HIGH LUMINOSITY OPERATION OF THE KEKB

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Abstract

The history of the KEKB commissioning is characterized by struggles with three obstacles, namely the electron-cloud instability, the beam-beam blowup and beam current limitations from many reasons. A rapid improvement in the luminosity in this year (2001) has been made by progress in each of these three problems. This report summarizes this year's progress of the KEKB accelerator, since the history of prior days is covered by other reports[1][2][3].

1 PRESENT PERFORMANCE

Fig. 1 shows the history of the KEKB luminosity. The top row shows a history of a peak luminosity. As is seen in the figure, the improvement of this year is remarkable. The second row shows a history of a daily integrated luminosity. The third row shows a history of peak beam currents of a day. The bottom row shows a history of an accumulated luminosity by the Belle detector.

Table 1 shows a parameter list of the KEKB at the record peak luminosity. This table tells characteristic features of the KEKB. The present KEKB is filled with a beam at every 4th RF bucket. In the design[8], the number of bunches is 5000 which means that every RF bucket is filled with a beam. As is described below, the specific luminosity is decreased when the number of bunches is increased from the every 4th RF bucket case by reducing bunch spacing. Although we tried longer bunch spacing, 4 RF bucket spacing is the best choice at the present KEKB. The other parameters are chosen under this restriction of the bunch spacing. It is notable that the bunch currents of the present KEKB are much higher compared with the design values particularly in the HER (high energy ring). This is also the consequence of the bunch spacing restriction. To compensate this unusually high bunch current to some extent, the horizontal emittance of the HER is enlarged compared with the design. On the other hand, the LER bunch current is not so high as the HER. The luminosity does not increase even with higher LER beam current. It is believed that this saturation of the luminosity with the LER current is due to the single beam blowup from the electron cloud instability. The low value of the vertical beam-beam parameter of the LER is also explained by this single beam blowup. The horizontal and vertical beta functions at IP has been determined by a trial and error method. The vertical beta functions are much lower than the design values.

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2 RECENT PROGRESS

2.1 *Electron cloud instability*

Studies on the nature of this instability are reported elsewhere[4][5]. To mitigate this instability, solenoid coils have been wound around the LER ring. Works for solenoid winding were done three times, namely September 2000, January 2001 and April 2001. In those works, 800 m, 430m and 40m of the ring were covered with solenoid coils, respectively. A typical length of the solenoid coils is about 50cm, although there is some variety in length. A typical field strength is around 45 Gauss at the center of each solenoid when excited with a current of 5 A. Fig. 2 shows effectiveness of the solenoids. The horizontal axis is a bunch current product of the tow beams. The vertical axis is a specific luminosity which is defined as a luminosity divided by a number of bunches and by the bunch current product in the unit of $10^{30}/\mathrm{cm}^2/\mathrm{sec}/\mathrm{mA}^2$. This specific luminosity is a function of beam sizes and should be constant when there is no beam blowup. In Fig. 2, there are three lines which correspond to cases with all of solenoid magnets on, with all solenoid magnets off and with the solenoids of 450m wound January 2001 turned off. As is seen in the figure, the specific luminosity drops drastically when all solenoid magnets are turned off. The figure also shows that the solenoids wound January 2001 is effective to increase the luminosity That indicates that this year's improvement of the luminosity partially owes this solenoid winding.

Even with all solenoid magnets on, the specific luminosity has a beam current dependence. However, a beam-beam blowup is included in this blowup. We need to separate it from the blowup. For this purpose, an experiment with a longer bunch spacing was done. In this experiment, bunch spacing was 24 RF bucket which is 6 times larger than the usual one. With the 24 RF bucket spacing, no beam blowup is observed in a usual bunch current region. Therefore, we assumed that the electron cloud instability is negligible with

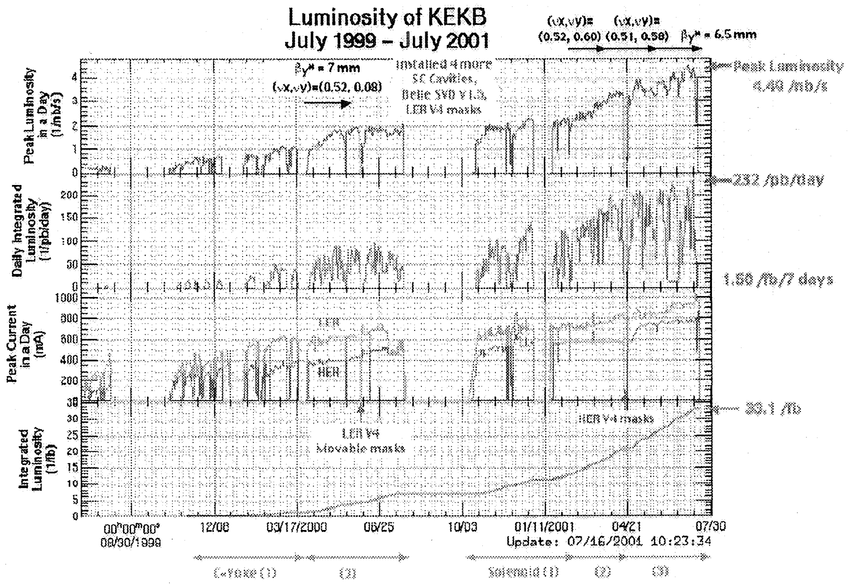

Figure 1: History of the KEKB luminosity.

this bunch spacing. Also in the experiment, a specific luminosity was measured as a function of the bunch current product. This experiment was done on March 10 2001. Fig.3 shows a result of the experiment. As is shown in the figure, there is no big difference in the specific luminosity between these two bunch spacing conditions at that time. This result indicates that the effect of the electron cloud instability is negligible in the usual beam current range even with 4 RF bucket spacing. A similar experiment was done also at the end of December 2000. At that time, there were a big difference in the specific luminosity with the 4 and 24 RF bucket spacing cases. Combining the results of the two experiments, it could be concluded that the solenoid magnet wound January 2001 removed the main effect of the electron cloud instability in the beam current region used in usual operation in the 4 RF bucket spacing case.

However, this does not means that the electron cloud instability has been overcome completely by the solenoid magnets. In the usual operation with 4 RF bucket spacing, the luminosity shows saturation to an increase of the LER beam current. In the 24 RF bucket spacing case, however, the specific luminosity stays almost at the same level even with much higher LER bunch currents, which is shown also in Fig. 3. In the region where the bunch current product is larger than 4.5 mA^2, the LER current was increased with the HER current almost kept constant. In Fig. 3, the beam current ratio of the two beam is also shown. This result indicates that the luminosity could be doubled by increasing the LER current provided that the electron cloud instability can be suppressed completely.

2.2 Working point

At the beginning of February 2001, vertical tunes of both rings were moved from just above the integer resonance to just above the half integer resonance. Before the change, the tunes are very near to the design values. These design tunes were determined by strong-weak beam-beam simulations. Recently, we newly made a tune survey with a strong-strong simulation code[6]. Results of the simulations predicted that the vertical tunes above the half integer resonance give a better luminosity than the design tunes[7]. Ac-

	LER	HER
ε_x (nm)	18 (18)	24 (18)
β_x^*/β_y^* (m)	0.59/0.0065 (0.33/0.010)	0.63/0.0065 (0.33/0.010)
bunch current (mA)	845 (2600)	715 (1100)
# of bunches	1154 (5000)	
bunch current (mA)	0.73 (0.52)	0.62 (0.22)
bunch spacing (nsec)	8 (2)	
bunch length (mm@MV)	6∼8@6.0 (measurement)	5.7@11.0 (calculation)
ξ_x/ξ_y	0.069/0.053 (0.039/0.052)	0.048/0.030 (0.039/0.052)
ν_x/ν_y	45.51/43.58 (45.52/44.08)	44.53/41.59 (44.52/42.08)
Lifetime (min@mA)	160@800	300@700
Luminosity ($/\mathrm{cm}^2/\mathrm{sec}$)	4.49×10^{33} (1.0×10^{34})	

Table 1: Present performance compared with the design. (Values in parentheses are the design values.)

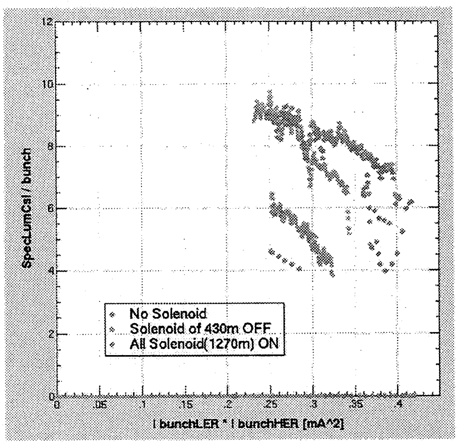

Figure 2: Effect of solenoid magnets on the luminosity.

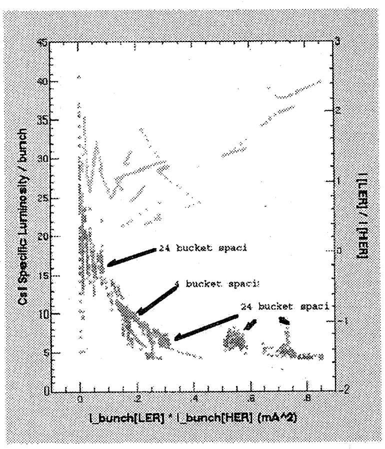

Figure 3: Comparison of the luminosity with different bunch spacing.

cording to those results, we changed the vertical tunes. Just after changing the tunes, the luminosity did not increase so much. However, the stability of the beam operation was improved due to less large orbit drifts. In the middle of March, the fractional part of the LER (horizontal and vertical) tunes were changed from (0.52,0.60) to (0.51,0.58). Although the amount of the tune change was small, the luminosity shows some jump as is shown in Fig.1.

2.3 *Beam Current*

In the history of the KEKB, the beam currents have been limited from many reasons which include the detector beam background. Among those, the most serious limitation has come from tolerance of several hardware components to a high beam current. We have solved those hardware problems mainly by replacing hardware components in question with the new ones with which the problems were fixed. Most recently, the HER beam current was limited by the HOM power limit of movable masks for protecting the Belle detector from the beam background. In the middle of April, we replaced the movable masks with those of a new version. In the old version of the masks, some trapped modes existed and they need HOM dampers. Acceptable power limit of the HOM dampers restricted the HER beam current. In the new version, a masking function is realized by deforming the vacuum chamber itself. Since there is no trapped mode, they need no HOM dampers. After replacing the masks, we could increased the HER beam current and the luminosity also increased. The luminosity jump in the end of April as shown in Fig. 1 was brought by this beam current increase.

3 BEAM-BEAM PARAMETERS

The beam-beam parameters calculated from the luminosity are listed in Table 1. In the calculation, we assumed that the vertical beam sizes of the two beams are equal, since we use so-called "iSize feedback" system. This system aims at maximizing the luminosity by controlling the vertical emittance of the stronger beam (usually HER). It is also assumed that there is no beam-beam blowup in the horizontal direction, since we do not observe serious beam size blowup in the horizontal direction. The"hourglass" effect from a finite bunch length and degradation of the beam-beam parameters due to a finite crossing angle are also considered. As for the bunch length, 7mm is assumed. As is seen in Table 1, the vertical beam-beam parameter of the HER is notably low. This is also explained by the single beam blowup of the LER from the electron cloud instability. To confirm this, an experiment with longer bunch spacing was done. In this experiment, the bunch spacing was 24 RF buckets and no single beam blowup was observed with this bunch spacing. Beam-beam parameters obtained in this experiment is listed in Table 2 together with those in the usual bunch spacing of the 4 RF buckets. As was expected, the HER vertical beam-beam parameter with 24 RF bucket spacing ($\sim$ 48nsec) is larger than that with 4 RF bucket spacing. In this experiment, the luminosity saturated at a higher LER bunch current compared with the case in usual operation. This indicates that the luminosity saturation with the LER current in the usual operation comes from the LER single beam blowup. In this experiment, a much more serious HER beam blowup than in the usual operation was observed when the LER beam current increased. We had very short time to search parameters for suppressing the HER blowup in the experiment. It seemed that the HER blowup could be suppressed with more machine tuning and higher beam-beam parameters could be achieved.

Another feature of the KEKB parameters is that the working points are close to the half integer resonance as is shown in Table 1. Particularly the horizontal tunes are very near to the resonance. In this situation, of importance is an effect that the beta function and the emittance are affected by the beam-beam force (dynamic-beta and dynamic-emittance). These effects have been studied by using the SAD code. In the simulation, only the linear part of the beam-beam kick was taken into account. Fig. 4 shows a result of the simulation. In the figure, the beta function of the LER at the IP and the horizontal emittance

	spacing	case 1	case 2
ξ_x/ξ_y (LER)	8 nsec	0.069/0.053	0.017/0.052
ξ_x/ξ_y (HER)	8 nsec	0.048/0.030	0.018/0.029
ξ_x/ξ_y (LER)	48 nsec	0.061/0.033	0.018/0.033
ξ_x/ξ_y (HER)	48 nsec	0.075/0.038	0.028/0.035

Table 2: Beam-beam parameters with and without the dynamic-β effects. In the case 1, the effects of the dynamic-β are ignored. In the case 2, we count the effects of the dynamic-β.

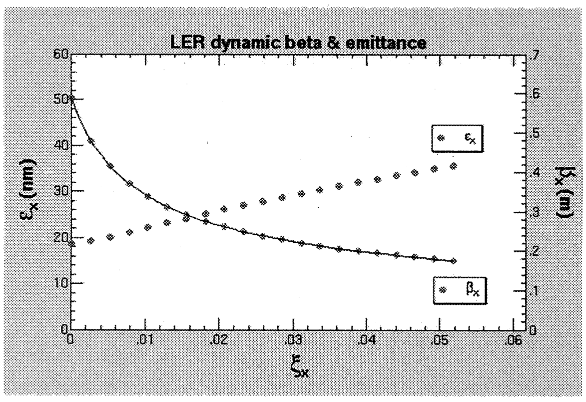

Figure 4: Calculations of the dynamic beta and dynamic emittance effects with a horizontal tune of 45.51 as function of the (nominal) horizontal beam-beam parameter. The calculation was done by using the SAD code. The solid line shows a beta calculation from an analytical calculation using a simple one-turn transfer matrix.

are depicted as function of the (nominal) horizontal beam-beam parameter. Also shown in the figure is the beta function which is calculated by an analytic calculation. The beta function can be calculated by estimating a change of an one-turn transfer matrix with the beam-beam kick. The analytic calculation well agrees with that from the SAD code. As is seen in the figure, the horizontal beta function at the IP drastically shrinks with the horizontal tune of 45.51 and the emittance is enlarged to a large extent. What one should note here is that a change of beam size in one beam due to the beam-beam effect brings an additional dynamic beta and dynamic emittance effect to the other beam. Therefore, the effect should be solved consistently for the two beams. This effect is also included in the calculation. As a result of these changes, the horizontal beam size at the IP decreases to a some extent and the horizontal beam-beam parameter decreases as is also shown in Table 2. In the KEKB, there is a tendency that the closer horizontal tune to the half integer resonance brings a higher luminosity. This tendency seems to be explained by the dynamic beta and dynamic emittance effects. These effects also explain why we can reach extremely high beam-beam parameters in the usual sense in the horizontal direction shown in Table 1.

4 FUTURE PLANS

The most natural way to increase the luminosity in the current situation of the KEKB is to increase the number of bunches. As is mentioned above, the present filling scheme is basically 4 RF bucket spacing. Although we have tried 3 RF bucket spacing several times, every time the specific luminosity with 3 RF bucket spacing was worse than that with 4 RF bucket spacing even in the beam current region where the single beam blowup in LER is not visible. We have not yet understood the reason for this luminosity degradation with 3 RF bucket spacing.

At the present KEKB, the luminosity is not limited by the beam current limitations in the sense that the luminosity does not increase with a higher HER or LER beam current. With a higher LER beam current, the luminosity saturation comes from the single beam blowup from the electron cloud instability. To suppress this instability, we will install more solenoid coils in the LER in this summer. As for a long term plan, we have a plan to replace vacuum chambers in the ARC section with ante-chambers. Also we have a plan to exchange the electron and positron beams between the two rings, which means that the positron beam current can be decreased for the same luminosity. With a higher HER beam current, the luminosity saturation comes maybe from the beam-beam blowup of the LER beam. To mitigate this situation, we will try to increase the HER emittance from 24nm to 30nm shortly. Another possibility for the luminosity improvement is to shorten the bunch length of the two beams. We are preparing for a measurement of the LER bunch length and for shortening it, since HOM heating of SCC HOM dampers in HER prevents us from shortening that of the HER.

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