KEKB B–FACTORY, July 2002 – July 2003

KEKB Achieved the design luminosity, 10^{34} cm^{-2}s^{-1}

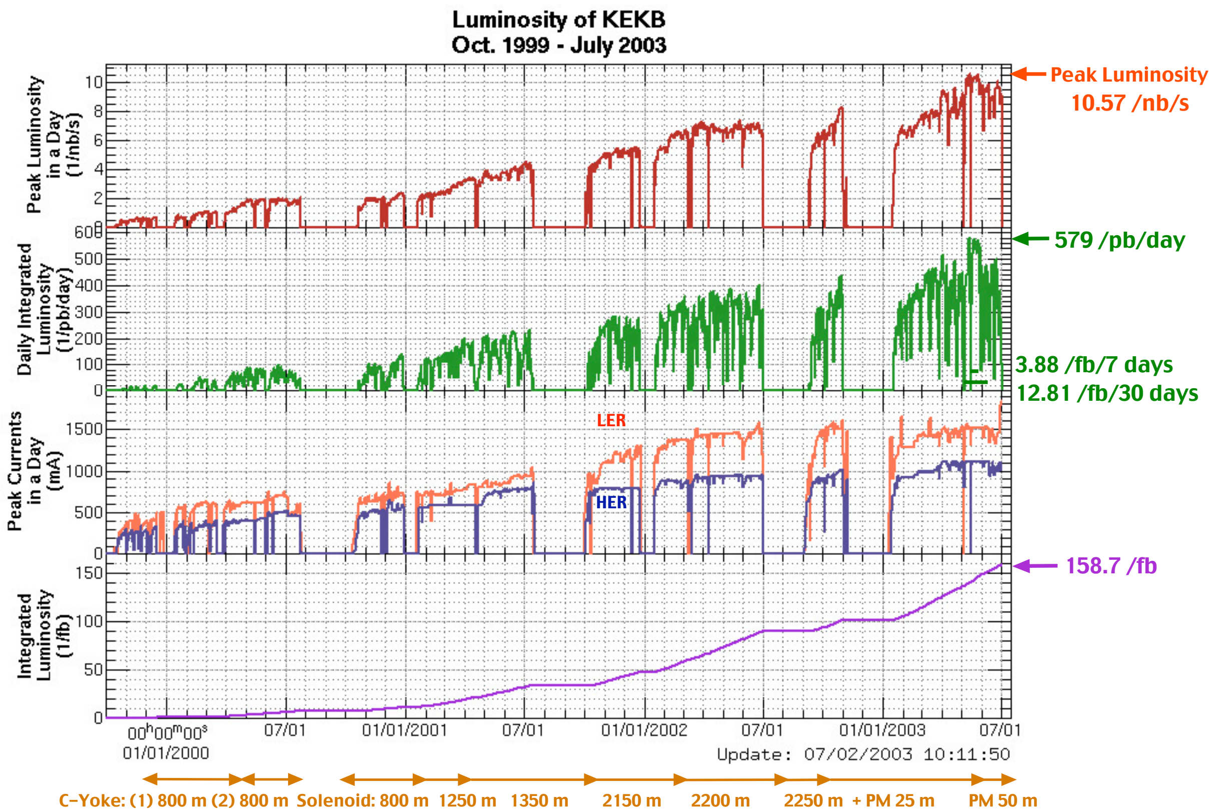

Figure 1: The history of KEKB performance since 1999. The rows are (top to bottom) the peak luminosity in a day, the daily integrated luminosity, the peak stored current in the LER and the HER, and the integrated luminosity in Belle, respectively. The integrated luminosities are the numbers recorded by Belle. The arrows at the bottom show the progress of the length of solenoid/permanent magnets to suppress the electron-cloud instability in the LER.

At 7:26 am on Friday May 9, 2003, the luminosity indicator in the KEKB Control Room showed 10.308 /nb/s of the Belle CsI luminosity monitor. This was the first moment when KEKB reached its design luminosity, 10 /nb/s ($\equiv 10^{34}$ cm^{-2}s^{-1}). It was in the 12,458th fill since the collision experiment started at KEKB in May 1999. As a usual morning shift, the control room was rather quiet, having each person on the shift of the KEKB/Belle Commissioning Group (KCG/BCG) and a few ring/linac operators of Mitsubishi Electric System & Service Engineering. Soon or later people came into the control room one by one, expressing their words of praise. Dr. Shibata who was on the KCG shift told “I was just there as a shift, doing nothing special, but I was so pleased and happy,” at the KCG meeting in the morning. This was the start of the new era of the history of the particle colliders. Actually this achievement was not an accidental event

at all, since KEKB repeated the luminosity almost in every fill in the following days, making the records of daily/weekly/monthly integrated luminosity. "The luminosity of 10^{34} cm^{-2}s^{-1} is", said the KEK Director Y. Totsuka, "so epoch-making as a sprint break 10 seconds for 100 m," at the press conference held on May 14.

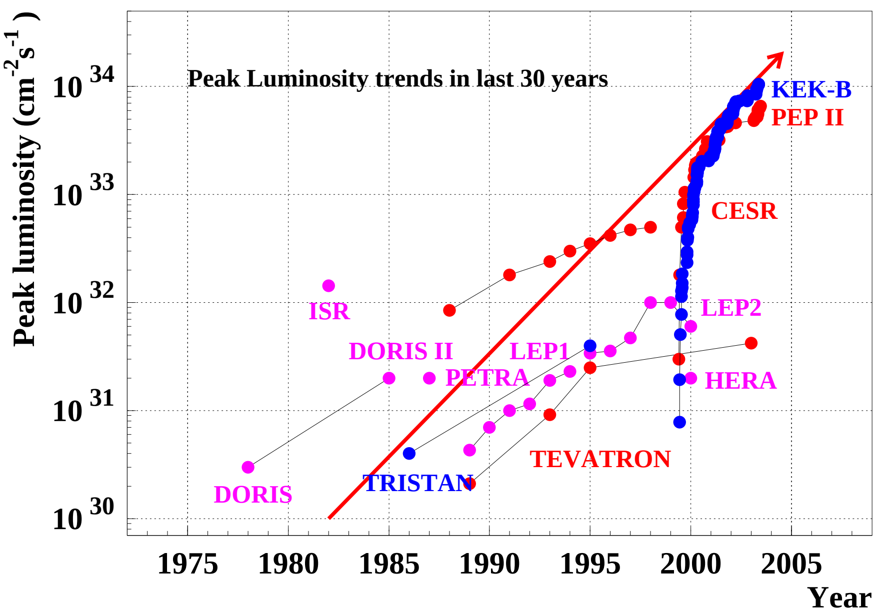

Figure 2: Trends in peak luminosity of the colliders of the world over the past 30 years. 10^{33}cm$^{-2}s^{-1} \equiv 1$ /nb/s. The arrow represents 1 order growth in 5 years.

Figure 1 shows the history of KEKB performance since Oct. 1999. Though having number of breaks and slumps, the overall performance has been continuously improved toward the design luminosity. Four years were necessary for KEKB to achieve the design luminosity. Was it too long or not? The period of startup was specified as "100 /fb in the first 3 years" in the *KEKB Design Report*, and KEKB achieved 100 /fb in October 2002, and 150 /fb in 4 years. So the speed of startup satisfied the plan very well. Figure 2 shows 30 year history of the luminosity of colliders in the world. The startup speed of KEKB was even remarkable in the history of the colliders, driving the trend.

Table 1 compares major machine parameter corresponding to the best peak luminosity, recorded on May 13, comparing to one year ago and also the design. The peak and the integrated luminosities for each period were improved by 45–50% in a year. Note that the beam currents were nearly unchanged in the LER in one year, and only 14% increased in the HER. The machine parameters such as β^*s and emittances did not change so much. The increase of the luminosity was brought by the smaller vertical beam size at collision, which was made possible by various improvements and tuning in the operating conditions.

The major differences between the best achieved and the design are in the number of bunches (thus bunch spacing). Although the solenoid windings were so extended as to cover roughly entire drift spaces, the effect of the electron cloud did not disappear completely. The threshold of the vertical blow-up was increased to about 1.8 A for near-4 bucket spacing. The threshold was lower for shorter spacings. Even below the threshold,

Table 1: Progress of machine parameters

Date	5/13/2003		5/27/2002		Design		
	LER	**HER**	**LER**	**HER**	**LER**	**HER**	
Current	1.38	1.05	1.37	0.92	2.6	1.1	A
Bunches	1265		1224		5000		
Bunch current	1.09	0.83	1.10	0.75	0.52	0.22	mA
Spacing	1.8 or 2.4		2.4		0.6		m
Emittance ε_x	18	24	18	24	18	18	nm
β_x^*	59	58	59	61	33	33	cm
β_y^*	0.58	0.70	0.62	0.70	1.0	1.0	cm
Hor. Size @ IP	103	118	103	121	80	80	μm
Ver. Size @ IP	2.2	2.2	2.8	2.8	1.9	1.9	μm
$\varepsilon_y/\varepsilon_x$	4.7	2.9	7.2	4.8	2	2	%
Beam-beam ξ_x	.093	.068	.080	.074	.07	.07	
Beam-beam ξ_y	.065	.051	.048	.041	.052	.052	
Luminosity	10.57		7.35		10		/nb/s
$\int$Lum/day	579		399		~ 600		/pb
$\int$Lum/7 days	3876		2524				/pb
$\int$Lum/30 days	12809		8783				/pb

the specific luminosity per bunch still seemed to degrade for shorter spacings. Actually, the average bunch spacing was reduced from 4.08(=49/12) buckets to 3.77(=49/13) buckets during this period, but in a few trials spacing less than 3.5 buckets did not give good specific luminosity. (To utilize the 2-bunch/pulse injection scheme, the bunch fill pattern must have the periodicity of 49 buckets.) The specific luminosity with 3.5 buckets might not be much worse than 3.77 buckets, but it was not usable due to higher heating of IP bellows until the summer 2003. As the number of bunches were much smaller than the design, the bunch current was so higher than the design, especially in the HER. Such high current caused higher HOM losses in all components. The ferrite HOM absorber in the superconducting cavity (SCC) in the HER now absorbs 10 kW/cavity, which already exceeded the design and the tested power level.

Improvements in the Summer 2002

Number of improvements were done for the hardware using the summer shutdown in July and August, 2002.

- Four ARES cavities were added in the LER. As the number of cavities in the LER reached the design, the rf system in the LER has been able to store the design current, 2.6 A, This did not result in an immediate increase of the beam current in the actual operation, since other issues such as heating of components, electron cloud, etc have been restricting the current.
- Movable masks were improved both in the LER and the HER. In the HER, 4

Figure 3: A combination of a winged HOM damper and a horizontal movable mask for the LER.

horizontal and 8 vertical masks were replaced with Ti-head, moving-chamber type (Ver. 4.5) to relax the higher-order modes (HOM) and reduce the damage of the head by an accidental large hit of beam. In the LER, 3 newly designed "winged" HOM dampers were attached near the horizontal masks at the D3 section. Each damper mounts an SiC rod in each one of two winged wave guides which is connected to the beam pipe with 15 degrees (Fig. 3). This damper absorbs the HOM generated at the movable masks via TE-like modes which couples to the beam due to the asymmetry of the mask geometry. One more absorber was also installed in the LER during the winter shutdown.

- The cooling of the vacuum chamber at the interaction point (IP) was reinforced. The cooling itself was successful, but the left side bellows got deformed during the installation, and made a restriction on the beam current through the operation until summer 2003.
- More rf shields are attached at NEG pumps to reflect the HOM from the movable masks.
- More solenoids were wound at remaining straight sections and tiny spaces between magnets. The increment in the effective length of the solenoid was around 50 m (total 2250 m). Later in Octobler 2002 and June 2003, assemblies of permanent magnets with longitudinal field component at the beam pipe were attached on the beam position monitors (BPM) where regular solenoid winding were rather difficult (Fig. 4).
- The mirror chamber to extract the synchrotron light in the LER was replaced with Cu from SUS to reduce the heating.

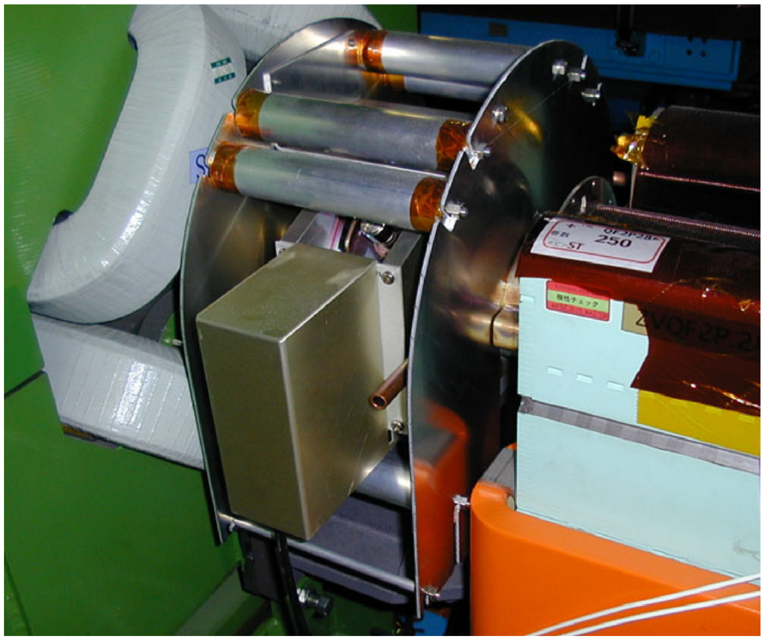

Figure 4: An assembly of permanent magnets to cover a BPM to suppress the remaining electron cloud in LER. 105 and 240 units were installed in Oct. 2002 and June 2003, respectively.

- The control system of the He refrigerator for the super conducting cavities and also the superconducting quadurupoles (QCS) and the Belle solenoid were renewed. Since then all cryogenic systems have been controlled at a single control room at Nikko by a single team of operators.

- Components broken in the previous run, such as a few wiggler coils and bunch-by-bunch feedback kickers and amplifiers were repaired.

Progress in the Fall 2002

Heaven and Hell. The fall run started on September 2 with vacuum scrubbing for two weeks. Physics run started on Sept. 13. As seen in Fig. 1, the luminosity was smoothly recovered without big breaks. On October 2, the integrated luminosity (Belle recorded) exceeded the BaBar's number, then 93.80 /fb, for the first time. Then KEKB/Belle became the front runner of the luminosity frontier in every meaning. The peak luminosity reached the then-record 8.26 /nb/s and the specific luminosity per bunch was improved by up to 15% compared to before the summer. Nothing seemed to prevent this march of victory. The integrated luminosity also surpassed 100 /fb on Oct. 26. We could even have a small party on Oct. 28 with two Nobel Prize winners, M. Koshiba and B. Richter, to celebrate the achievement (Fig. 5), but that was the peak of the Heaven.

Good and ill luck are next-door neighbors. On Oct. 30, a strange rise of vacuum pressure was observed at the IP. Physics run was ceased and leak check were done carefully from outside of Belle, but no leak was found at that moment. Since the phenomena looked as if a fresh surface had appeared near the IP, vacuum scrubbing by beam was done for a day.

Figure 5: At the party on October 26, 2002, celebrating the integrated luminosity 100 /fb. Two Nobel Prize winners, M. Koshiba (center) and B. Richter (center-right) came with the former Director of KEK, H. Sugawara (center-left).

As the dynamic pressure did not improved by the scrubbing, the vacuum was opened and inspection by telescopes and CCD fiber scopes were done from the both sides of the IP. The inspection did not find the cause of the leak, except mysterious dark spots on Au coated section of the taper on the right hand side of the IP chamber, which would be eventually understood irrelevant by the inspection after dismantle. Then another vacuum scrubbing was tried for 1.5 days, and on November 7, leak of He gas into the IP beam pipe happened in a larger scale. The source was the cooling gas for the Be chamber at the IP, and it was quickly confirmed by replacing the gas with Ar. Though the exact location of the leak was not identified yet, it was inevitable to disassemble the IP chamber and replace.

Figure 6: The leak points were identified as tiny pin holes on the body of the Be chamber at the IP.

The recovery process was performed quickly by tight cooperation between the Belle and the accelerator staffs. It was decided to reuse an old Be chamber with tapers which had been operated until the summer 2000. Along with the recovery work, the cause of the leak was investigated. Sooner or later it was found that the leak was at the body of the Be pipe, 2 cm from the edge of the left hand side (Fig, 6). They were a few tiny pinholes, probably caused by the very fast flow, nearly the speed of sound, of the He gas that brought Al particles etched from the outer section. Thus the cause was not attributed to the beam current, but the beam current was somewhat limited at certain level during the run until the summer 2003.

Besides the replacement of the IP chamber, the unexpectedly long winter shutdown was spent for repairing components including a few ARES cavities and couplers, voltage monitor for the SCC, rf power supplies, a few bellows around the IP, movable masks, the abort chamber for the HER, etc.

Progress in January – June 2003

After the recovery of the IP chamber, KEKB resumed the beam operation on January 10. The first one week was dedicated for the vacuum scrubbing, and the physics run started on Jan. 17. As mentioned above, a limit on the total current was set at 2.2 A. It was raised to 2.4 A and 2.6 A on February 20 and April 1, respectively. As seen in Fig. 1, the luminosity raised as the currents became higher, but the increase of the luminosity was far better than the increase of the current. Actually during the period from January to May 2003, the specific luminosity per bunch was improved by 19% and 35% from October 2002 and May 2002, respectively. This improvement in the specific luminosity was not achieved by any single reason, but by integration of lots of progress in many aspects of the machine operation. Let us list some of them as following (the order does not matter).

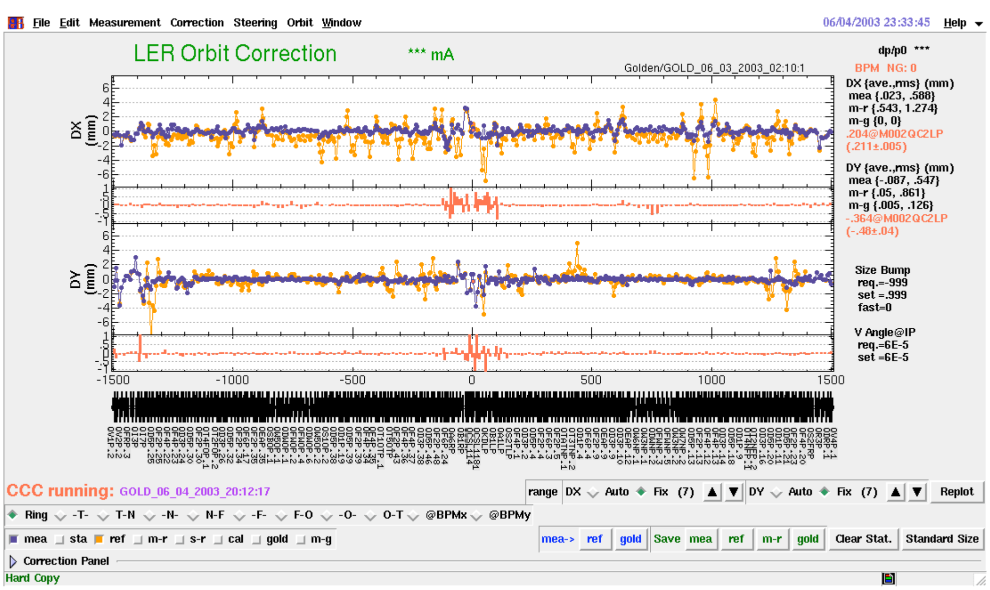

Figure 7: The historically accumulated closed orbit (orange) were cleared all around the LER, and the new orbit (blue) came much closer to the ideal.

Clearing historical orbits and fudge factors Historically the closed orbits of KEKB had been accumulation of perturbations including bump orbits at sextupoles for optics correction. Each time the optics correction were added on the existing orbit, thus the closed orbit gradually drifted from the design orbit. The deviation reached around ± 5 mm at the worst location. Such big deviation of orbit caused unnecessary change in the beam optics beyond the range of the usual optics correction, which only tweaks a quadrupole family with many magnets by a fudge factor of a single power supply. During this period the closed orbits, except the HER horizontal, were once corrected as close as to the design orbit (Fig. 7). At the same time, the fudge factors of normal and skew quadrupoles were reset to zero, except the skew components of QCS. Then optics correction was applied on the cleared orbit. The resulting fudge factors became far smaller than the previous ones. As the result, beam optics attained broader tune spaces with enough life time, which contributed higher luminosity.

Three correctors were added in the HER upstream the IP to correct the orbit within the allowable magnitude of the field for the incoming synchrotron light to the silicon vertex detector.

Beam-mapping of BPM One progress was made in the BPM system to fully utilize the beam-mapping method. BPMs had been used mapping functions determined by calibration prior to the installation. These mapping coefficients must be updated as the impedances of connectors, cables, switches varies in time. The most effective way to recalibrate the mapping is the so-called beam-mapping method. During this period it was done for all BPMs in both rings. The result was remarkably good. The consistency error of BPMs was reduced from about 0.3 mm rms to 5-20 μm rms by the beam-mapping. The offsets of BPMs determined by the Quad-BPM measurement were also reduced 50% to 100 μm by using the result of the beam-mapping. The clearing of the orbit history was also more effective by using the beam-mapping.

Better algorithms in orbit correction From the beginning of KEKB, the continuous closed-orbit correction (CCC) maintained the closed orbit, correcting the distortion from the golden orbit, which was determined by the optics correction. One issue of the CCC had been a long term drift of the orbit arising from the correction algorithm itself. The drift of orbit disturbed the beam optics to degrade the luminosity, and also caused a deviation of the beam energy to miss the resonance at $\Upsilon(4S)$. Thus the setting of the corrector magnets had to be restored periodically, and the setting of the ring energy had to be adjusted at initialization of the magnets on every maintenance day. The defect of the algorithm was eventually found: a constraint to maintain the tunes unaffected to the orbit correction was the reason and after removing the constraint the drift was reduced to less than 1/10, and the beam energy was well stabilized (Fig. 8).

Improvements in optics correction The optics correction further evolved especially in the β-correction. As for the β-measurement, the effect of sextupoles on the single-kick orbit was cancelled by taking the difference of bipolar kicks. The correction algorithm now fully incorporated with β, phase, and tune corrections. Horizontal bumps and sextupole movers became also usable for the correction. The resulting deviation of β function was about 3% rms all around the ring, even at the horizontal tune 0.506.

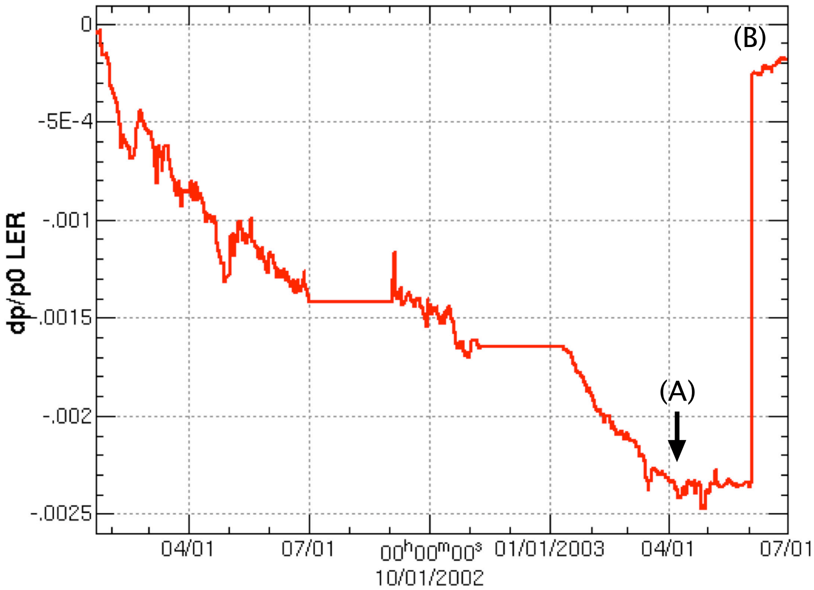

Figure 8: The energy deviation of the LER due to the orbit drift since Feb. 2002. It was stabilized by the change of the algorithm of the closed orbit correction in the beginning of Apr. 2003 (A). The accumulated deviation was reset to near zero by clearing the historical orbt in the beginning of June (B).

Better choice of tunes As the orbit and optics corrections became better and better, the choice of the betatron tunes obtained more freedom. The typical operating point of the LER was (0.506, 0.547) which was very close to the best point predicted by beam-beam simulations. The HER tune was around (0.511, 0.570), which was still a little apart from the ideal. It was possible to set the horizontal tune to 0.502 for a low current beam, but for a high current beam it loses the pilot bunch not in collision. The reasons that the HER optics was less stable than the LER might be (1) the orbit clearing was not done for the HER (2) deviation of the optics due to resistive wall impedance is higher due to the race-track chamber (3) the choice of sextupoles was not matured.

Tune feedback system was newly developed to manage the tunes at collision. Tunes are measured by non-colliding pilot bunches sitting at the end of the bunch train (head of the abort gap). Tunes are automatically adjusted to an empirical function of beam current of each ring.

Better tuning knobs The global optics correction was not enough to reproduce the best luminosity. Tuning knobs to tweak the optical parameters at the IP were necessary. Knobs to control vertical waists, longitudinal collision point, vertical dispersions and dispersion angles, and x-y coupling parameters have been used to maximize the luminosity. The dispersions and couplings were independently controlled by vertical bump orbit at sextupoles near the IP. Though the minimum number, 6 per ring, of sextupole families had been used, but it was increased to 8 families/ring. This reduced the height of the bump to 1/5 and the side effects of the bumps became tolerable.

Stable operation The operation was more or less stable in February, March, and

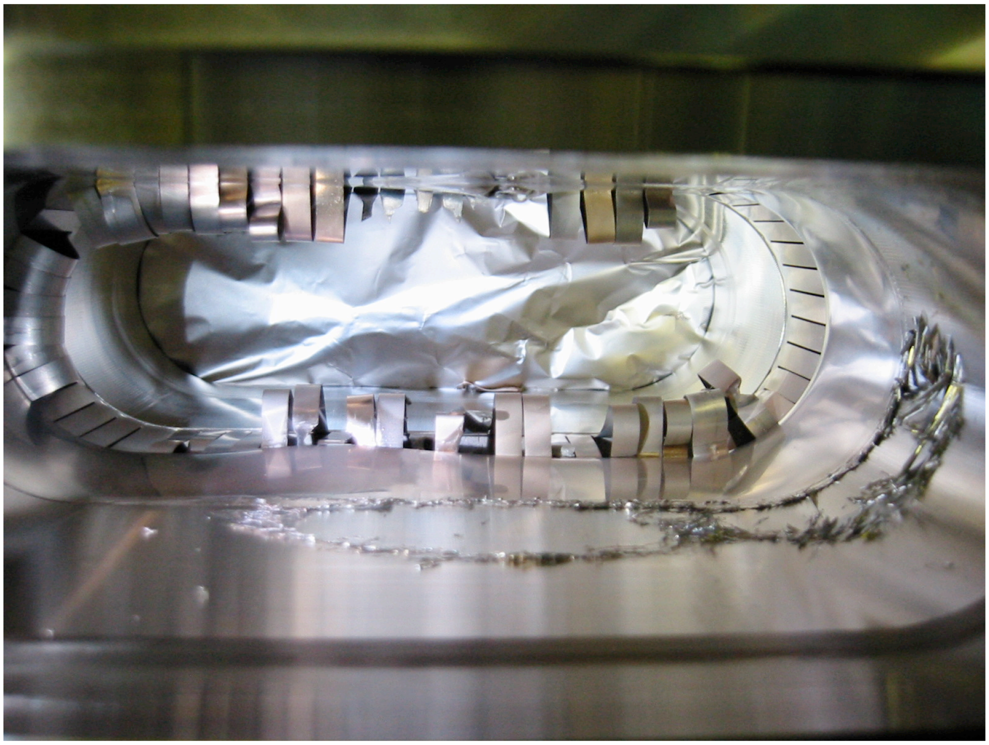

Figure 9: The damaged bellows chamber in the Tsukuba straight section of the HER. The rf-shielding fingers were melted and destroyed, while sputtered metal was seen at the bottom. This was happened in the end of March 2003.

May. As the total current was still limited by Belle in February and March, the machine was so stable that the record of none-abort interval, 54 hours, was made. At the end of March, a bellows in the HER at Tsukuba straight section (QC4RE) was damaged, and the operation became more or less unstable until its replacement in the beginning of May (Fig. 9). After the replacement May was stable again to rewrite all luminosity records. Number of troubles happened in June, such as reduction of flow of the cooling water at Oho area, damage of a beam stopper in the HER, etc. Other damages on horizontal movable masks in the HER and septum chambers in the both rings were also found after the shutdown, but they should have disturbed the stable operation in June. The HER could not store more than 1 A without collision, which had been well achieved before June. Though it was managed to store 1 A with the LER beam in collision, such operation was less stable and causing abrupt beam aborts.

The rf systems, both ARES and the SCC were quite stable during the entire period. The rate of aborts caused by the rf systems was roughly once/day. The SCC successfully stored the world's highest current, 1.1 A. The LER stored up to 1.86 A in a trial collision at the end of June.

One unsolved issue was a day-night variation of the luminosity. Typically on a fine day in high temperature, the luminosity at the beginning of a fill degraded by 10–15%. It was due to mysterious blow-up of the HER beam at collision. It calmed down in the evening without any particular tuning of the machine. The day-night difference did not happen on a cloudy or a rainy day. The temperature itself might not be relevant, since it happened in March whose day temperature was lower than the night temperature in

May. Many speculation were made on the reason and investigations were done, but no conclusion has not been reached yet.

Injection Throughout the entire period, the 2 bunch injection scheme of positrons was regularly applied. The injection rate was greatly improved in the both rings making the records 3.5 mA/s and 5.2 mA/s for the LER and the HER, respectively. The injection efficiency often reached 100%.

Appendix

In March 2003, the KEKB accelerator team, including the injector group, won the Suwa Prize from Foundation for High Energy Accelerator Science for achieving the world's highest luminosity.