1.1 Review of Crab crossing in KEKB

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1.1.1 Introduction

KEKB had been operated with collision scheme with a finite crossing angle of 11x2 mrad. The peak luminosity was 1.76x10^{34} cm^{-2}s^{-1} at 1340mA and 1660mA for electron and positron current. Crab cavities were introduced to compensate the crossing angle effectively and to realize the head-on collision in 2007. Head-on collision gave a high beam-beam performance in a beam-beam simulation [1]. We targeted a high beam-beam parameter larger than 0.1. The operation using the crab cavities has been done since February 2007. The maximum luminosity was achieved 2.11x10^{34} cm^{-2}s^{-1}. The chromatic coupling was corrected to achieve the luminosity [2]. Machine parameters for the peak luminosity without and with crab cavity is summarized in Table 1. The crab crossing in KEKB is reviewed in this part.

Table 1: Machine parameters to achieve the peak luminosity without and with crab cavities.

Parameter	*Unit*	*w/o crab*	*w crab*
Circumference, C	m	3016	3016
Emittances, ε_x (HER/LER)	10^9 m	24/18	24/18
bunch population, $N_{-/+}$ (HER/LER)	10^{10}	6.3/7.8	4.7/6.5
hor, beta function at IP, β_x	cm	55/6	120/120
ver. beta function at IP, β_y	cm	10	0.59/0.59
Number of bunch, N_b	…	1335	1584
Total current, $I_{-/+}$	A	1.34/1.66	1.19/1.64
Luminosity, L	10^{34} cm^{-2}s^{-1}	1.76	2.11

1.1.2 Motivation for the crab crossing

1.1.2.1 Beam-beam limit with or without crossing angle in simulations

Collision with a finite crossing angle (11mradx2) had been adopted in KEKB to manage IR design for multi-bunch collision. The collision performance toward the luminosity 1x10^{34} cm^{-2}s^{-1} was studied by using beam-beam simulations. While crab cavities had been developed to be back up for troubles in the collision with the crossing angle. The luminosity was achieved to be 1.7x10^{34} cm^{-2}s^{-1} without crab cavities. The luminosity was achieved at a high bunch current; therefore a burden on vacuum components was vey heavy.

The crab cavity was in the limelight to upgrade KEKB again. Beam-beam simulations showed very high performance with crab cavity. The luminosity with or without crab cavity is simulated using weak-strong and strong-strong code, named

BBWS and BBSS, respectively [1]. Figure 1 shows the beam-beam parameter (ξ) estimated by the simulated luminosity as follows,

$$\xi_{\pm} = \frac{2 r_e \beta_y}{N_{\pm} \gamma_{\pm} f} L$$

where r_e, γ, and f are the classical electron radius, relativistic factor and the collision repletion, respectively.

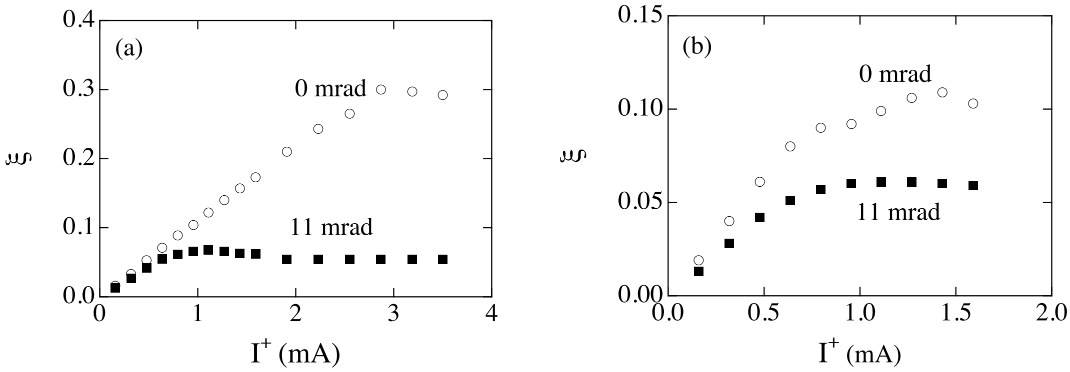

Figure 1 Beam-beam parameter as functions of positron current. Electron current is changed with the same ratio. Plots (a) and (b) are obtained by beam-beam simulation codes with the weak-strong (BBWS) and strong-strong (BBSS) model, respectively.

Another key point for the high luminosity is the tune-operating point. The horizontal tune is very closed to a half integer in CESR and KEKB. The luminosity increases for approaching the half integer. Simulations also showed very high performance especially with crab cavity at the operating tune.

1.1.3 Operation with crab cavity

1.1.3.1 KEKB performance before installation of the crab cavities

The operation started with crab cavities at February 2007. One crab cavity was installed in each ring to save the budget. The beam tilts in x-z plane in all the position (s) of the ring. The tilt angle is characterized by a kind of dispersion dependent of z, $x=\zeta_x z$. $\Delta\zeta_x$, which is induced by the crab cavity, follows to linear transverse equation of motion and is satisfied to the periodic boundary condition. The dispersion ζ_x and its derivative ζ_x' are matched to the half crossing angle and zero at the collision point for the both rings. In the beam-beam simulation, tolerance for the crab angle was tight, especially in the strong-strong simulation, as shown in Figure 2. The crab angle depends on the crab cavity voltage, and the horizontal beta functions at IP and the crab cavity. The crab cavity gives a transverse kick to the beam, when the rf phase is deviated from zero. The valance of the crab cavity voltages of the two rings was determined by whether the relative position of two beam at IP do not change for change of crab phase. The crab voltages are scanned with keeping the valance. Typical voltages are 0.97MV and 1.45MV for LER and HER rings, respectively, where β_x's are 51 m and 122 m at the crab cavities.

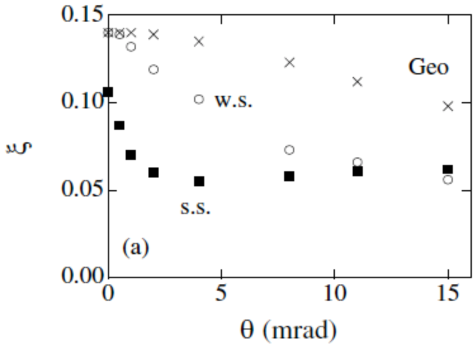

Figure 2: Beam-beam parameter for crossing angle. Three kinds of dots are given by geometrical luminosity (Geo) and simulated luminosity using weak-strong (w.s) and strong-strong (s.s) model.

The luminosity tuning has been done everyday since the start of 2007. Figure 3 shows the achieved specific luminosity. The luminosity given by the simulation is plotted, where two lines, Simulations I and II, are given for β_x*=0.8 m and 1.5 m, respectively, using the strong-strong simulation (BBSS). Black and blue dots depict measured luminosity with and without crab cavity. The specific luminosity was measured at the operation with 100 bunches (49 bucket spacing) to avoid high current issues, for example electron cloud or heating of vacuum components. The luminosity increased (the specific luminosity decreased) with keeping the beam-beam parameter in the measurement. The beam-beam parameters with and without crab cavity were 0.09 and 0.07, respectively. The gain of the crab cavity was about 20%. While the simulations showed higher luminosity and beam-beam parameter, especially at higher current product.

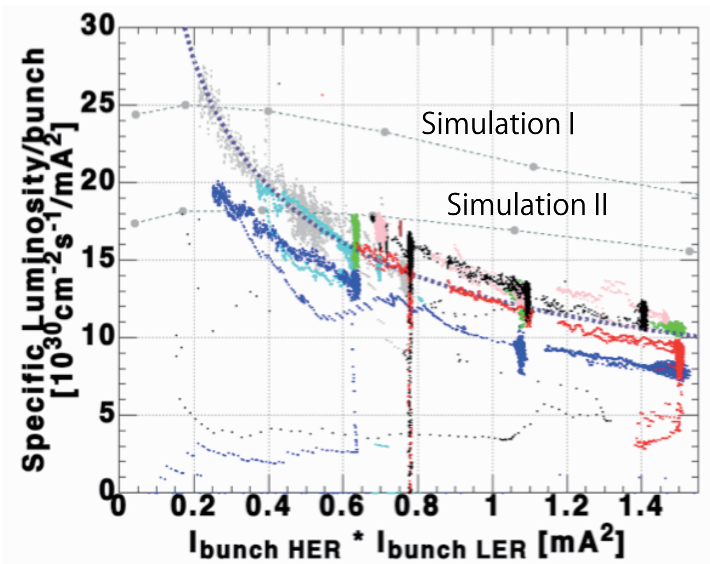

Figure 3: Specific luminosity as function of current product of two beams.

1.1.3.1 Correction of x-y coupling at IP

Luminosity performance strongly depends on the machine condition. Main tuning knobs are collision offset [3], x-y coupling and vertical dispersion at IP in KEKB. The number of parameter for the collision offset is three, horizontal and vertical offset and vertical crossing angle. The number is six for x-y coupling and vertical dispersion for each ring, thus the total is twelve. These parameters are scanned one or two times in a day. Vertical waist position, horizontal dispersion and chromaticity at IP were also scanned a few times in a week. The crab voltage was scanned a few times in a month. The luminosity was 60-70 % of the peak at the early stage of recovering after a long shutdown. It spends a couple of month to reach the peak level of luminosity.

We are not sure whether our luminosity is really limit. It is only true result that we spent three years to get the peak luminosity. In 2009, we realized chromatic coupling limited the luminosity. The luminosity increased 25 % due to scanning the chromatic coupling. We had actually believed the luminosity before the chromatic coupling correction had been a rigid limit.

Luminosity tuning using the down hill simplex optimization has been done for the twelve coupling and dispersion parameters. The luminosity was saturated at the peak level in 4-8 hours in the optimization. The optimization process was also reproduced by the beam-beam simulation. Errors for the parameters, which were several unit of tuning knob in the operation, were applied, and then optimized values, which should be zero, were searched using the simplex method. Figure 4 shows the luminosity evolution for the simplex iterations. The luminosity should be achieved $2.5\text{x}10^{31}$ $\text{cm}^{-2}\text{s}^{-1}$/bunch, but was saturate at $1.4\text{-}1.5\text{x}10^{31}$ $\text{cm}^{-2}\text{s}^{-1}$/bunch; 60% of the target value. The degradation is consistent with the measured value.

The knob scan process for each parameter was also examined using the beam-beam simulation. The optimized luminosity was again around 60 % of the target value. These facts show the complex of multi-parameter optimization.

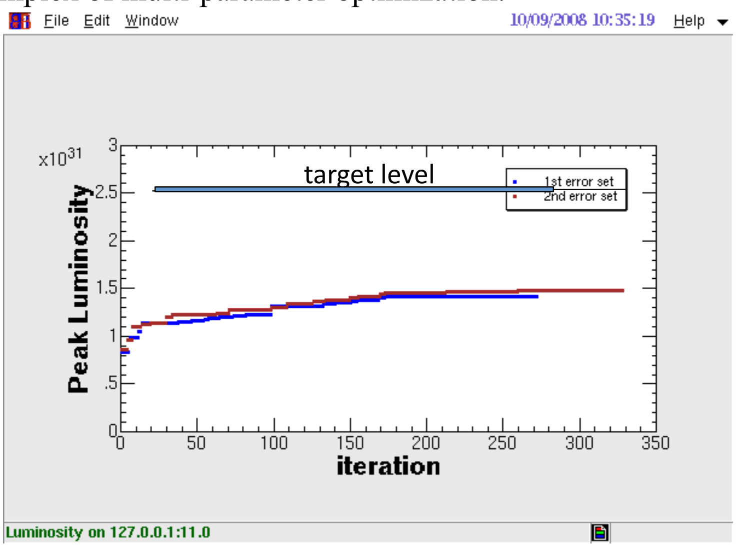

Figure 4: Luminosity optimization in the beam-beam simulation (BBSS). (by M. Tawada)

x-y coupling and dispersion at IP were ambiguous as absolute values, though they are scanned everyday. Efforts to measure the absolute values have been done. They were measured by turn by turn monitors nearby IP [4,5]. We used two sets of monitors for the measurement. First set, named QCS monitor, is two monitors outside of finial quadrupole magnets named QCS. Second set, named OctoPos monitor, is two monitors inside of QCS monitors. The two sets are not synchronized each other. Several results given by OctoPos monitors are presented here. Figure 5 shows the phase space plot characterize x-y coupling. X-y coupling is characterized by 4 parameters, R1[rad], R2[m], R3[m^{-1}], R4[rad], which are related to correlation of x-y, p_x-y, x-p_y, p_x-p_y, respectively. R1 and R2, which are related to y, are sensitive for the luminosity, while R3 and R4, which are related to p_y, are less sensitive. The parameters were scanned as is discussed before. Figure 6 shows R4 variation for R4 knob scan. R4 linearly changes and the gradient is 0.88. This fact showed the knob scan change the R parameters correctly. The absolute value was still ambiguous. Table 1 shows the coupling parameters measured April and May 2009. In this period, machine was well tuned, while the coupling parameters were finite values. R2 of LER was around 0.01. We doubted R2 for the reason why the luminosity is lower than simulations. Figure 7 shows the luminosity as a function of R2 given by the beam-beam simulation. This strong dependence on R2 has been observed in measurements. Considering the luminosity, R2 does not deviate so large. R2 is sensitive for the measurement because it is related to y not p_y. Ambiguity on rotation of monitors was not clear. R3 and R4 were deviated from zero. The monitor has enough sensitivity for R3 and R4 in this range. Luminosity seems better for finite R3 and R4. We did not have clear answer how coupling corrected yet.

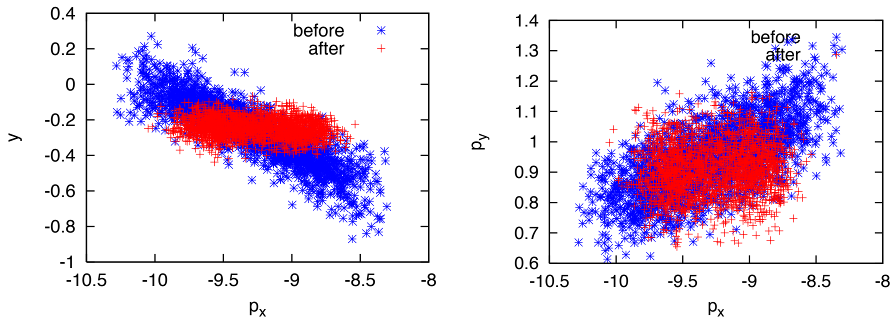

Figure 5: Phase space at IP measured by nearby turn by turn monitors (OctoPos).

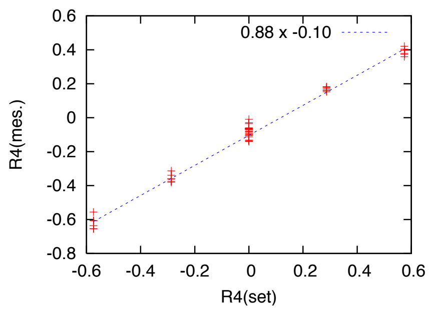

Figure 6: R4 variation for the Knob scan.

Table 1: Measurements of the coupling parameters in 2009.

		4/30	5/13	5/26
HER	r1	0.0112	0.0142	0.00974
	r2	0.00163	0.00139	0.00169
	r3	0.0616	0.111	0.0618
	r4	-0.0547	-0.0926	0.0245
LER	r1	0.0104	0.0085	0.00961
	r2	0.0137	0.0137	0.0131
	r3	0.673	0.189	0.221
	r4	-0.144	0.0277	-0.061

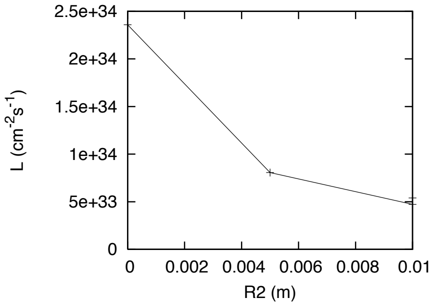

Figure 7: Luminosity as a function of R2 in a beam-beam simulation (BBSS).

1.1.3.1 Chromatic coupling at IP

Correction of the chromatic coupling was very efficient. The source of the chromaticity is complex IR magnets configuration, solenoid, compensation solenoids and final superconducting quadrupoles (QCS). The existence of the chromaticity was suggested by a beam size measurement in tune space [6]. The chromatic coupling was measured by off-momentum vertical orbit change for horizontal orbit distortion [7]. The effect of the chromatic coupling for the beam-beam performance was studied by the beam-beam simulations [2]. Figure 8 shows the beam size measurement in the tune space and chromaticity for R4. Coupling and their synchrotron sideband peaks are seen in the figure. The sideband peak is induced by the chromatic coupling. The chromaticity was not negligible for the beam-beam performance, because it spread 0.1-0.2 for $+\text{-}\sigma_{\Delta p/p}$ in HER as shown in the figure. The beam-beam simulation showed that 15-20 % of luminosity increase was expected. Skew sextupoles are installed in 2009 spring. The operation with the skew sextupole started at April 2009, and exceeds 2 $\times 10^{34}$ $cm^{-2}s^{-1}$ [8].

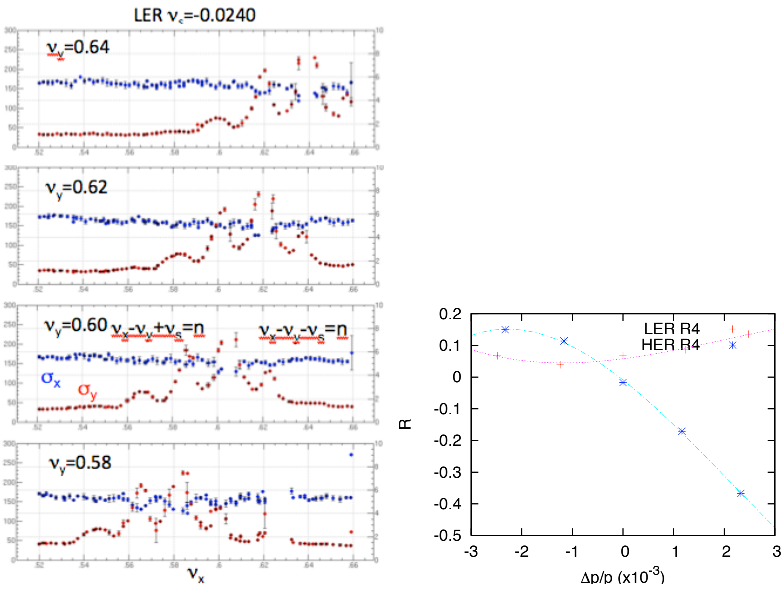

Figure 8: Measurement of the beam size in tune space and of chromaticity for R4 (by Y. Ohnishi & K. Ohmi).

1.1.3.2 Luminosity degradation due to Beam noise

A static offset between two colliding beams degrades luminosity due to less geometrical overlap and effect of an asymmetric beam-beam force. Turn by turn offset makes worse the luminosity performance sensitively in strong nonlinear system. For very flat beam (aspect ratio of the beam size at IP is 1/100), the vertical noise is more sensitive than horizontal. We doubted the first noise as a source of luminosity degradation. Figure 9 shows the luminosity degradation for the turn by turn noise given by simulation and measurement. In the simulation, noise of 5% amplitude of the vertical beam size degrades the luminosity 2.6 to 1.6 $\times 10^{34}$ $cm^{-2}s^{-1}$, 60%. The quantum excitation due to the synchrotron radiation is 2% of the beam size. The noise less than 2% is not effective, because it is hidden by the quantum excitation. In the figure, 10% of degradation is seen for the noise of 2% beam size.

A feedback kicker driven by a noise generator applied a noise into the beam. The noise level of the bunch oscillation was measured by turn by turn position monitors. The luminosity as a function of the noise amplitude is plotted in the right picture of Figure 9. The measurement showed less sensitive for the noise than the simulation. The measured luminosity is lower than simulated one. The luminosity for 5% or 10% amplitude roughly agrees with measured one. Unknown noise, x-y coupling or other optics issue may disturb to go to the very high peak.

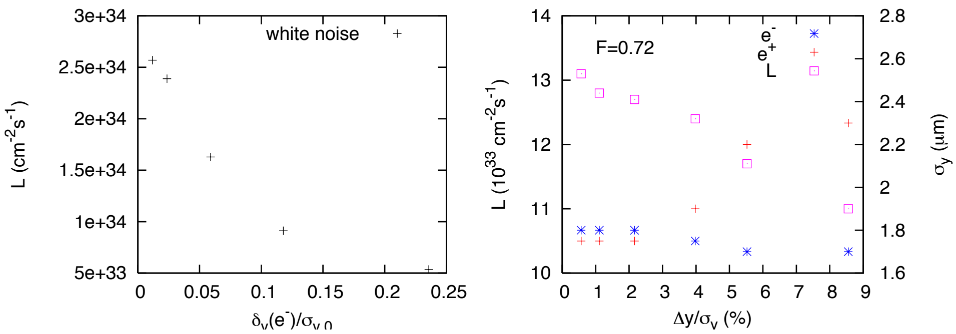

Figure 9: Luminosity for the vertical beam fluctuation amplitude. Left and right plots are given for the simulation and measurement (by M. Tobiyama & K. Ohmi).

1.1.3.3 Beam life time issue related to the collision

In an early stage of crab operation, beam lifetime issue at collision was very serious. The beam-beam simulation showed better performance for the beam lifetime as shown in Figure 10. Horizontal offset, in which positron beam is out side of the electron beam at IP, gave a harmfully short lifetime: that is, lifetime was asymmetry for the horizontal collision offset. The lifetime issue was cleared for changing the closed orbit at the crab cavity and relaxation of the horizontal beta function at the crab cavity and IP. A quadrupole magnet near the crab cavity limited the aperture. The beta function in the crab cavity was chosen to be high to reduce the crab cavity voltage. The voltage of LER crab cavity was limited around 10 MV. To get designed crab angle, beta function at crab cavity was enlarged 0.8-0.9 m.

Dynamic beta and emittance enhanced the aperture limitation, especially the dynamic beta was very strong because the operating point with horizontal tune 0.505 very close to the half integer. The beta functions are 0.9 m and 198 m at IP and at the quadrupole near the crab cavity without collision, while 0.2 m and 1100 m with collision. The horizontal beta function at IP was limited to be 1.2 m for that without crab cavity of 0.55m [9].

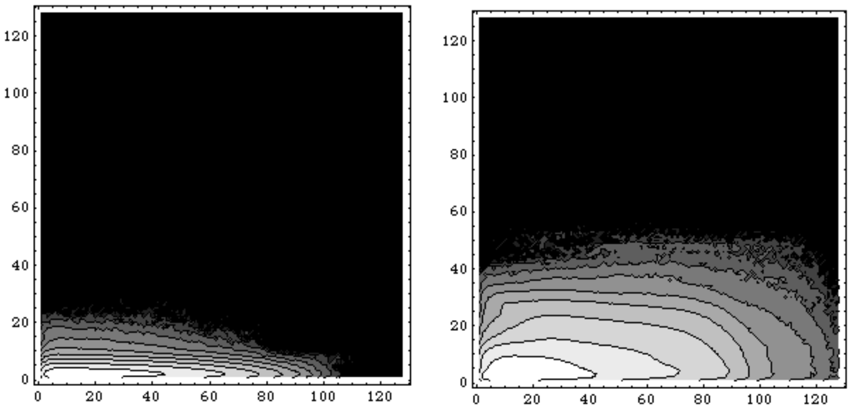

Figure 10: Beam distribution in the transverse space with (left) and without (right) crab cavity given the beam-beam simulation (BBWS). The full scale of the pictures is 0-12.8 σ_x, 0-64 σ_y for horizontal and vertical, respectively.

1.1.3.4 Other possibilities for Luminosity degradation

The design or zero current bunch length is 5mm for the both ring. The bunch lengthening should be week in an impedance estimation [10]. The bunch length was measured by a streak camera[11] and beam spectrum [12]. Energy spread was estimated by hadron event ratio in Belle detector. The impedance, which was consistent with the bunch lengthening and energy spreading, was empirically represented by a resonator model with L=106 nH, R=22.9 kΩ, C=0.22 fF and L=109 nH, R=12.5kΩ, C=0.69 fF for LER and HER, respectively. The effect of bunch lengthening to the luminosity performance was not dominant for the degradation [13].

Beam tilt in whole the ring, because one crab cavity is installed in a ring. Tail part of a bunch is kicked by the transverse wake field, thus the bunch shape is distorted like banana shape. The distortion was estimated for the wake field, W_x=1.7x10^6 m^{-2}, which was given by the current dependent tune shift in horizontal, $d\nu_x/dI$=4 A^{-1}. The distortion and other effects were negligible.

1.1.4 Summary

Crab cavity has been operated to target a very high beam-beam performance of the head-on collision in KEKB. Maximum luminosity 2.11x10^{34} cm^{-2}s^{-1} was achieved by crab cavity and chromatic coupling correction. Luminosity gain due to the crab cavity was about 20%, though 2 times gain was expected. Several reasons the luminosity degradation is discussed. They are X-y coupling and their chromatic aberration, fast beam noise, aperture related to dynamic beta and beam lifetime, bunch lengthening, and wake effect for the tilt beam. The very high luminosity area has narrow structure in several kind of the parameter scan. The luminosity is obtained by a kind of singular property for the operating point very close to the half integer, so called literally cutting-edge. It may be necessary to overcome further difficulties.

Some regret points, large horizontal beta, one crab cavity per ring etc., remained, though they may not be essential obstacles to achieve the target luminosity.

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