both cavities should be cryogenically tested with the complete RF system before any installation is started.
9. While the Committee believes that the crab cavity program will be successful, it requests that the KEK management create a road map for KEKB operations under two different scenarios:
    a. The crab cavity is successful and KEKB operations continue at ~400 fb^{-1} per year.
    b. If after considerable effort, the crab cavity is unsuccessful, KEKB operations continue at ~200 fb^{-1} per year.

    It would also be extremely helpful for planning and optimizing operations if the KEK management could provide an indication of the kind of information that would influence a decision on SuperKEKB (e.g. new physics found at Upsilon 3S or 5S).
10. The Committee recommends studying carefully the tolerances of the new crab lattices to check if they are more susceptible to errors, such as orbit drift, and identify the causes of the luminosity fluctuation.
11. The Committee recommends measuring the nonlinear dispersion as an additional check of the optics model.

12. The Committee recommends that a close follow-up of the failures of the standard vacuum components should be made to establish critical operating parameters, and to put limits on them.
13. The Committee recommends studying the effect of C-type magnets mounted on the antechamber, adding a solenoid field, and reducing the secondary electron yield (SEY) (e.g. by coating or surface treatment) in simulations of the electron cloud densities on the beam axis.
14. The Committee expresses strong support for further studies of low SEY coatings and for testing these coatings under machine conditions.
15. The Committee recommends that an effort be made to understand the mechanism of the sidebands, their role of being a signature of the electron cloud instability onset, and their apparent correlation to the luminosity.
16. The Committee supports the proposal by the KEKB team to directly measure the photo-electrons in the quadrupoles; it may give clearer information on the electron cloud in the quadrupoles. Refined simulations of this effect should also be continued.
17. The Committee recommends that efforts should be made to estimate the power deposited at the joints between different parts of the coaxial coupler using the presently understood mechanical tolerances.

B) Findings and Recommendations

1) KEKB performance and near term plans

KEKB operated very stably until the summer shutdown in 2005 when the machine optics was changed to be compatible with the crab cavities. The start-up was not easy and it took many weeks to recover the previous performance level. A new record luminosity of 1.627 x 10^{34} $cm^{-2}s^{-1}$ was established on December 19, 2005 indicating that the machine performance had been fully restored.

The daily integrated luminosity took longer to recover, exceeding 1 fb^{-1} per day on January 22, 2006, and later reaching a new world record value of 1.183 fb^{-1} per day. The daily luminosity has shown a much greater variability than before the summer shutdown, so the weekly and monthly integrated luminosity records set in March 2005 have still not been exceeded.

Some fraction of the slower increase in long-term integrated luminosity is due to the overall percentage of scheduled time that the complex was delivering physics, which decreased from 85.6% in 2004 to 78.8% in 2005 (it should be noted that these rates are extremely high for a machine of this complexity, which is being pushed to the limit). The increase in accelerator downtime was confined to September and October 2005 and can be attributed to difficulties in restoring the accelerator following the summer shutdown (the downtime in September 2005 alone exceeded the total accelerator downtime in 2004). Since the accelerator downtime has returned to the historically low values, accelerator downtime is not considered to be a long-term risk to the physics program. The Belle downtime increased from 0.6% of scheduled time in 2004 to 8% of scheduled time in 2005. This increase was due to burning of the power connectors to the Silicon Vertex Detector (SVD). The BELLE downtime has already returned to the historically low values.

More importantly, the peak luminosity that is attainable is still fluctuating from day to day. Problems with day-night variations in the beam position monitor readings were tracked down to thermal problems with the cables exposed to the elements, and this was corrected by adding insulation. There is now a suspicion (but no evidence yet) that the remaining variability may be due to physical movement of the beam position monitors themselves due to warping of the vacuum chambers due to synchrotron radiation heating. This should be investigated further.

The KEKB Team are concerned that the data indicate that the possible luminosity is now reaching a plateau. The Committee agrees that there is unlikely to be any major breakthrough in luminosity, with the exception of the crab cavity program. Pursuing the installation of the crab cavities is therefore the highest priority. However, everyone should be aware that there will undoubtedly be a learning period of several months, during which the peak and integrated luminosities will be significantly below the recent record values.

2) Physics by BELLE

Belle continued to accumulate data at a high rate in the past year. The integrated luminosity was 159 fb^{-1} in 2004 and 189 fb^{-1} in 2005. In 2005, a peak luminosity of 1.627 x 10^{34} $cm^{-2}s^{-1}$ was reached. So far, Belle has accumulated a total over of 550 fb^{-1} (compared with 300 fb^{-1} at BaBar) and 565 million BBbar events. During the last year it has published 43 journal papers. However, there seems to be a leveling off of the weekly and monthly integrated luminosity in 2006.

One of the thrusts of Belle experiments has been the measurement of the parameters of the unitary triangle. With 386 million BBbar events analyzed, the value of $\sin 2\varphi_1$ has been measured to be 0.69 with 5% accuracy. This is consistent with the Standard Model, and serves as a solid anchor for explorations beyond the Standard Model. The $B_0 \rightarrow \rho^+\rho^-$ isospin analysis gives the most precise measurement of φ_2 as 96° with 13% accuracy. The $B \rightarrow DK$ Dalitz mode gives some handle on φ_3. The $b \rightarrow d\ \gamma$ penguin or $b \rightarrow d$ gluon penguin modes give a measure of V_{td}/V_{ts} ratio.

A second thrust of Belle is to search for new physics beyond the Standard Model. The $B_0 \rightarrow \varphi K^0$ penguin is potentially sensitive to new physics. With input from Belle, a simple average over all modes that specify $\sin 2\varphi_{1\mathrm{eff}}$ is found to be 2.6 standard deviations from $\sin 2\varphi_1$. This might be a tantalizing hint of new physics.

A number of new resonances have also been discovered with the available data. In addition, a few engineering runs were made at Upsilon (3S) and (5S) energies during the past year. They give integrated luminosities of 1.86 fb^{-1} on Upsilon (5S) and 3 fb^{-1} at Upsilon (3S).

There is some difficulty in the data acquisition system not being stable. In addition, there seems to be some sensitivity of the luminosity monitor to changes in accelerator operation. These problems are being handled by the Belle group.

3) Optics

The lattices suitable for the crab cavities were implemented in two stages, first in the HER and then in the LER, after the summer shutdown 2005. After the implementation of the crab lattices, the luminosity recovery following the shutdown took much longer than usual. After several months, both lattices were modified in such a way that the changes were isolated to be inside the Nikko straight section, retaining the phase advances across the section, and this resulted in a new peak luminosity record. However, the fluctuation of the luminosity is (still) larger than the historical data prior to the summer shutdown. We recommend studying the tolerances of the new lattices carefully to check if they are more susceptible to errors, such as orbit drift, and to identify the causes of the luminosity fluctuation. A possible solution to reduce the fluctuation is to optimize the chromatic compensation in the lattices.

The Committee is pleased to see that efforts were made to understand the non-linear properties of the machine, in particular the study of the nonlinear chromatic optics. It was found that there were significant differences between the optical model and the actual measurement of the chromatic beta beating. The difference was mostly attributed to strength errors in the sextupole magnets at the level of a few percent. It is encouraging to seeing the convergence of the fudge factor as the correction was iterated. However, the residual remained nearly one percent. A possible cause of the residual is that the underlying model itself may not be accurate enough. The Committee recommends measuring the nonlinear dispersion as an additional check of the optics model.

4) Vacuum components R&D

The Committee is impressed by the large amount of progress, which has been made over the last year with the design of improved vacuum components.

a) Problems with ‘standard’ components

There is a concern that some ‘standard’ components have started to fail during the recent running period; most notable are the standard vacuum bellows with finger contacts and the finger contacts in vacuum gate valves. These component failures have a direct implication on the overall efficiency of the machine. Photographs were shown indicating that these vacuum problems start to limit the increase of integrated luminosity. The Committee recommends that a close follow-up should be made to establish critical operating parameters, and to put limits on them. Observing the outside temperature of vacuum bellows or of the other vacuum components may not be sufficiently rapid to be a machine interlock. Detecting vacuum bursts could be a better ‘early warning system’. The occurrence of such vacuum bursts has been reported on several occasions.

b) New copper beam pipes

New versions of copper beam ducts with an antechamber have been developed to gain experience with the manufacturing process. These chambers have antechambers on one or both sides for trapping the synchrotron radiation and for a linear NEG pump. Symmetric cooling channels are provided for uniform cooling of the chamber to reduce temperature gradients. A trial section has been manufactured and tested successfully in a wiggler section with beam currents up to 1.7A. The photoelectron current was found to be reduced by several orders of magnitude. Nevertheless, multipacting can still occur at higher currents due to secondary electrons in the central beam duct. To further suppress and trap photoelectrons, one could consider small C-type magnets around the antechambers. Solenoid fields would still be needed for the central beam pipe to suppress multipacting at higher currents. Coating the central beam pipe with low secondary electron yield material is a very promising solution which should also be investigated.

The Committee recommends studying the effect of C-type magnets mounted on the antechamber, adding a solenoid field, and reducing the secondary electron yield (SEY) (e.g. by coating or surface treatment) in simulations of the electron cloud densities on the beam axis.

c) Comb-type bellows

Three versions of the proposed new comb-type bellows have been tested and the results were presented in this meeting. Version 2, which includes an outer back shield for the low frequency and DC components as well as a set of small combs without contact fingers, gave the best overall performance. A test model installed in the machine showed acceptable heating of ~90º C and no pressure bursts at currents up to 1.7 A. This RF bridge concept can be applied to gate valves as well, and the Committee encourages the team to test a new valve of this design in the machine as soon as it becomes available from the company.

Since the operating principle of the comb-type RF bridge has been demonstrated successfully in the machine, it would be good to complement the final design with impedance calculations, and to optimize the geometry of the comb fingers, e.g. fewer, but wider fingers, maximum gap and length of fingers, ease of assembly and mounting in the machine, etc. The goal would be to have better control of the separation between the teeth.

d) Vacuum flanges

Conventional Con-Flat vacuum flanges are not suitable for machines with very short bunches. The design of the new MO- flanges eliminates any step or gap between flange pairs. Very promising test results have been obtained and were shown to the Committee with flanges made out of stainless steel and with copper gaskets. Future work will include real-life testing of flanges made out of Cu-alloy. Since some of these flanges will have to be very large and attached to heavy vacuum chambers, it will be good to follow established assembly and mounting procedures which take account of the actual situation in the machine. Sufficient statistics and operating experience must be gained to assess the reliability of the new MO-flanges.

e) Movable masks

A first design concept of a low impedance movable mask was presented at the 10th Accelerator Review Committee, and an update of the ongoing R&D work was presented at this meeting. The main features are a head made of carbon on a ceramic support stem. Several basic design parameters and impedance limits are not sufficiently defined, so a model was built for testing. Since detailed specifications are missing, the Vacuum Group has tried to find solutions for sub-parts of the movable mask design e.g., how to make the carbon head, how to make the support with a given electrical conductivity to avoid charging up and how to solve related electromagnetic problems.

f) Low secondary electron yield coating

Following the presentation in the last Accelerator Review Committee, the Committee had expressed strong support for further studies of low SEY coatings and for testing these coatings under machine conditions. Since the issue of the Electron Cloud Instability remains a central issue for the luminosity upgrade, this recommendation is maintained.

5) Electron cloud instability measurement

Detection of the betatron sideband in the bunch-by-bunch spectra has substantiated the single-bunch head-tail mechanism of the LER vertical beam size blowup caused by the Electron Cloud Instability (ECI).

In line with recommendations of the previous Committee meeting, a new comprehensive series of experimental studies of the sideband position, threshold and intensity has been performed in LER, both in single-beam mode and in colliding-beam mode.

With a single beam, the observed dependence on the RF voltage and chromaticity is consistent with the strong head-tail theory. The initial beam size has no effect on the instability threshold, being much smaller than the effective cloud size contributing to the wake, as was predicted by simulation of the cloud response to the bunch displacements.

Recently, sideband studies were carried out on bunch trains with 3-bucket and 2-bucket spacing. The interpretation of the spectra where the sideband splits-off from the main betatron tune is challenging. The measured sideband pattern with different settings of the initial betatron tune indicated that the sidebands vanish with the operating conditions that give the best beam-beam performance. This is an intriguing observation, and more studies on these correlations are needed.

Sideband spectra were observed in LER in colliding-beam mode with the test bunch placed in an off-collision bucket to avoid smearing of the colliding bunch spectra. A localized 2-bucket spacing was arranged in a bunch train with a 3.5-bucket spacing by injecting an extra bunch ahead of the test bunch. The sideband thresholds were measured either at constant cloud density (topping-up the extra bunch while the test-bunch intensity decayed) or at constant test-bunch intensity (while the extra bunch ahead was decaying). Both measurements showed that the thresholds, both in the cloud density and in terms of the bunch current, are in agreement with previous measurements in the single-beam mode. But the point of these measurements was to correlate those thresholds with the degradation of the specific luminosity that is characteristic of the 2-bucket spacing collisions. Indeed this correlation was observed, thereby confirming that ECI in collision can cause the onset of beam-beam blowup even before the single-beam size blowup threshold is reached. Thus, the KEKB luminosity performance is shown to be limited by ECI.

An important study was carried out to explain the reason for the non-zero horizontal collision offset needed for the best luminosity. The maximum luminosity corresponds to the minimum sideband intensity in the bunch spectrum. So, ECI manifests itself on the scale of a single bunch, causing the oscillations of the bunch tail. The specific luminosity is improved when the HER bunch is shifted horizontally so that it collides mostly with the LER bunch head, rather than colliding with the bunch tail, which is diluted by ECI.

The Committee recommends that an effort be made to understand the mechanism of the sidebands, their role of being a signature of the ECI onset, and their apparent correlation to the luminosity. The study should include the use of sideband measurements as a monitor for optimizing the luminosity performance of KEKB. To this end, more studies are encouraged to confirm the reproducibility of the sideband spectra.

An experiment was performed that indicated a correlation between bunch luminosity and the location of the bunch in the bunch train. It was found that a bunch following a 3-bucket space has a consistently higher luminosity than a bunch following a 4-bucket space. This is a convincing indication of the ECI having an effect on the luminosity.

6) Beam measurements

A set of beam measurements were presented that investigate effects near the half-integer tune. These are important measurements since the horizontal tune of both rings is very close to the half integer, and theoretical analysis, numerical simulation, and luminosity scans all show that such a working point is desirable. However, the half integer must be approached very carefully, since the beta beat and the emittances can become large when the half integer stop band is approached.

During these measurements it was shown that the Proton Synchrotron (PS) magnet cycle caused fluctuations of some quadrupole currents. This modulated the tune, and it was found that this modulation was worse close to the half integer, potentially making it significantly harder to approach half integer tunes. However, since PS operation has recently been discontinued, a further analysis of this effect is not necessary. Some of the measurements presented might have been made while the PS was in operation and this makes their interpretation somewhat problematic.

For example it was shown that the spectrum of the LER horizontal tune of a pilot bunch develops a peak at the half-integer. This peak is stronger when the tune is closer to the half-integer and it also tends to increase with increasing chromaticity. There is no satisfactory explanation for this effect at the moment. Candidates are (a) asymmetrically populated islands of even order (even though it is not clear why the slow tune excitation procedure should populate islands asymmetrically), or (b) a perturbation due to the PS (but since the PS no longer operates it will be hard to further analyze this effect). Since operation close to the half-integer is essential, we strongly recommend that either it is possible to determine that the old measurements were in fact taken while the PS was off, or that these measurements be repeated without the PS. Furthermore, the simulation effort should be continued, and should include errors in the accelerator model as well as off-momentum particles.

Beam size measurements for a parasitic bunch close to the half integer were performed with a gated CCD camera, and with the interference device. Both lead to similar results for the small increase of the beam size and the width of the stop band. A much stronger increase of the beam size was observed for bunches under collision, mostly caused by the dynamic beta beat. However, the theoretical understanding of the beam size change as a function of tune does not seem to be complete. While it was observed that the measured beam size as a function of H-mode frequency agrees well with the simulated beam size as a function of unperturbed tune, it would be good to have a better understanding of this correlation.

A second set of measurements was presented which concerned tune-shifts that provide information about wake fields.

The most important effect that was considered is the wake of the electron cloud. For these measurements a pilot bunch with a variable distance after the bunch train was used. It was verified that the tune shift decreases with distance after the bunch train, as the electron cloud density decreases. It is interesting to see that this decrease is smaller when all the solenoid magnets are on. This indicates that much of the tune shift is due to the electron cloud wake, which dies away more slowly when the solenoids trap the electron cloud at larger amplitudes.

An analysis of the tune shift as a function of the charge of the pilot bunch was also presented. This effect seems to be nearly completely eliminated by the solenoids, at least in the horizontal plane. This shows that the solenoids are also very effective in eliminating the head-tail effect of the electron cloud. However, the data is not very accurate and we recommend that these studies be continued experimentally and theoretically.

7) **Solenoids in quads**

Beam blow up induced by the Electron Cloud Instability (ECI) is still observed when the bunch spacing is reduced to 3.27 RF buckets or shorter. Recently the ECI effect caused by electrons trapped in the quadrupoles has been investigated both experimentally and by simulation. The experimental results show that solenoids with a field of 17 gauss, installed in 88 quads (25% of the total quads) in the LER have no clear positive influence on the ECI. These experiments include interesting measurements of the size of the sideband peaks, the separation between sideband-betatron peaks, the vertical beam size, and the effects on the luminosity with and without the solenoid fields in the quads. The simulation results show that the threshold electron density which causes ECI in the LER is about 7.4×10^{12} m^{-3}, while the experiments were done at an estimated density of 1.2×10^{12} m^{-3}. It therefore appears that the experimental result, while not inconsistent with the simulation, does not provide confirmation of the effect.

The Committee recommends that the KEKB team continue to study these effects, both experimentally and by simulations, since no clear physics explanation of the results has been found. The possibility still remains that the magnetic field (solenoid or otherwise) required to clear the electrons will be of the same order of magnitude as the pole-tip field in the quadrupole, which would be excessively high. If this is the case, electrons may accumulate in the quads, perhaps even reaching the threshold level. The Committee supports the proposal by the KEKB team to directly measure the photo-electrons in the quadrupoles; it may give clearer information on the electron cloud in the quads. If a significant electron density is observed, a cure needs to be found. This study may have important implications for reaching higher luminosity.

8) New QCS

The design and construction of a new QCS R&D magnet for SuperKEKB is going well. This new QCS is designed according to the basic requirements for an Interaction Region magnet. A design with three double-layer pancake coils was selected, and calculations show that both the two-dimensional multipole components and the integral multipole components meet the requirements. The construction process of this new QCS is also well organized, and includes coil winding, curing, end spacers, and several hundred construction tools. The measured coils had some geometrical errors which, according to calculations, cause acceptable field deformations. However, further improvements of the dummy coil blocks for curing the coils and some tooling for tuning the axial coil length should be considered to improve the performance of this R&D magnet. Magnet testing is planned for June 2006.

9) Injector Upgrade

The injector linac has to supply four different beams to the various accelerators. The other accelerators would also prefer to have continuously injected beams for topping up when KEKB is in continuous-injection mode operation. The only way to meet these demands is to utilize electronic control of the klystron RF phases for beam energy adjustment in each section of the transport lattice. The Injector Group has developed a three-phase plan for simultaneous injections to the four machines. They installed a new beam transport line to the Photon Factory in the summer shutdown in 2005 as the first phase of this work. It bypassed the ECS system, and halved the time required for switching beams between KEKB and the Photon Factory. This year, they are going to install the fast beam-mode switch for improved injection to the KEKB and PF electron beams as the second phase of the plan. In the final stage next year, it will fully operate the fast beam-mode switches for injection into all four machines.

They also confirmed that the transport efficiency is about 90% for the electron beams through the bypass hole on the positron target. It would require more machine studies to confirm the simulations of the beam parameters. The Committee extends its congratulations to the Injector Group for their excellent ideas and the success in last year's work. We believe the project will be carried out successfully with careful fine adjustments of the phase controls and with fast-switching magnets.

10) Crab Cavity Overview

Implementation of crab cavities is the largest single opportunity remaining to the KEKB accelerator team to substantially increase the luminosity for BELLE. The quality and intensity of the effort being applied to the realization of the crab cavities is first class and entirely appropriate to their importance. The Committee was provided with an excellent overview of the status of development and construction activities, which was followed by a number of talks to address details of the program.

Three crab cavity systems are being constructed: one will be retained for test and development while the other two will be installed, one in each of the rings. Construction is well advanced and, for the most part, has gone well, including vertical testing of the cavities themselves, first cool-down, and low-power testing of the prototype in a horizontal configuration. Successful development of RF power couplers, helium jacket, cryostat, tuners and other peripheral devices, higher order mode dampers and RF power systems were covered in separate talks which are discussed later in this report.

A leak developed during the first stages of cryogenic cavity testing, but it was rapidly diagnosed and repaired. All cavities have been processed and vertically tested, with acceptable results, after dealing with multipacting and field emission issues. The most significant challenge presently facing the team is the *in-situ* assembly of the coaxial coupler. This component serves to tune the crab cavity and provides a conduit to conduct any HOM power deposited in the cavity by the beam to an absorbing load.

The inner conductor of the coaxial coupler is a very long component which, in the present design, is fabricated in three segments and assembled in place, within the beam pipe. The connection mechanism between segments is similar in concept to the bayonet connector used to fasten a lens to an SLR camera body. Successful connection of these two components requires very careful alignment of the two parts, insertion of the end of the outboard segment into a receiving socket in the end of the niobium segment, followed by a 30˚ rotation to lock the two segments together. Up to now, after about three weeks of work, the two inner segments are assembled, but connection to the outermost segment has been unsuccessful, apparently because of an alignment problem.

The Committee was asked to address the following questions:

1. How to assemble the coaxial coupler:
    a. Assemble the three pieces vertically?
    b. Welding? If so, how and when?
    c. Silver coating?

The experiences of the cavity assembly team to this point seem to indicate that the fundamental problem is, in fact, one of alignment. Insertion of the male part of the connector into the female part proceeds smoothly, but rotation is difficult from the beginning, becoming steadily more difficult until all motion stops after about 15˚ of rotation.

After reviewing the mechanisms in use, it seems that conversion to a completely different assembly technique, as suggested by the question, would not be the best course of action. Instead, attempts to improve alignment should be continued. The fixture holding the very heavy outer segment should be evaluated for bending, and if necessary, stiffened. The load on the fixture might be reduced by removing the notch filter prior to assembly.

2. How to ensure the RF / beam shielding:
    a. Does silver coating also work for that purpose?
    b. Welding? If so, how and when?

Welding would not seem to be a practical solution at this point, since it would probably not work unless the cavity/cryostat system were completely disassembled, and then reassembled around the complete coaxial center conductor. Silver plating might be helpful, if it can be done without significant generation of particles that might migrate into the cavity to cause field emission. But the key is likely to be the design of a support system that removes or mitigates transverse loads on the connecting mechanism through improved alignment. As an alternative solution, assembly with self-fixing screws and RF gaskets should be considered now, to be ready if the primary solution cannot be made to work.

3. When should the improved coaxial coupler be installed? After the beam test of the current design?

The Committee is agreed that the cavities should be installed in the rings at the earliest possible time, and commissioned, so that the benefits and limitations associated with them can be determined. Improvements of various kinds will almost certainly be indicated, and the improved center conductor can be installed as part of a general upgrade project. Certainly, installation of the cavities should not be delayed while the improved coupler is designed, approved and constructed.

11) Tapered Coaxial Coupler

The RF experts have identified parasitic modes inside the coaxial coupler which could generate high impedances at the open end leading to beam instability. In particular, there is a dipole mode with a $\lambda/4$ resonance at 595 MHz (Q of $\sim 10^6$), defined by the stub support position. Various modifications are foreseen to allow propagation of this mode to the HOM damper, and thus damp this resonance. The first involves tapering the coaxial line, with the diameter increasing along the length, to lower the cut-off frequency to below 600 MHz. The second involves machining the outer diameter of the inner conductor "tip cutting" to raise the $\lambda/4$ mode frequency and lower the R/Q. The last involves a modification to the notch filter "cut slots" to split the TE mode stop-band, so that the $\lambda/4$ mode is not prevented from reaching the HOM damper. Calculations of the resulting $\lambda/4$ mode impedance suggest that for low intensity operation, tip cutting is unnecessary; the other two modifications providing a sufficiently low impedance of ~ 30 kΩ. For high intensities, tip cutting is necessary to lower the impedance by a further factor of five to ~ 6 kΩ. The impedances of the other modes have been calculated and all now seem to be sufficiently low. It was also claimed that tip cutting lowered the peak electric field on the inner conductor slightly but caused a detuning of the cavity, which necessitating a 5 mm shift of the conductor to restore the resonant frequency.

The Committee congratulates the RF engineers, both for finding the problem and for the proposed solution. However success depends on the accurate placement of the cut-off and notch filter frequencies, which so far rely mainly on calculation. The Committee recommends that all these parameters be measured on the bench before installation, using the final coaxial structure and cavity.

12) RF couplers of crab cavity

The RF input coupler of the crab cavity needs to provide 100kW. It is a coaxial, capacitive coupler with an RF window outside of the cryostat and a T-support structure. It was assembled after rinsing and drying and was baked at 80°C. Diagnostic devices are an electron sensor, an arc detector and a vacuum gauge.

The coupler has been in a test stand which allowed for standing and travelling wave tests. The stand includes a series circuit with two couplers, an accelerating cavity coupler, and the crab cavity coupler, and a phase shifter. The conditioning went very smoothly, typically within eight to 15 hours, and power levels of 250KW for travelling wave operation and 100KW for standing wave operation were achieved without major problems. In the case of standing wave conditioning, the phase shifter was adjusted such that power nodes on the coupler were shifted in steps of 5cm. Trips originated from electron loading were accompanied by vacuum breakdown, but were rapidly recovered. No major multipacting levels were observed and thus no countermeasures were necessary.

In conclusion, the crab cavity RF input coupler seems to perform well and no further measures are necessary.

13) Cryostat, jacket, etc.

The design of the cryostat for the crab cavity presented to the Committee is straightforward and effective. It features magnetic shielding assembled directly onto the cavity for maximum effectiveness, although the consequent need for high permeability at low temperatures forces the use of more expensive materials. In this application, where initially only two cavities are being built, the additional material cost is modest, and the shielding improvement is significant.

It also features a limited volume of liquid helium through the use of separate helium vessels, or jackets. One of these is for the cavity itself, and one provides coolant flow to the niobium-tipped coaxial center conductor, which couples HOMs to an external load, as well as being the primary tuner for the cavity. The main cavity helium vessel incorporates a heating element to maintain a constant load for the helium refrigerator. The cryostat utilizes the standard 80 K, liquid nitrogen cooled thermal shield to reduce the heat load to the 4.2 K helium circuit.

Heating of the niobium center conductor will be a maximum near the peak, where the structure is exposed to the maximum RF magnetic fields. It is therefore important to assure adequate liquid helium flow to the tip from the support stubs where the coolant enters. The center conductor itself has an annular structure with elements to channel the flow to the tip, and the exhaust may be sub-atmospheric to ensure both adequate flow and potentially lower resistivity.

14) Peripheral devices

The Committee was given an overall view of the status of the cavity peripheral equipment; all have made good progress. The vacuum design for the crab cavity is complete. An RF shield has been designed to isolate the vacuum pumps from the coaxial beam line. It should be verified that the regular pattern of holes does not allow resonant coupling of the high frequencies into the pump. This would create a high beam impedance and deposit HOM power in the pump. The HOM damper, notch-filter, coaxial coupler and input coupler have all been manufactured and are ready for assembly. The electrical ‘filter’ characteristics of the ensemble of the first three should be measured after assembly on the cavity. The complex tuner design has been slightly modified to facilitate manual pre-tuning; a wise decision. The tuner is being put together on a special test stand. This can be used to test reliability, determine possible back-lash and setting accuracy, and also to measure the tuning speed of the piezo/mechanical combination as a function of the stroke amplitude. Cryogenic transfer lines have been designed and are under construction. The design of these lines is simple but elegant, and with the 80˚K shield should produce low heat loss. The installation of these lines on the D10 test stand will allow the isolation efficiency to be measured.

15) HOM absorbers

The Committee was presented with a description of the processes by which the higher order mode dampers were fabricated, processed and tested. The ferrite dampers benefit from a high degree of similarity to those already in use on the superconducting cavities. Two dampers, one for the large beam pipe and one for the coaxial coupler, are required for each of the two crab cavities. The production of dust from the porous material has not been observed and has not caused problems during operation. Processing included extensive outgassing, primarily for water, to reduce the possibility that evaporated gases from the dampers could affect the performance of the cavity when they condense and freeze on the cryogenic surfaces.

The use of organic O-rings for the bake out is questioned and this production step may be simplified by providing a vacuum oven where several absorbers could be outgassed simultaneously. During the final vacuum test, which can only be done once the end flanges have been put on, it would be desirable to measure the residual gas composition. Once completed, the maximum allowed temperature is given as 60°C, which appears to leave only a small temperature margin as compared to the operating temperature. A limited set of high power tests demonstrated that the absorbers are probably sufficiently robust to perform reliably with beam for long periods.

However, the ferrite in one of the absorbers cracked during such a test. While it was found that further testing does not increase the length of the cracks, the Committee would like to point out the danger of relying on a cracked ferrite, even as a spare. During operation, particulates from the crack could find their way into the superconducting cavity.

Low-power tests with a copper cavity demonstrated that the coaxial coupler and ferrite damper were very effective in damping cavity higher order modes up to 1.5 GHz. The only exception was the TE_{111} mode around 875 MHz, which does not couple well to the coaxial line, but which is not expected to be a problem. Damping of the crab mode is prevented by a notch filter that reflects energy at that frequency back to the cavity. The damper was also tested in a beam-pipe transmission configuration. Attenuation of RF energy was relatively low, with a maximum of 4 dB at 1 GHz, falling to 2 dB at 500 MHz and 2 GHz. Thus HOM power above 2 GHz, which is certainly expected from the short bunches, will propagate out of the cavity, preferentially through the large beam pipe, but will not be effectively absorbed by the damper installed just outside the cryostat for that purpose. Since a similar setup is used for the accelerating cavities, problems are not expected, but it would probably be wise to be alert for them.

16) Horizontal test of crab cavity

The horizontal test that is proposed will test the assembly of the cryostat without the coaxial beam pipe. It will test that the previously observed leak does not reopen under cold/warm cycles; it will check that no significant motion occurred under transport, and it will verify that the static loss corresponds to the predictions. Also the coupler can be tested in its cold state. We believe that all these things are important activities.

The cool-down test was very successful. So far the static heat load was measured to be about 30W, as expected, and it was shown that the vacuum leak does not reopen during cool down., Several vacuum bursts were observed during heat-up, and it was not clear whether the amount of released gas was consistent with the vacuum level before cool-down, or whether, in fact, a leak should be suspected. A closer analysis seems necessary. The cool-down is evaluated with 14 monitors, and there were no unusual observations; however it was however not mentioned how these data correspond to thermal calculations.

A frequency shift of 0.6 MHz during cool-down to 4.2K was measured, which reportedly corresponded to expectations. Somewhat less expected was the change of the loaded Q, which suddenly increased at low temperature. It is suspected that the cooling of the inner conductor of the coupler changed its length, and therefore the coupling coefficient. If this is the case, the observed loaded Q of 1.3×10^6 might not be representative of an operational value, since the inner conductor will be at a different, presumably higher temperature during operation with power. However, one should also investigate alternative explanations which are more relevant to the crab cavity operation, since this effect is not observed in the accelerating cavities.

17) RF system for crab cavity

The RF system of the crab cavity was presented to the Committee, the presentation concentrating on beam-loading issues and phase error tolerances, with a summary of the present construction status and a brief overview of the beam-control system.

The required RF power depends on the kick voltage and the induced beam-loading voltage. For a 1 mm difference between cavity center and beam position, the power increases by ~ 20 kW for the range of Q_L (loaded Q) values considered ($1\text{-}3 \times 10^5$), and for the nominal beam current. This is acceptable, since the total power (<100kW) is well within the RF coupler capability of 200 kW. However the "beam loading" power increases as the square of the beam-offset, hence it is important to keep the total beam offset below 1 mm. For the Q_L values chosen, it is possible to operate the cavity at up to 30º off-tune before coupled bunch instability growth rates exceed the radiation damping rates; this should an easy target. However, it will be necessary to control the beam using bunch-by-bunch feedback in parked mode, even though the cavities can be de-tuned by up to 100 kHz.

Phase errors lead to a horizontal offset at the IP and affect the beam-beam performance; the magnitude of the effect depending on the phase noise correlation time. The tolerances are quite tight, 0.27º at the crabbing frequency. Slow phase errors can be readily corrected, but fast changes which depend on the quality of the beam-control system are more difficult to predict. It would be very interesting to measure the noise on the complete system (beam-control loops, high power and cavity) before operation with beam. In principle, the noise should be defined by the low-level beam control system. The effects of transient beam-loading on the phase are largely self compensating if the beam–abort gaps pass the cavities simultaneously. At high beam currents, it may be necessary to optimize the intensities in HER and LER.

The RF power system, which is based on existing 1 MW klystrons, has been installed and the waveguides already head down towards the ring. Since the power in the couplers is limited to 200 kW, klystron operation should be reliable; we note that any RF power loss will lead to a beam abort. The beam control system is fairly conventional and based on the existing well-proven KEKB superconducting cavity system. It includes RF feedback, klystron correction loops, cavity voltage phase and amplitude loops and tuner loops. In addition, the horizontal position of the coaxial beam pipe can be adjusted. As mentioned above, all these can and should be tested with the rest of the system in the laboratory if time allows.

Globally the RF system has been very well and exhaustively studied and is well on the road to completion. While the crab cavity remains a challenging project, all the necessary RF tools seem to be in place.

18) Installation of crab cavity

A very detailed plan of the installation of both crab cavities was presented. The plan for installation techniques was supported by a set of convincing photographs and drawings, and the timeline that was presented to the Committee after the talks showed detailed planning for work, both in industry and at KEK. While it is hard to verify the soundness of these timelines in the time available, it became clear that planning has been taken very seriously.

The actual installation has been planned carefully; the tunnel geometry, pass-ways, etc. have been taken into account. The neighboring beam line is very close to the cryostat vessel and the installation therefore has to be performed very carefully; this has been also taken into account in the planning. The masses that have to be moved over very crucial equipment lead us to suggest that this activity should be practiced with a wooden model of the correct dimensions.

The timing of the crab cavity installation has not been fully specified yet. Four possibilities were presented. After significant discussion, the Committee makes the following recommendation:

Finish one crab cavity and start processing and testing it with RF power outside the tunnel, while building the second cryostat in parallel. Both cavities should be tested with RF before any installation is started. Both cryostats should then be installed, if possible during the summer shutdown, and should be commissioned simultaneously. We are not convinced that commissioning of one ring with a crab cavity, and one without, will lead to information that can be used to significantly improve the second cavity in a reasonable time. We rather think that this could lead to a significant loss of luminosity during the time in which only one crab cavity is installed.

19) Beam commissioning with crab cavity

A crab lattice was prepared and implemented in summer 2005. It should first be established that this lattice is as robust as the previous lattice for production runs. More attention should be given to the accumulation of experience in actual running and tuning before the installation time. A slower start-up after a long shut-down, for example, could be interpreted as a sign of non-robustness of the crab lattice, and that possibility should be minimized by the installation time. The phase advances between the crab cavity and both the IP and the streak camera have been optimized.

A well-considered plan has been presented for the commissioning of the crab cavity runs. This plan is to start immediately following the installation of the crab cavity. The Committee suggests adding an engineering commissioning period after the installation but before beam commissioning with the purpose of debugging the system as a whole. A detailed plan of the zero-stage operation with beam may also be useful: i) with the crab cavity in passive mode, finding its electrical beam center so its effective electrical axis can be aligned with the normal beam orbit; ii) with the crab RF on, finding the zero phasing where the orbit shift in the crab cavity itself is zero; iii) calibrating the crab RF amplitude against the crabbing angle observed with the streak-camera; iv) finding the working point range limitation from synchro-betatron resonances caused by the crab cavity with the non-zero chromaticity needed in KEKB; v) checking the noise sources and their magnitudes of the main and crab RF systems.

The goal of this commissioning session is to establish that the crab crossing scheme increases the specific luminosity. The Committee wishes to re-iterate the fact that using a single crab cavity without the compensating one is a new concept, and, in addition, crabbing has never been done before. The Committee wishes to support the early start of this commissioning plan by the KEKB team.

Many issues involving the crab cavity are likely to need attention during the commissioning stage. For example, the $\lambda/4$ dipole mode (barely above cut-off) propagates in the coaxial coupler and is not absorbed well by HOM damper. This can be solved by tip cutting. In the current design, with a tapered coaxial coupler without tip cutting, the beam current is limited to approximately 700 mA, above which the instability growth rate exceeds the feedback capability. The Committee recommends operating initially with the present design, and this will limit the beam current for higher luminosity operation. Another possible issue might be multipacting in the coaxial coupler. Previous test runs indicate that a one-hour conditioning can overcome this concern.

Still other issues may involve orbit feedback to better than 0.5 mm at the crab cavity, the wider beam orbits during injection, and potential sensitivity to fast phase jitter. When the cavity is parked off-resonance, the beam stability will have to be assured by a feedback system. Considerations of ways to relieve this requirement might be useful. Finally, trips of the crab cavities with the necessary beam aborts may be an operational concern.

The proposed focal point of the commissioning, after the initial phase of streak camera measurement for the crabbing angle, has been given to the achievement of a high beam-beam tune-shift limit of $\xi>0.1$. This can be achieved with a moderate single-bunch current by restricting the total number of bunches. The Committee concurs with this focus, and wishes to emphasize the great importance of achieving this goal as early as possible during the commissioning period.

In this sense, one beam-beam related concern caused by the crab cavity is that the abort gap transient causes an x-orbit separation of the two beams of ± 7 μm the IP (to be compared not only with the rms beam size of 100 μm but also with the ~20 μm horizontal sensitivity of the high-performance collision). The Committee recommends that effect of this separation on the specific luminosity be evaluated.

The Committee expects that beam commissioning will take about 30 days, but the previous luminosity levels may not be reached for several months after that.

Appendix A

KEKB Accelerator Review Members

Andrew Hutton	JLab (Chairman)
Yunhai Cai	SLAC (replacing John Seeman for this meeting)
Alexander Chao	SLAC
Warren Funk	JLab
Oswald Gröbner	CERN (retired)
Heino Henke	Technical University, Berlin
Georg Hoffstaetter	Cornell University
Trevor Linnecar	CERN
Won Namkung	POSTECH
Flemming Pedersen	CERN – unable to attend
Eugene A. Perevedentsev	BINP, Novosibirsk
David Rice	Cornell – unable to attend
John Seeman	SLAC – unable to attend
Wang Shuhong	IHEP, Beijing
Katsunobu Oide	KEK Secretary, Accelerator
Shin-ichi Kurokawa	KEK Secretary, Accelerator – unable to attend

Appendix B

Agenda of the Eleventh KEKB Accelerator Review Committee

March 21-23, 2006 in the Meeting room on the first floor of Building No.3, KEK

Mar. 21 (Tue.)		
8:30- 9:00	Executive Session	
9:00- 9:10	KEKB Overview	Katsunobu Oide
9:10-9:50	Progress since the last ARC	Yoshihiro Funakoshi
9:50-10:20	Physics by Belle	Yoshihide Sakai
14:35-15:50	Break	
10:40-11:00	Optics	Akio Morita
11:00-11:25	Vacuum components R&D	Yusuke Suetsugu
11:25-11:50	Electron cloud measurement	John Flanagan
11:50-12:15	Beam Measurements	Takao Ieiri
12:15-13:15	Lunch	
13:15-13:40	Solenoids in Quads	Hitoshi Fukuma
13:40-14:05	New QCS	Norihito Ohuchi
14:05-14:35	Injector Upgrade	Masanori Satoh
14:35-15:50	Break	
14:50-15:30	Crab Cavity overview	Kenji Hosoyama
15:30-15:55	RF characteristics of crab cavity	Yoshiyuki Morita
15:55-16:20	RF couplers of crab cavity	Kota Nakanishi
16:20-16:45	Cryostat, jacket, etc.	Hirotaka Nakai
16:45-17:10	Peripheral devices	Hirotaka Nakai
17:10-17:30	Executive Session	
17:30-	Reception	

Mar. 22 (Wed.)		
8:30- 9:00	Executive Session	

9:00- 9:20	HOM absorbers	Yoshiyuki Morita
9:20- 9:50	Horizontal test of crab cavity	Yasuchika Yamamoto
9:50-10:20	RF system for crab cavity	Kazunori Akai
10:20-10:35	Break	
10:35-11:00	Installation of Crab cavity	Masaaki Ono
11:00-11:20	Beam Commissioning Plan with Crab Cavity	Haruyo Koiso
11:20-11:50	PEP-II Status	Yunhai Cai
11:50-13:00	Lunch	
13:00-16:00	Tour for Crab cavity	Assembly Hall, Nikko, Nikko Tunnel
16:00-20:00	Executive Session with working dinner	
Mar. 23 (Thu.)		
8:30-11:00	Executive Session	
11:00-12:00	Close out with KEKB members	
12:00-12:10	Adjourn	