Beam-Beam Performance and Luminosity Optimization at KEKB

Y. Funakoshi (KEK)

(1) Present Status of KEKB

(2) Beam-Beam Tuning and observation of Beam-Beam Phenomena

(3) Simulations on Beam-Beam Effect

(4) Luminosity Optimization

Luminosity Formula

$$L \cong \frac{\gamma}{2er_e} \frac{I_{total}\xi_y}{\beta_y^*}$$

-->

$$L[10^{34} / cm^2 / sec] \cong 2.17 \times \frac{E[GeV] \times I[A] \times \xi_y}{\beta_y^*[cm]}$$

KEKB Design Parameters:

	LER	HER
E[GeV]	3.5	8.0
I[A]	2.6	1.1
ξ_y	0.05	0.05
β_y[cm]	1.0	1.0
L [10^{34}/cm^2/sec]	1.0	

Comparison of KEKB Design Parameters with achieved ones

	LER	HER
E[GeV]	3.5 3.5	8.0 8.0
I[A]	0.425 2.6	0.28 1.1
ξ_y	0.020(0.031) 0.05	0.008(0.013) 0.05
β_y[cm]	1.0 1.0	1.0 1.0
L [10^{34}/cm^2/sec]	0.073 1.0	

Present Luminosity Limitation of KEKB

(1) LER single beam blow-up

(2) Heating of movable masks for suppressing Belle background

(3) Beam blow-up due to the beam-beam effect

(4) Beam current limitation from the instabilities of the LER and HER

(5) Belle beam background

Strategy for Better Beam-Beam Performance

(1) Machine Error Detection and Correction
-> IP Beam Diagnostics and Corrections

(2) Tune Survey

IP Beam Diagnostics and Corrections

(1) IP Orbit Offset

(2) Crossing Angle

(3) Waist

(4) IP x-y Coupling

(5) IP Dispersion

(6) Others
chromatic beta ...

IP Orbit Offset

(1) Method of Measurement

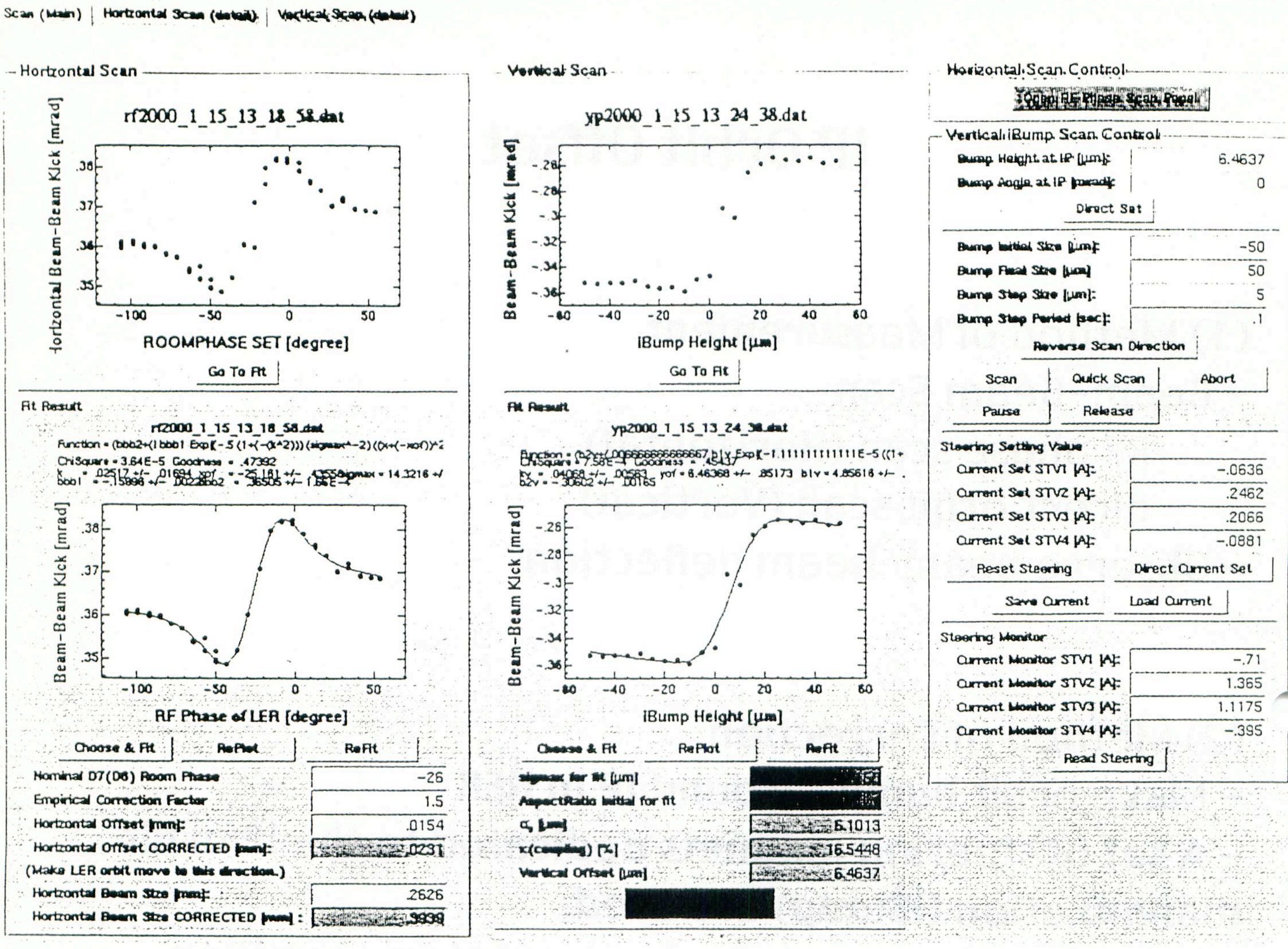
- Beam-Beam Scan
  - RF phase scan (Horizontal)
  - direct orbit scan (Vertical)
- Observe beam-beam deflection

(2) Method of Correction

- Make orbit bumps around IP in HER
- A set of steering magnets dedicated to the IP orbit manipulation (iBump) are used.
- Four iBump magnets for horizontal and another four for vertical

(3) Method of Maintaining the optimum condition

- iBump Feedback
- Target values for the feedback :
  - Difference of beam-beam kick for electrons and positrons


Scan (Main) | Horizontal Scan (detail) | Vertical Scan (detail)
Horizontal Scan
rf2000_1_15_13_18_58.dat
Horizontal Beam-Beam Kick [mrad]
ROOMPHASE SET [degree]
Go To Fit
Fit Result
rf2000_1_15_13_18_58.dat
ChiSquare = 3.64E-5 Goodness = .47392
Beam-Beam Kick [mrad]
RF Phase of LER [degree]
Choose & Fit
RePlot
ReFit
Nominal D7(D6) Room Phase -26
Empirical Correction Factor 1.5
Horizontal Offset [mm]: .0154
Horizontal Offset CORRECTED [mm]: .0231
(Make LER orbit move to this direction.)
Horizontal Beam Size [mm]: .2626
Horizontal Beam Size CORRECTED [mm]: .3939
Vertical Scan
yp2000_1_15_13_24_38.dat
Beam-Beam Kick [mrad]
IBump Height [μm]
Go To Fit
Fit Result
yp2000_1_15_13_24_38.dat
Beam-Beam Kick [mrad]
IBump Height [μm]
Choose & Fit
RePlot
ReFit
sigmax for fit [μm]
AspectRatio initial for fit
σy [μm] 6.1013
κ(coupling) [%] 16.5448
Vertical Offset [μm] 6.4637
Horizontal Scan Control
Open RF Phase Scan Panel
Vertical IBump Scan Control
Bump Height at IP [μm]: 6.4637
Bump Angle at IP [mrad]: 0
Direct Set
Bump Initial Size [μm]: -50
Bump Final Size [μm] 50
Bump Step Size [μm]: 5
Bump Step Period [sec]: .1
Reverse Scan Direction
Scan
Quick Scan
Abort
Pause
Release
Steering Setting Value
Current Set STV1 [A]: -.0636
Current Set STV2 [A]: .2462
Current Set STV3 [A]: .2066
Current Set STV4 [A]: -.0881
Reset Steering
Direct Current Set
Save Current
Load Current
Steering Monitor
Current Monitor STV1 [A]: -.71
Current Monitor STV2 [A]: 1.365
Current Monitor STV3 [A]: 1.1175
Current Monitor STV4 [A]: -.395
Read Steering

Crossing Angle

(1) Method of Measurement
- Horizontal (RF Phase) Beam-Beam Scan
- Observe beam-beam deflection in the vertical direction
- An asymmetric pattern of the deflection curve indicates the crossing angle.

(2) Method of Correction
- Make asymmetric orbit bumps around IP

(3) Method of Maintaining the optimum condition
- Continuous Closed Orbit Correction (CCC)
- iBump Feedback for HER

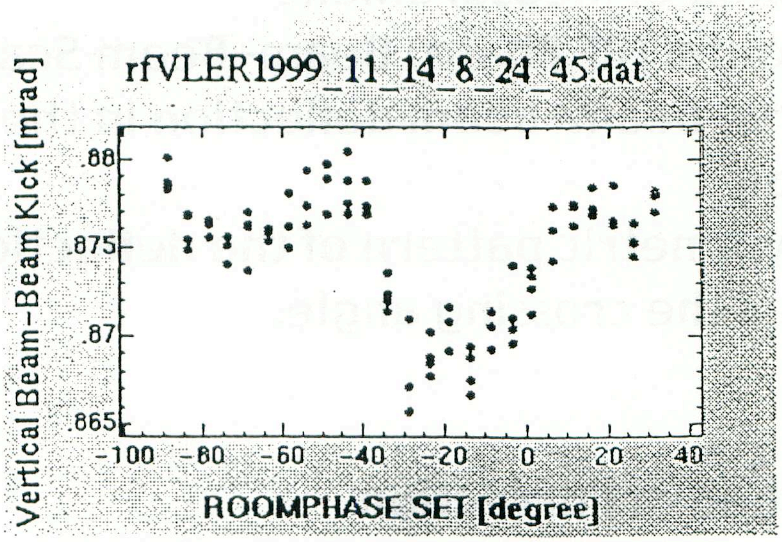


Figure 3: A typical vertical deflection curve in the horizontal scan with a large crossing angle.

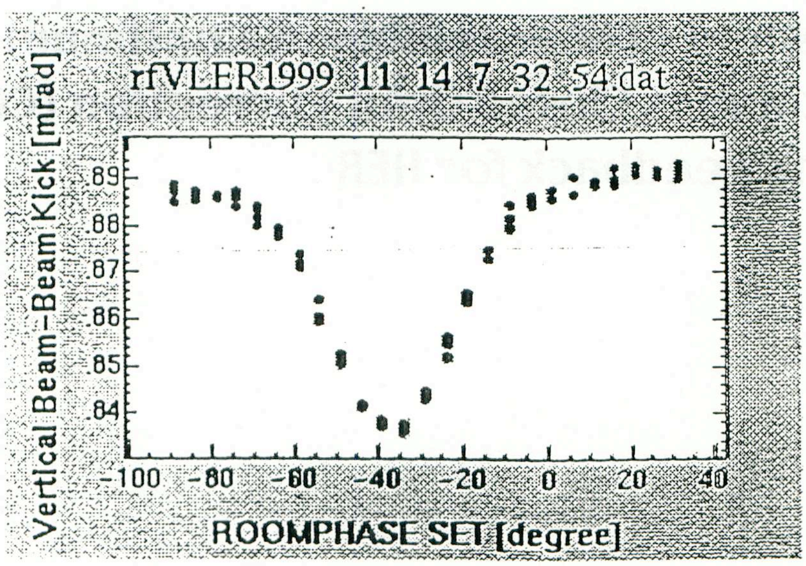


Figure 4: A typical vertical deflection curve in the horizontal scan with a large vertical offset.

Waist of beta function

(1) Method of Measurement
- Waist Scan by changing strength of quadrupole magnets around IP
- Observe luminosity and beam sizes

(2) Method of Correction
- Change strength of quadrupole magnets around IP

(3) Method of Maintaining the optimum condition
- no feedback
- After some optics change, we need to scan again.

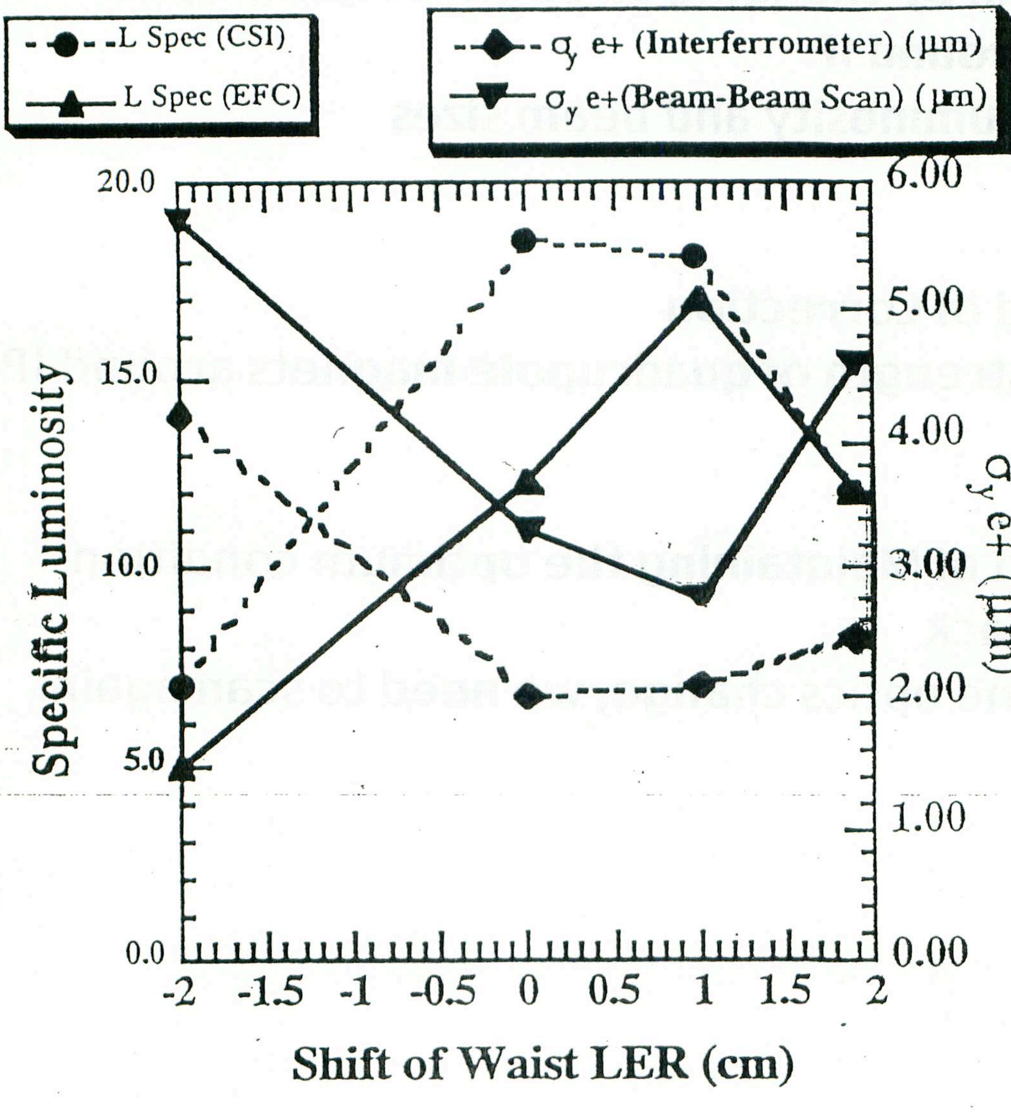


Figure 5: A typical result of LER waist scan.

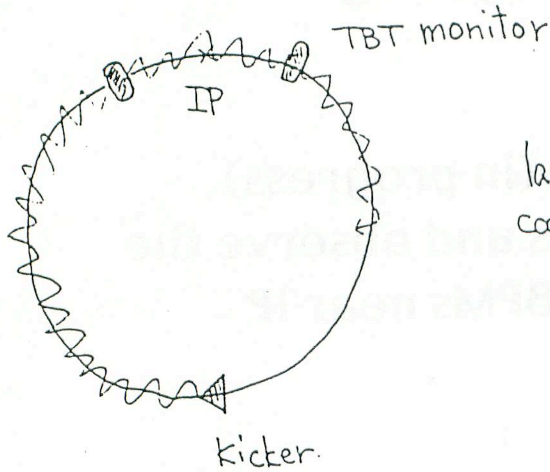
IP x-y Coupling

(1) Method of Measurement (in progress)
- Excite betatron oscillations and observe the oscillations with single pass BPMs near IP

(2) Method of Correction
- Trial and Error Method with an IP x-y coupling tool which uses skew quadruple magnets

(3) Method of Maintaining the optimum condition
- no feedback

XY Coupling measurement



lab. coordinate $\quad$ normal coordinate

$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} = \begin{pmatrix} \mu & 0 & r_4 & -r_2 \\ 0 & \mu & -r_3 & r_1 \\ -r_1 & -r_2 & \mu & 0 \\ -r_3 & -r_4 & 0 & \mu \end{pmatrix} \begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix}$$

IP Dispersion

(1) Method of Measurement
- Conventional method of measuring orbit difference with different RF frequencies
- Resolution of the measurement is around 0.5 mm at the IP.

(2) Method of Correction
- Global dispersion correction by making orbit bumps at sextuple magnets

(3) Method of Maintaining the optimum condition
- no feedback
- Continuous Closed orbit Correction (CCC) system contributes to stabilization of the IP dispersion.

ıissioning, we have tried lots
of the tunes is estimated from
efficiency, beam instabilities
. In Figs. 6 and 7, we show
in the LER. HER tunes were
of the LER. In the early days
rings were operated with hor-
integer as is seen in Fig. 6.
nean tunes which gave a bad
re some beam loss occurred,
g up the collision with nom-
ie with a circle symbol gave
erformance. The tune with a
ely good beam-beam perfor-
beam into the HER with this
ıd that beam injection perfor-
y optics corrections in many
performance imposes almost
of betatron tunes now. Al-
e the half integer give better
e beam-beam simulations, we
integer at that time. This was
beam currents with tunes be-
could above it where we were
ties. Subsequently, we found
k systems and relatively large
ppress the instabilities.
unes above the half integer.
ions as shown in Fig. 7 where
predict good beam-beam per-
ions, the best luminosity so
where the beam-beam simu-
The design tunes are located
aking, the beam-beam simu-
vations. However, the tunes
eam performance are not ex-
ldition, we found that a very
003 for example, can make a
osity, by 30% for example in

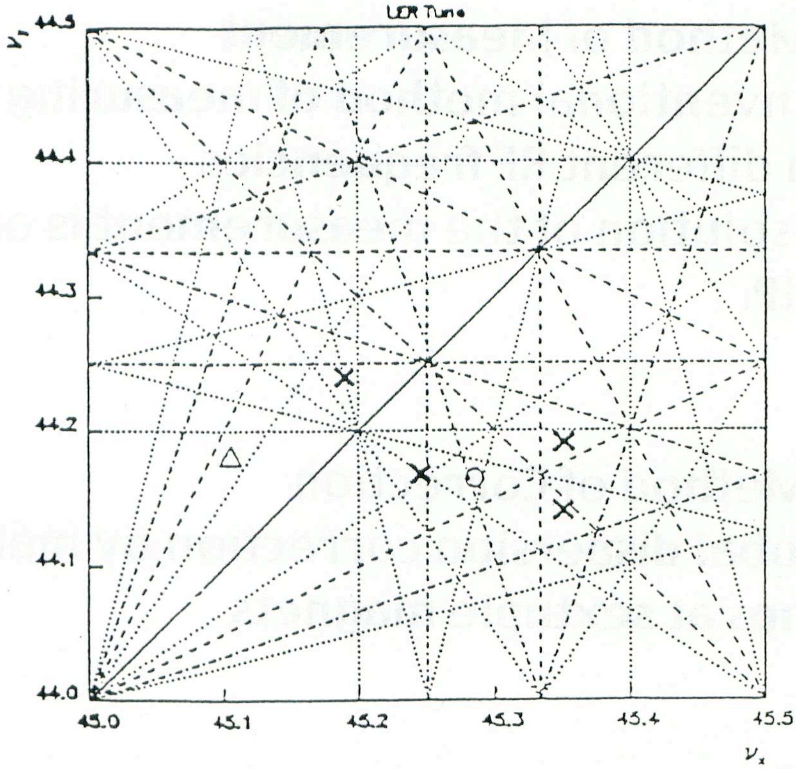


Figure 6: History of tune survey of the LER : the horizontal tunes are below the half integer resonance.

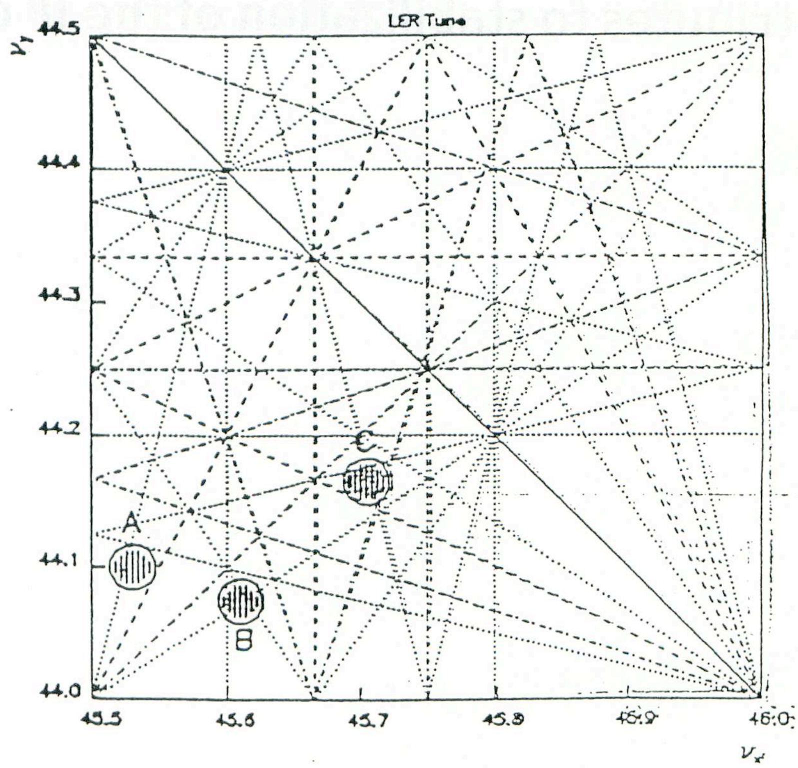


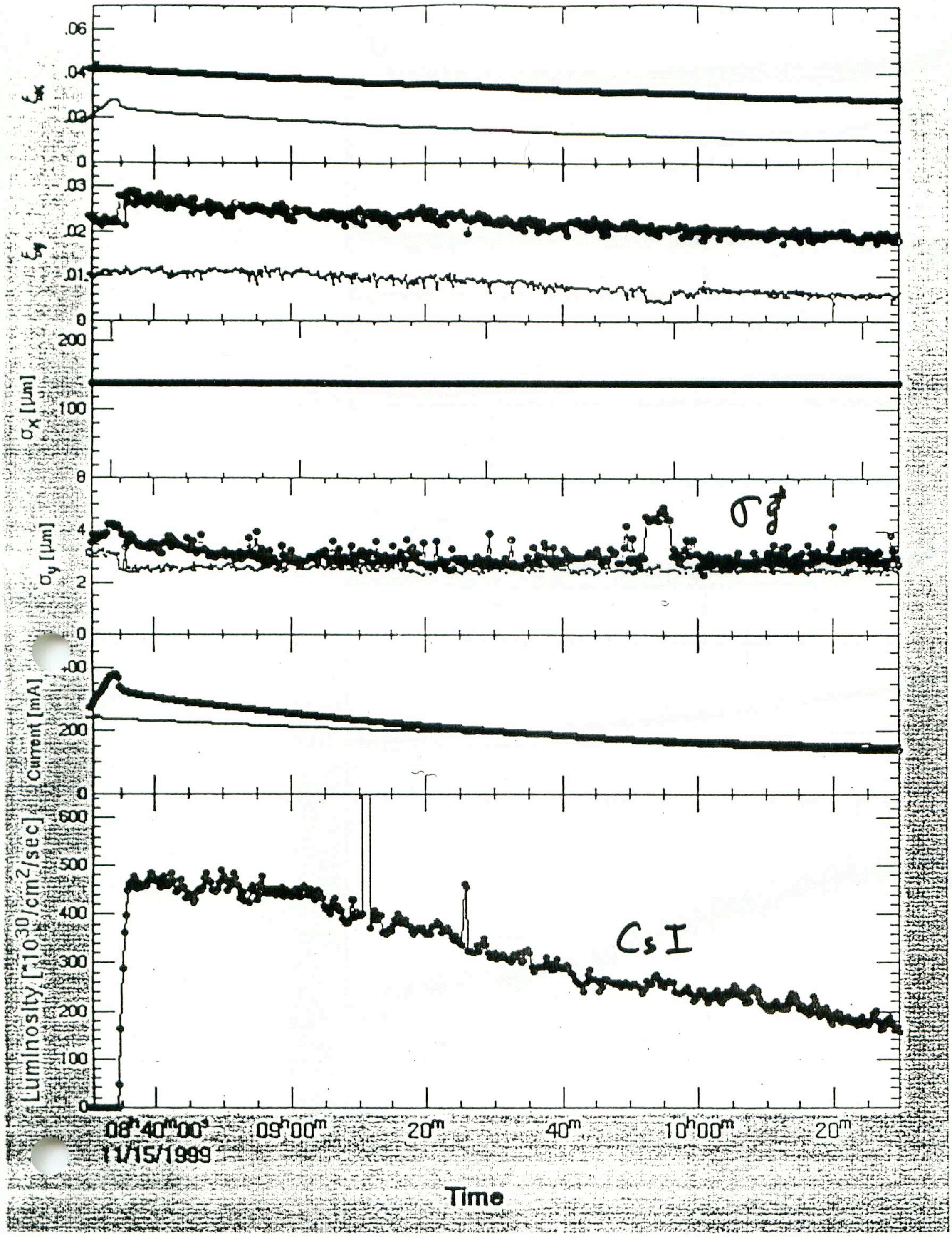
Figure 7: History of tune survey of the LER : the horizontal

Table 1: Machine parameters related to the luminosity in the normal emittance optics.

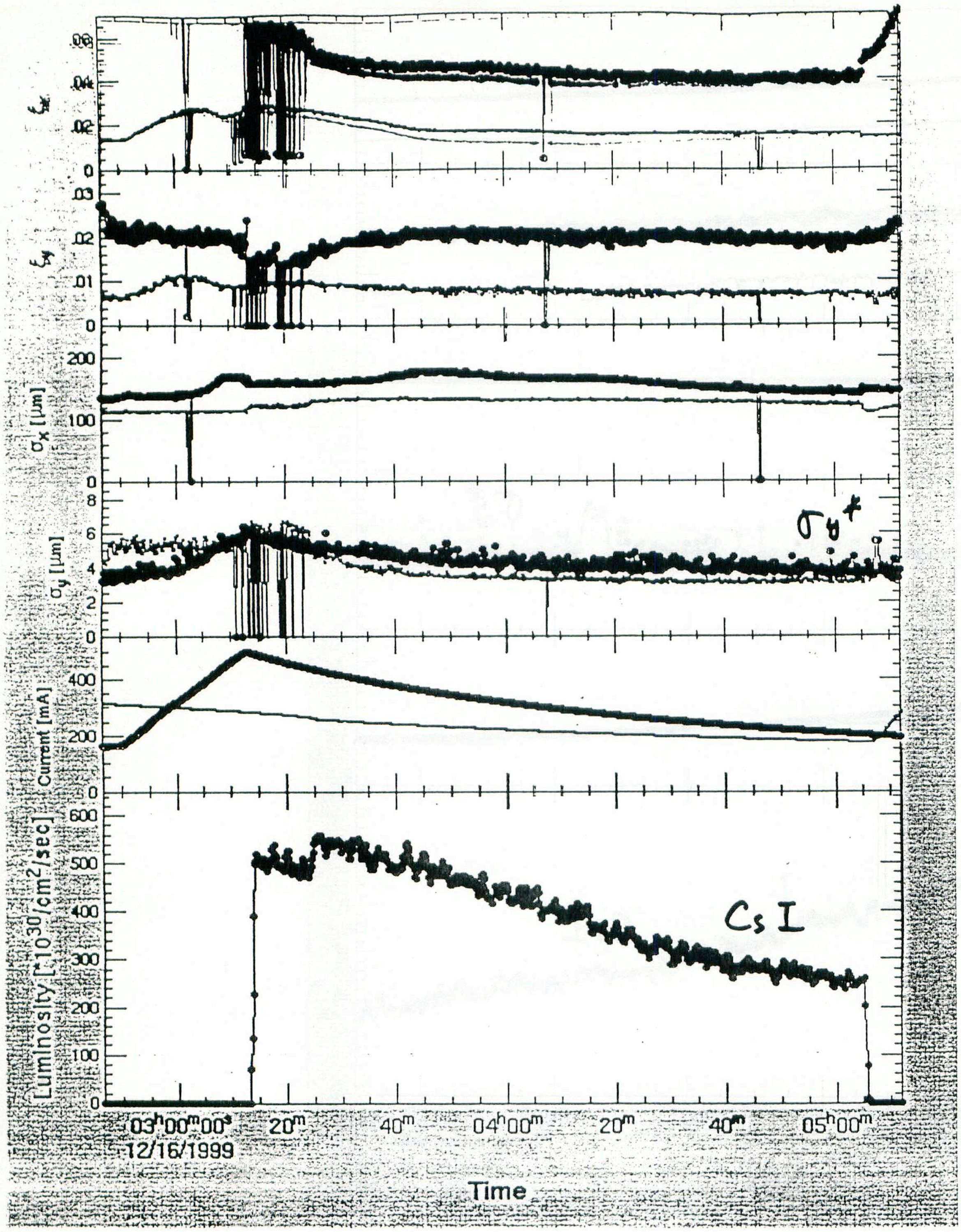
	LER	HER	
Hor. Emittance	17	18	nm
β_x^*/β_y^*	1/0.01 (0.33/0.010)		m
Beam Current	270 (2600)	220 (1100)	mA
Bunches	872 (5000)	872 (5000)	
Bunch Current	0.30 (0.52)	0.25 (0.22)	mA
Trains	8	8	
Bunches/train	120	120	
σ_x^*/σ_y^*	140/2.8	140/2.2	
Emitt. Ratio $\varepsilon_y/\varepsilon_x$	4.0 (1.0)	2.5 (1.0)	%
Bunch Length (calculation)	4.8@9.0	3.4@5.0	mm@MV
ξ_x	0.039 (0.039)	0.021 (0.039)	
ξ_y	0.030 (0.052)	0.012 (0.052)	
ν_x	45.584 (45.52)	44.549 (44.52)	
ν_y	44.123 (44.08)	42.153 (42.08)	
Lifetime	130@300	280@240	mim@mA
Luminosity from above parameters	5.1×10^{32}		/cm^2/sec
Luminosity Belle CsI	~~5.2~~ $\times 10^{32}$ (1.0×10^{34}) 5.9		/cm^2/sec

Table 2: Machine parameters related to the luminosity with the high emittance optics.

	LER	HER	
Hor. Emittance	30	30	nm
β_x^*/β_y^*	1/0.01 (0.33/0.010)		m
Beam Current	430 (2600)	270 (1100)	mA
Bunches	841 (2833)	841 (2833)	
Bunch Current	0.51 (0.87)	0.32 (0.37)	mA
Trains	32	32	
Bunches/train	29	29	
σ_x^*/σ_y^*	170/4.6	140/3.6	
Emitt. Ratio $\varepsilon_y/\varepsilon_x$	7.3 (1.0)	6.6 (1.0)	%
Bunch Length (calculation)	6.4@9.0	5.2@5.0	mm@MV
ξ_x	0.049 (0.039)	0.023 (0.039)	
ξ_y	0.023 (0.052)	0.010 (0.052)	
ν_x	45.526 (45.52)	44.537 (44.52)	
ν_y	44.131 (44.08)	42.114 (42.08)	
Lifetime	100@450	250@300	mim@mA
Luminosity from above parameters	5.7×10^{32}		$/cm^2/sec$
Luminosity Belle CsI	~~5.0~~ 6.7 $\times 10^{32}$ (1.0×10^{34})		$/cm^2/sec$

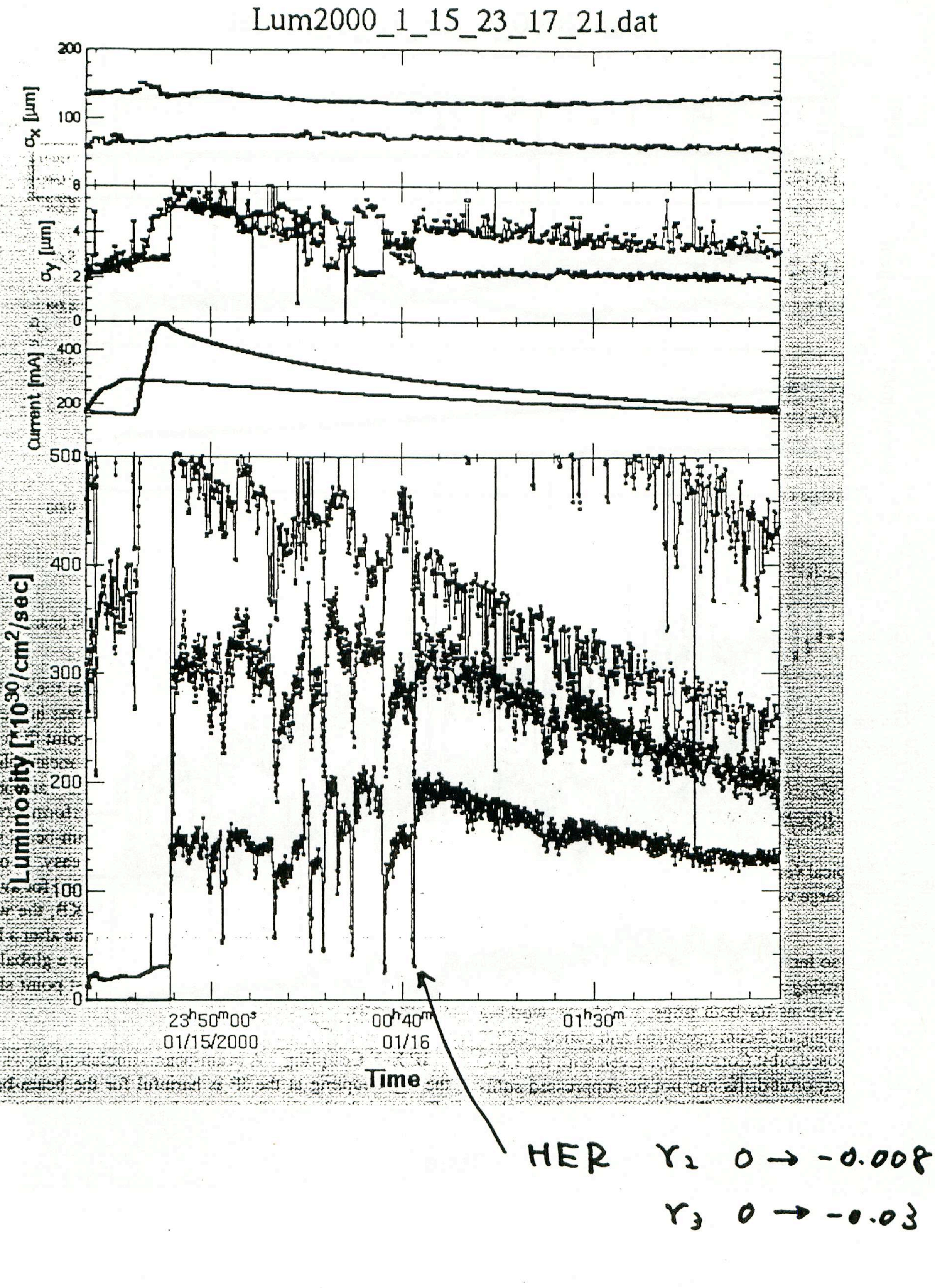


Normal Emittance Nov. 15/1999

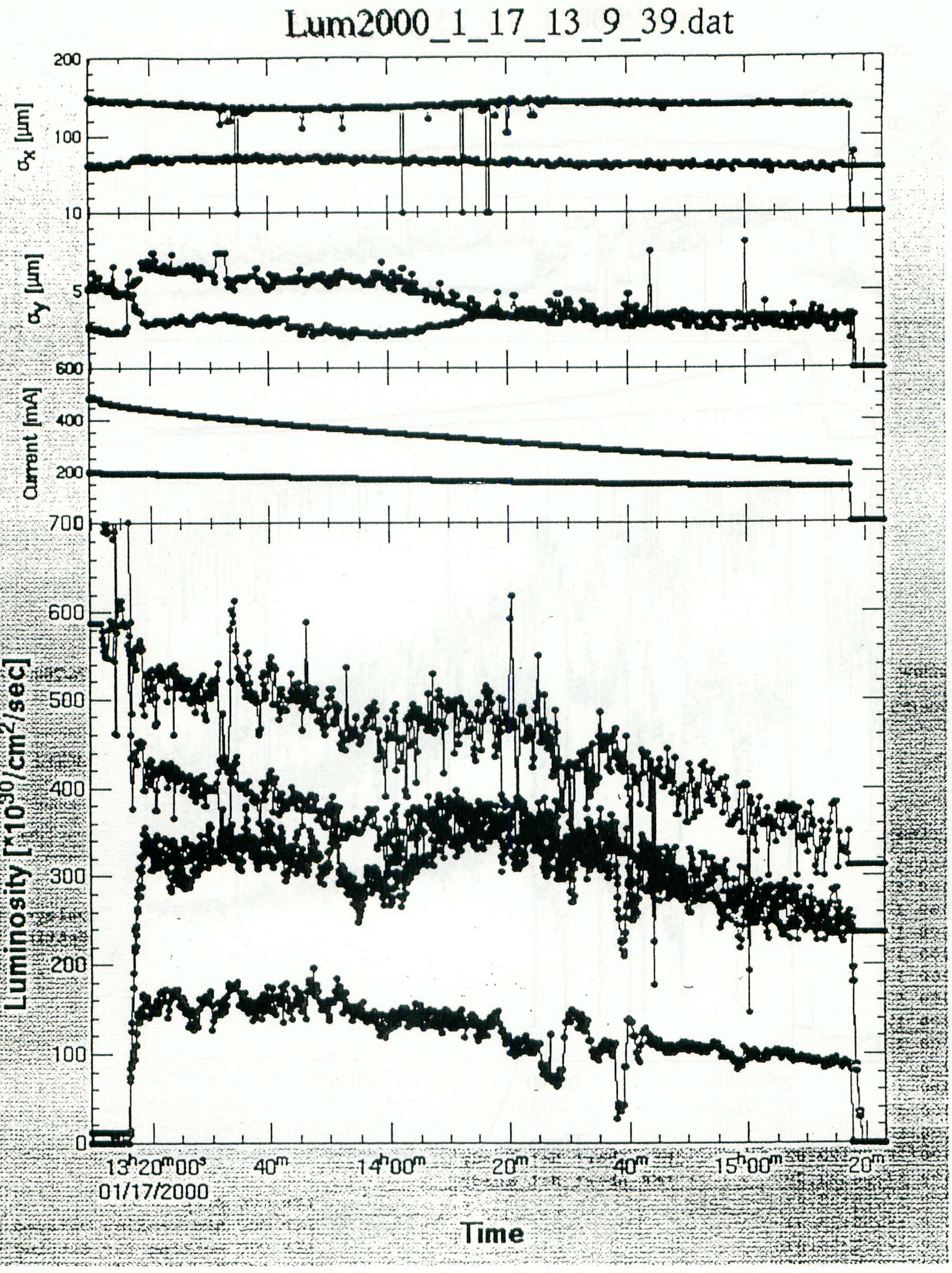


High Emittance Dec. 16 / 1999

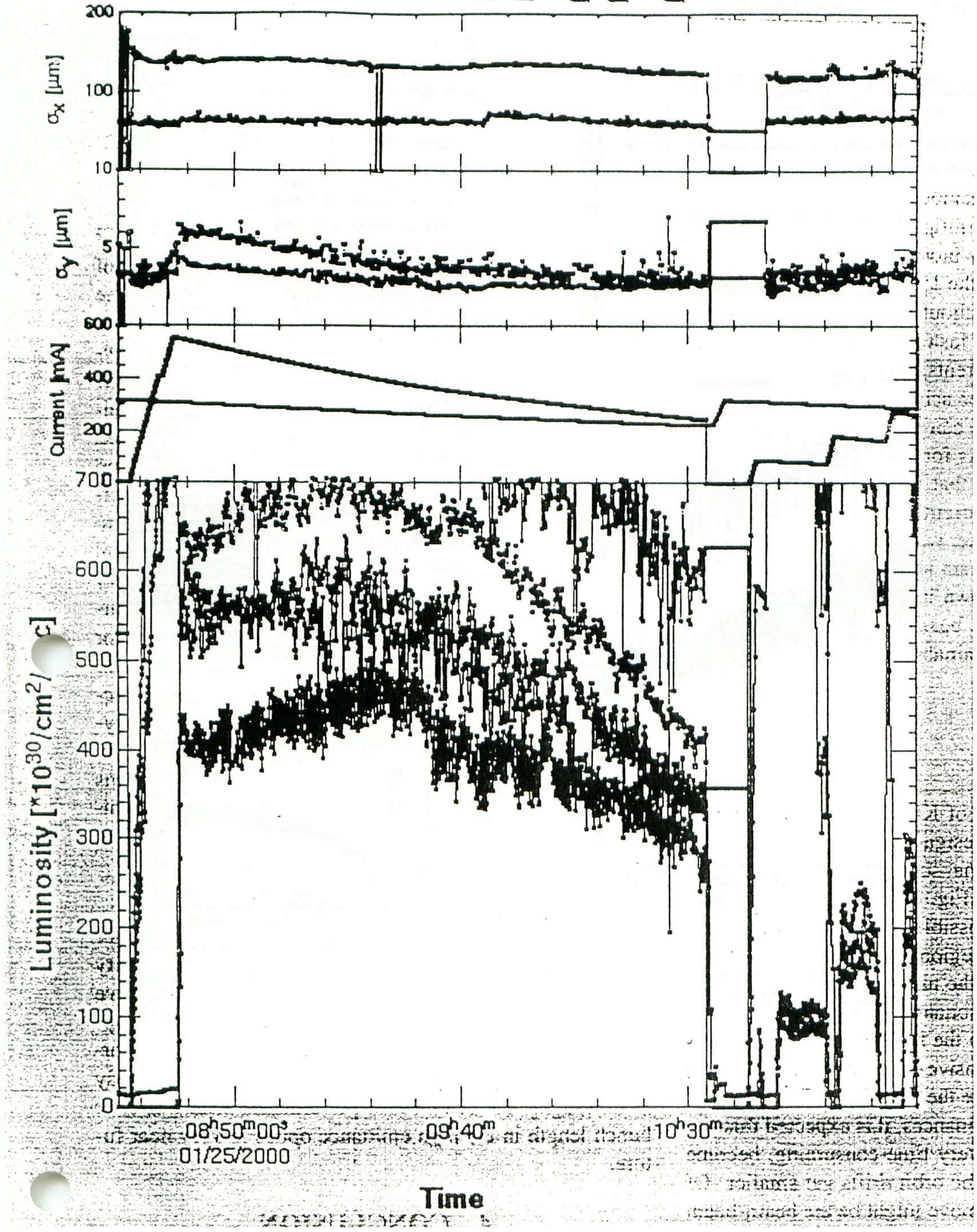
Luminosity History



Luminosity History



Lum2000_1_25_8_25_1.dat

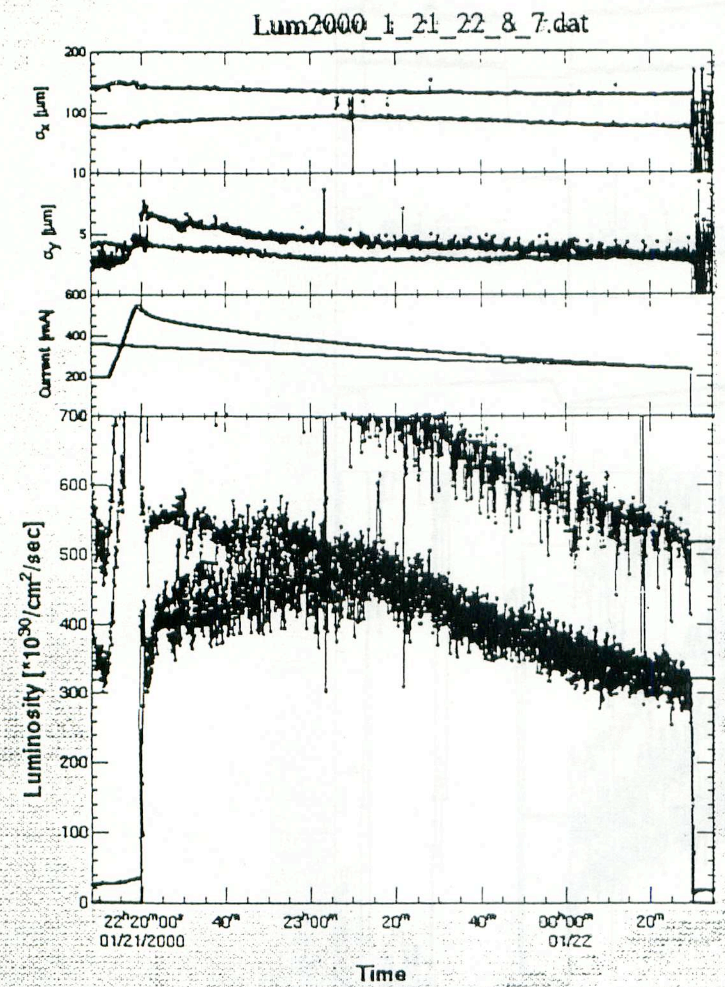


LER $\begin{cases} r_2 \quad 0 \rightarrow 0.002 \\ r_3 \quad 0 \rightarrow -0.002 \end{cases}$

File Edit Window 01/22/2000 00:34:19 Help

Beam Parameters Summary | Beam Beam Scan | Luminosity History | Feedback Display

Luminosity History

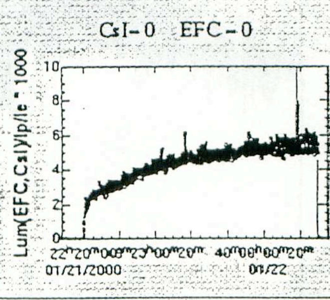


Luminosity

σ_x^* [m] (for Calculation)	1.7E-4
σ_x^* [µm] (LER)	106.2947
σ_x^* [µm] (HER)	88.9526
σ_y^* [µm] (LER)	8.1653
σ_y^* [µm] (HER)	5.3332
Total Beam Current (HER) [mA]	.0344
Total Beam Current (LER) [mA]	-.0335
Number of Bunches	721
Av. Bunch Current (HER) [mA]	4.77115E-5
Av. Bunch Current (LER) [mA]	-4.6463E-5
β_x^* [m]	1
β_y^* [m]	.01
κ (coupling) [%]	16.4558
ξ_{x}^* (HER)	-2.7789E-6
ξ_{x}^* (LER)	6.52233E-6
ξ_{y}^* (HER)	-6.8503E-7
ξ_{y}^* (LER)	1.60784E-6
Luminosity (Acc with σ_x(design))	-4.2533E24
Luminosity (Acc with σ_x(meas))	-7.3776E24
Luminosity (CsI)	-1E28
Luminosity (EFC)	-1E28

Start | Stop | Read

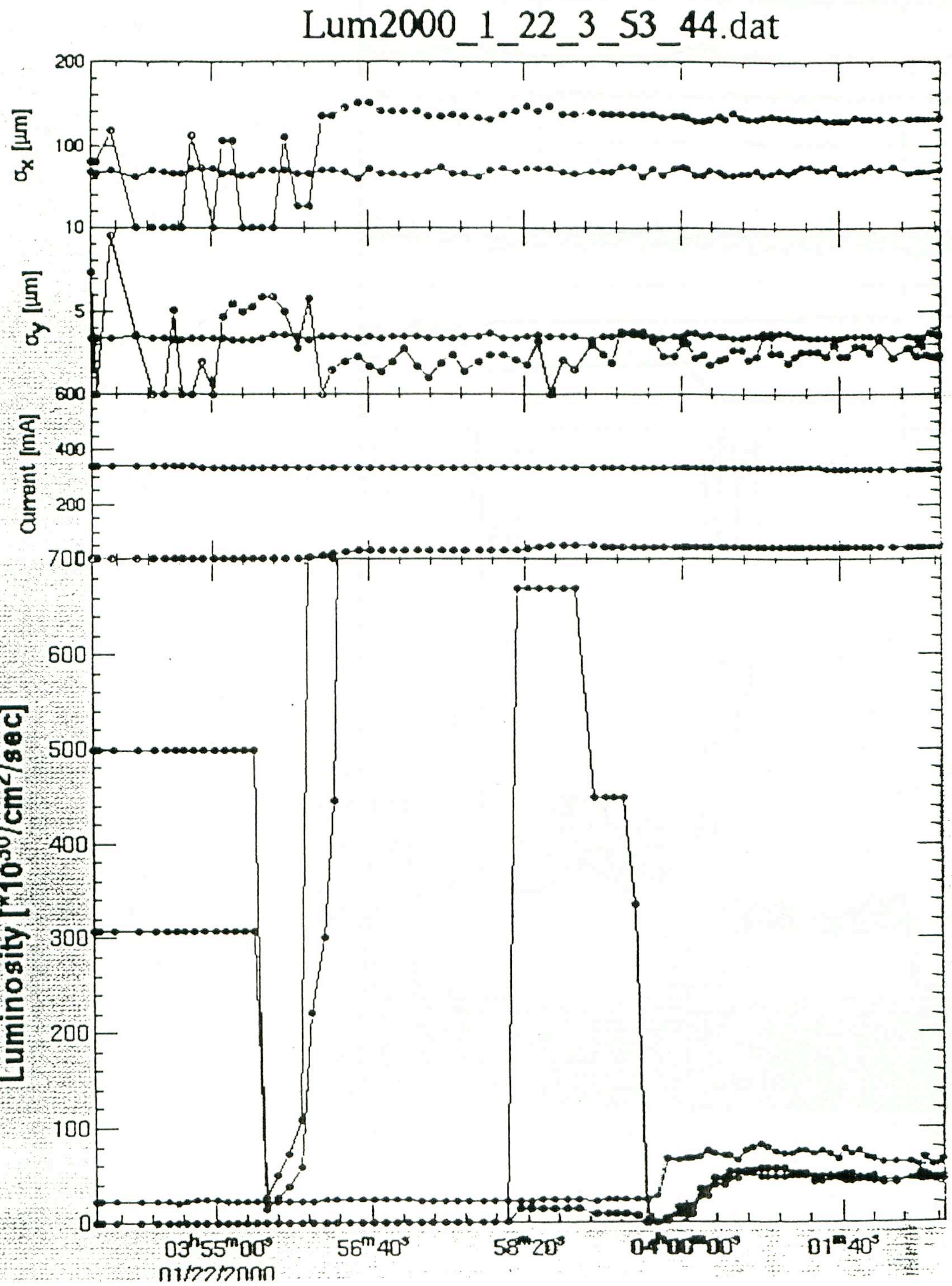
Specific Luminosity



Main Application Area

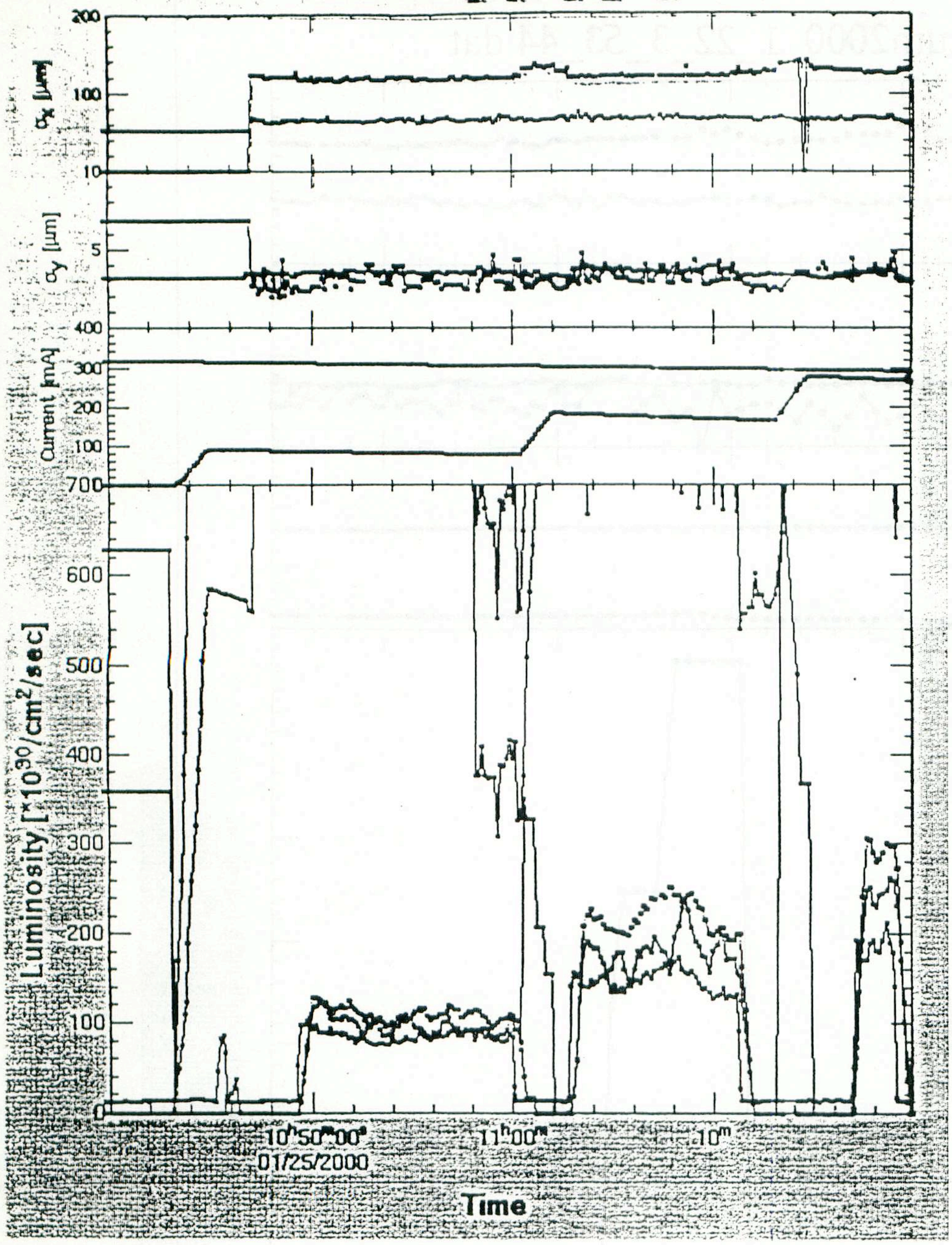
32/36 /4

Luminosity History



32/6/4

Lum2000_1_25_8_25_1.dat



Record Peak Luminosity

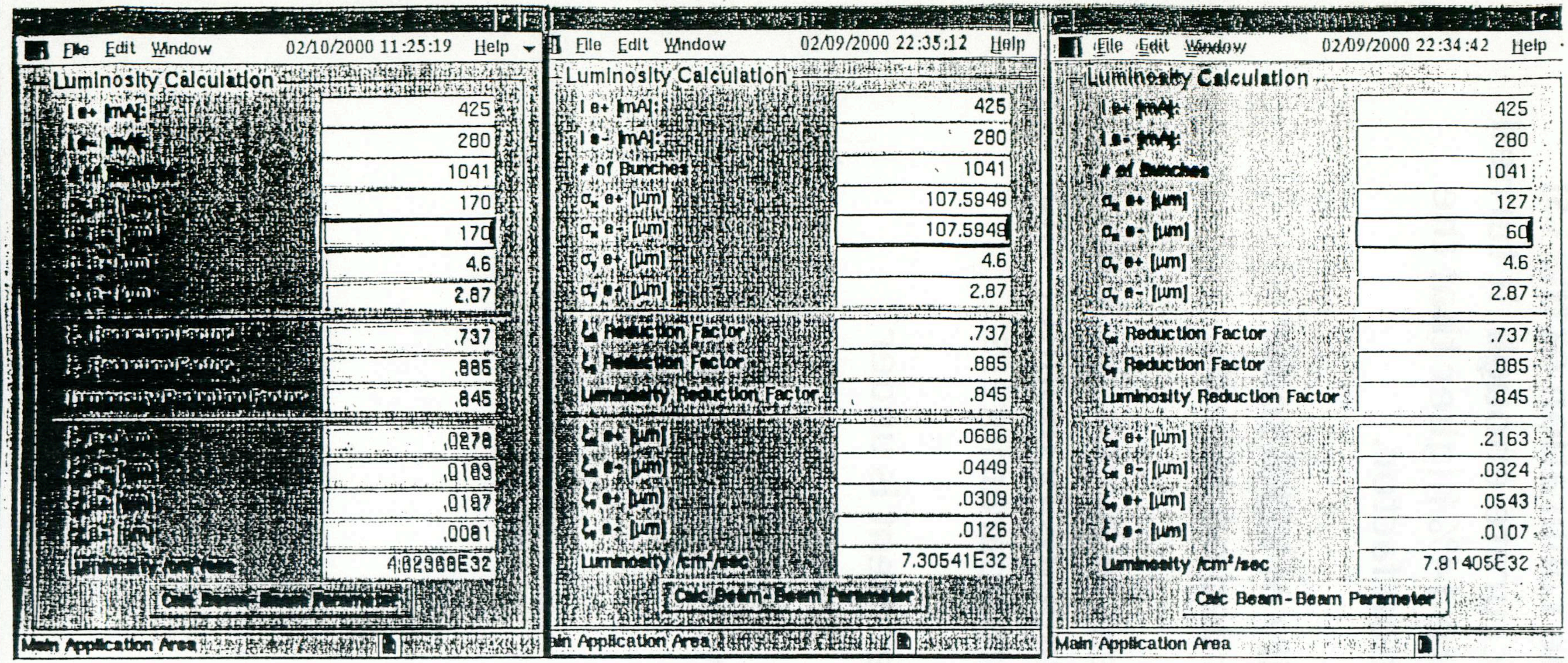
- Recently we found that the calibration of the CsI luminosity monitor is not accurate enough. It turned out that real luminosities are 14% higher that the values with the old calibration factor.

- The record peak luminosity of KEKB so far is 7.3 *10^32/cm^2/sec recorded on Jan. 25.

- There is a big disagreement between measured luminosities using the CsI luminosity monitor and calculations from accelerator parameters.

- The reason for this disageement is under investigateion.

- If based on the luminosity, we have rather higher beam-beam parameters.


File Edit Window 02/10/2000 11:25:19 Help
Luminosity Calculation
425
280
1041
170
170
4.6
2.87
.737
.885
.845
.0278
.0183
.0187
.0081
4.02968E32
File Edit Window 02/09/2000 22:35:12 Help
Luminosity Calculation
I e+ [mA]: 425
I e- [mA]: 280
# of Bunches 1041
σx e+ [μm] 107.5949
σx e- [μm] 107.5949
σy e+ [μm] 4.6
σy e- [μm] 2.87
ξx Reduction Factor .737
ξy Reduction Factor .885
Luminosity Reduction Factor .845
ξx e+ [μm] .0686
ξx e- [μm] .0449
ξy e+ [μm] .0309
ξy e- [μm] .0126
Luminosity /cm²/sec 7.30541E32
Calc Beam-Beam Parameter
Main Application Area
File Edit Window 02/09/2000 22:34:42 Help
Luminosity Calculation
I e+ [mA]: 425
I e- [mA]: 280
# of Bunches 1041
σx e+ [μm] 127
σx e- [μm] 60
σy e+ [μm] 4.6
σy e- [μm] 2.87
ξx Reduction Factor .737
ξy Reduction Factor .885
Luminosity Reduction Factor .845
ξx e+ [μm] .2163
ξx e- [μm] .0324
ξy e+ [μm] .0543
ξy e- [μm] .0107
Luminosity /cm²/sec 7.81405E32
Calc Beam-Beam Parameter
Main Application Area

Collision with Fewer Bunches

- Compared Beam-Beam Performance with 2 different number of bunches : 32/36/4 (1041 buches/beam) and 32/6/4 (174 bunches/beam)

- The two cases showed a completely different performance.

- In the case of 1041 bunches, a severe beam blow-up was observed at LER in some situation on setting up the collision.

- In the case of 174 bunches, almost no beam blow-up was observed in LER.

- We have not yet understood the reason for this big difference.

Beam–Beam Performance Summary

(1) Normal Emittance vs. High Emittance

1) Higher Luminosity with High Emittance
2) Higher Specific Luminosity with Normal Emittance
3) Beam Blow–up (High Emittance) is much improved by x–y coupling tuning

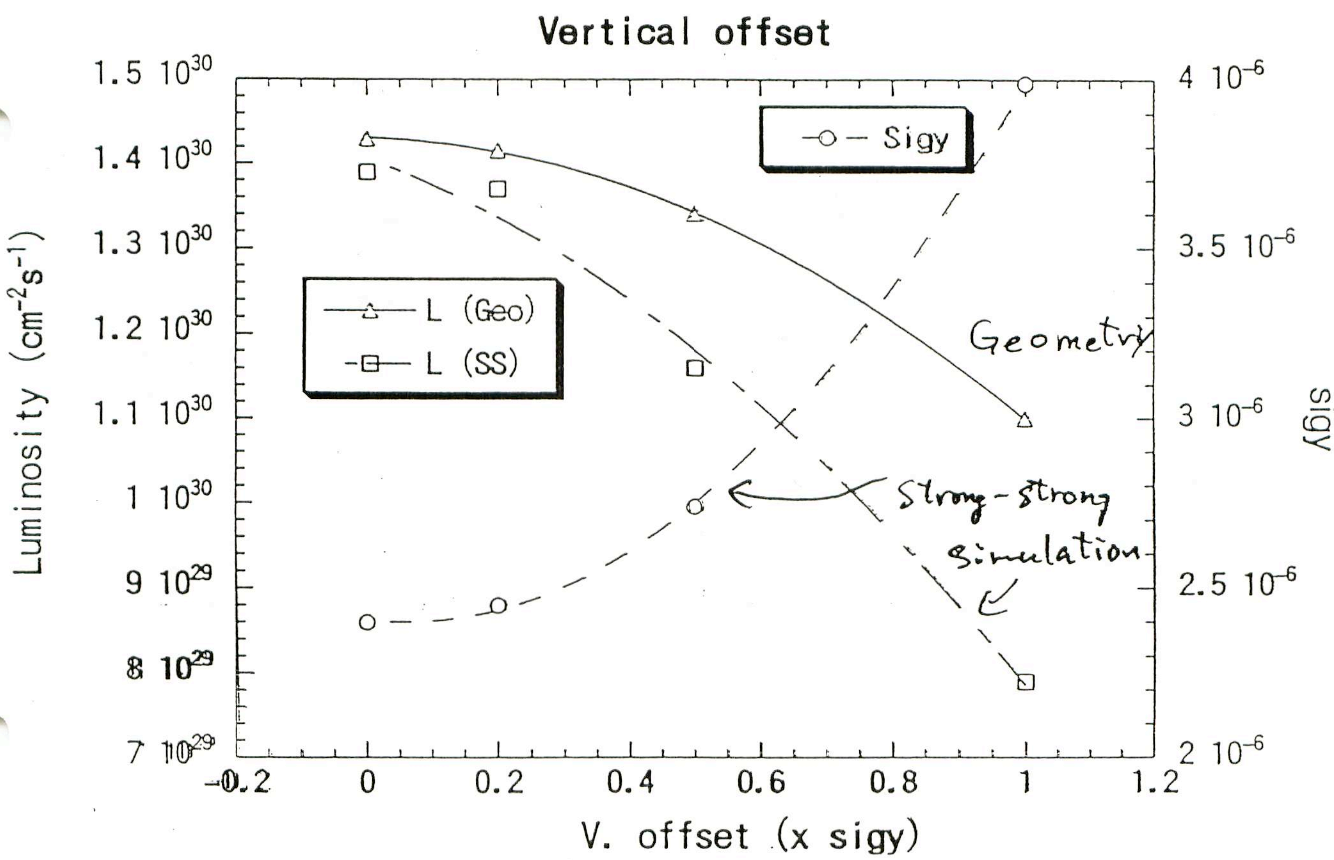
(2) Beam–Beam Parameters ξ_y

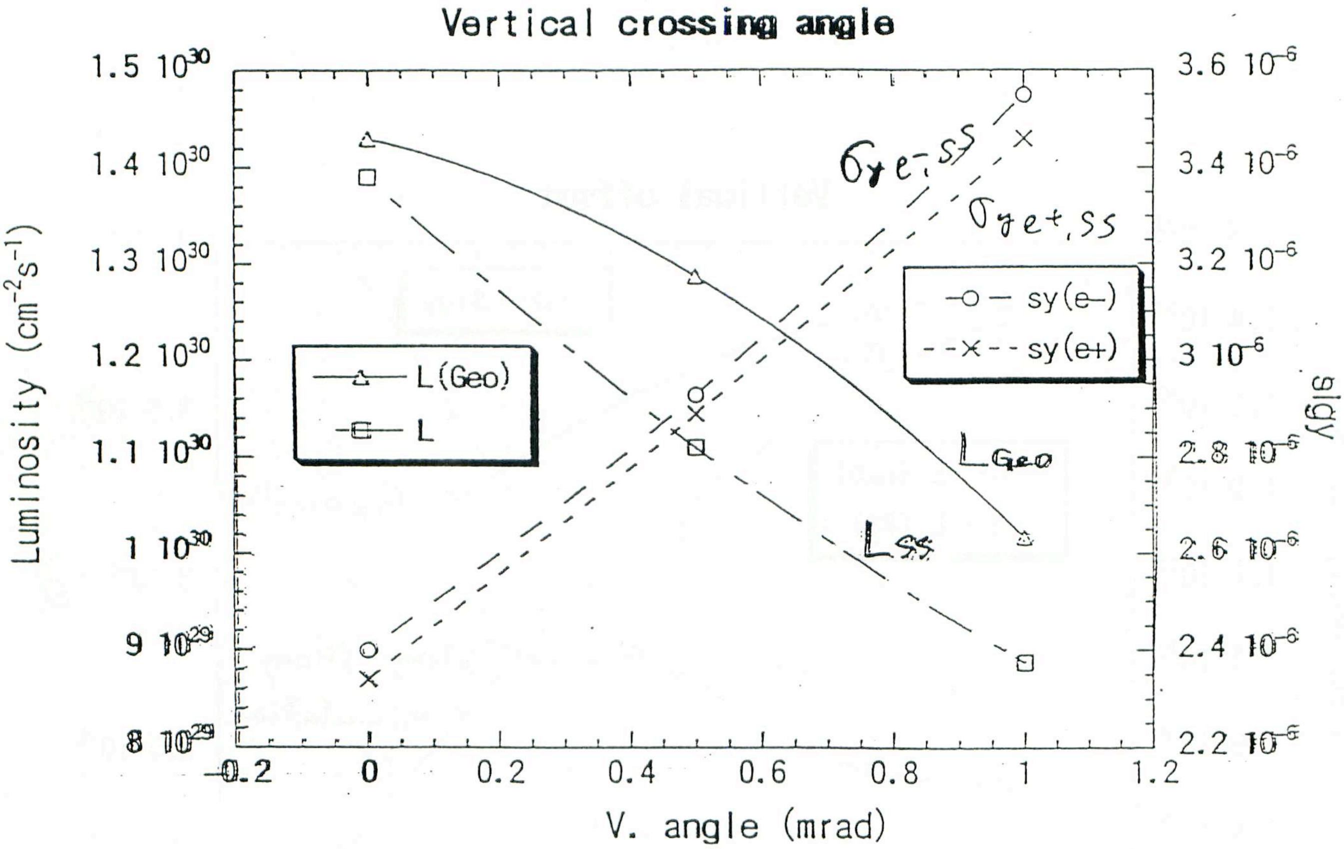
	LER	HER
Normal Emittance	0.030	0.012
High Emittance (Lum. max)	0.020	0.008
High Emittance (Dec. 1999)	0.023	0.010
High Emittance (fewer bunces)	0.019	0.020
PEP II	0.033	0.024

27

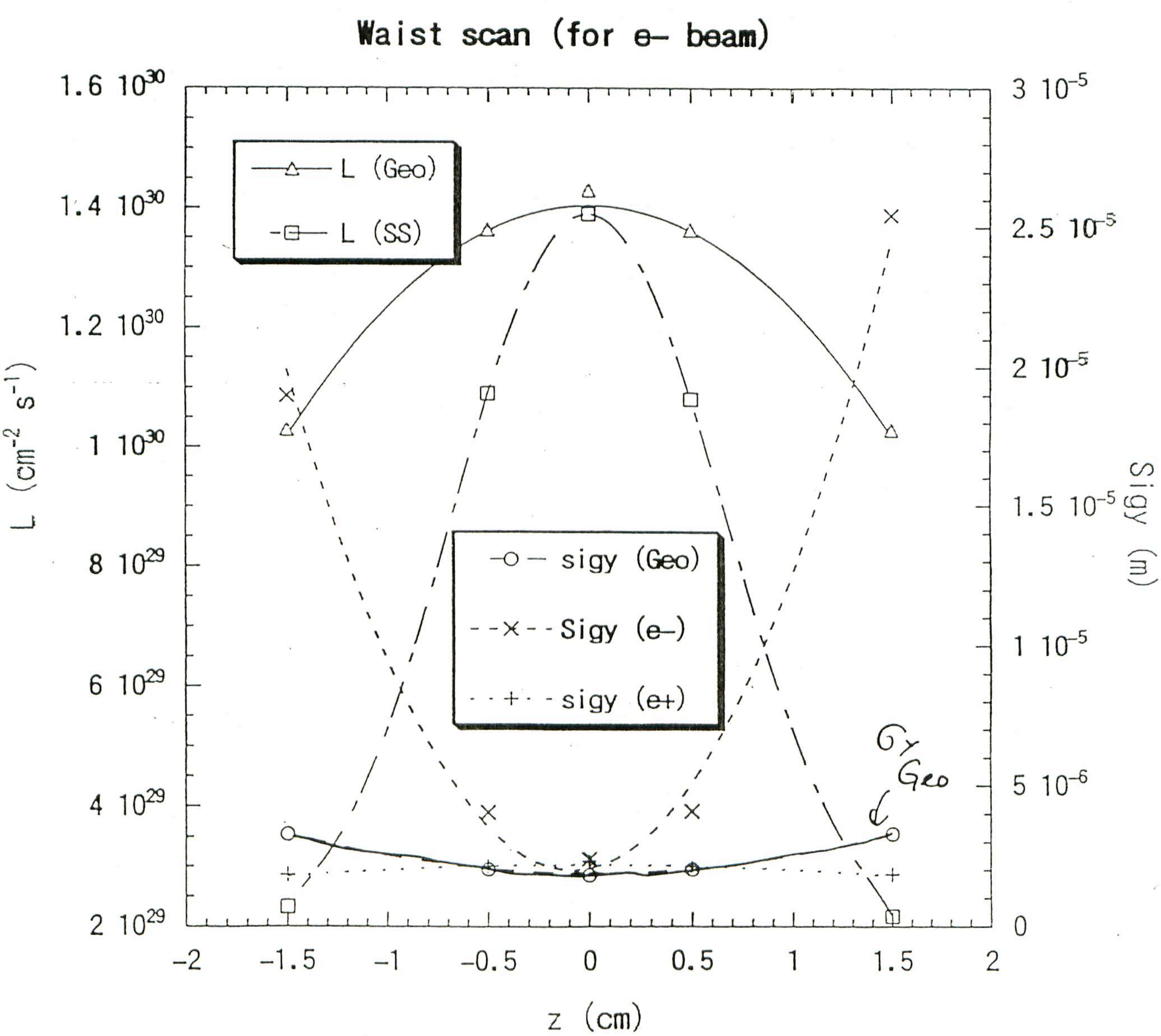
8 Simulation for the luminosity reduction

8.1 Offset collision




Vertical crossing angle
Luminosity (cm^-2s^-1)
sigy
V. angle (mrad)
1.5 10^30
1.4 10^30
1.3 10^30
1.2 10^30
1.1 10^30
1 10^30
9 10^29
8 10^29
3.6 10^-6
3.4 10^-6
3.2 10^-6
3 10^-6
2.8 10^-6
2.6 10^-6
2.4 10^-6
2.2 10^-6
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
L(Geo)
L
sy(e-)
sy(e+)
σy e-,SS
σy e+,SS
LGeo
LSS

8.2 Waist error



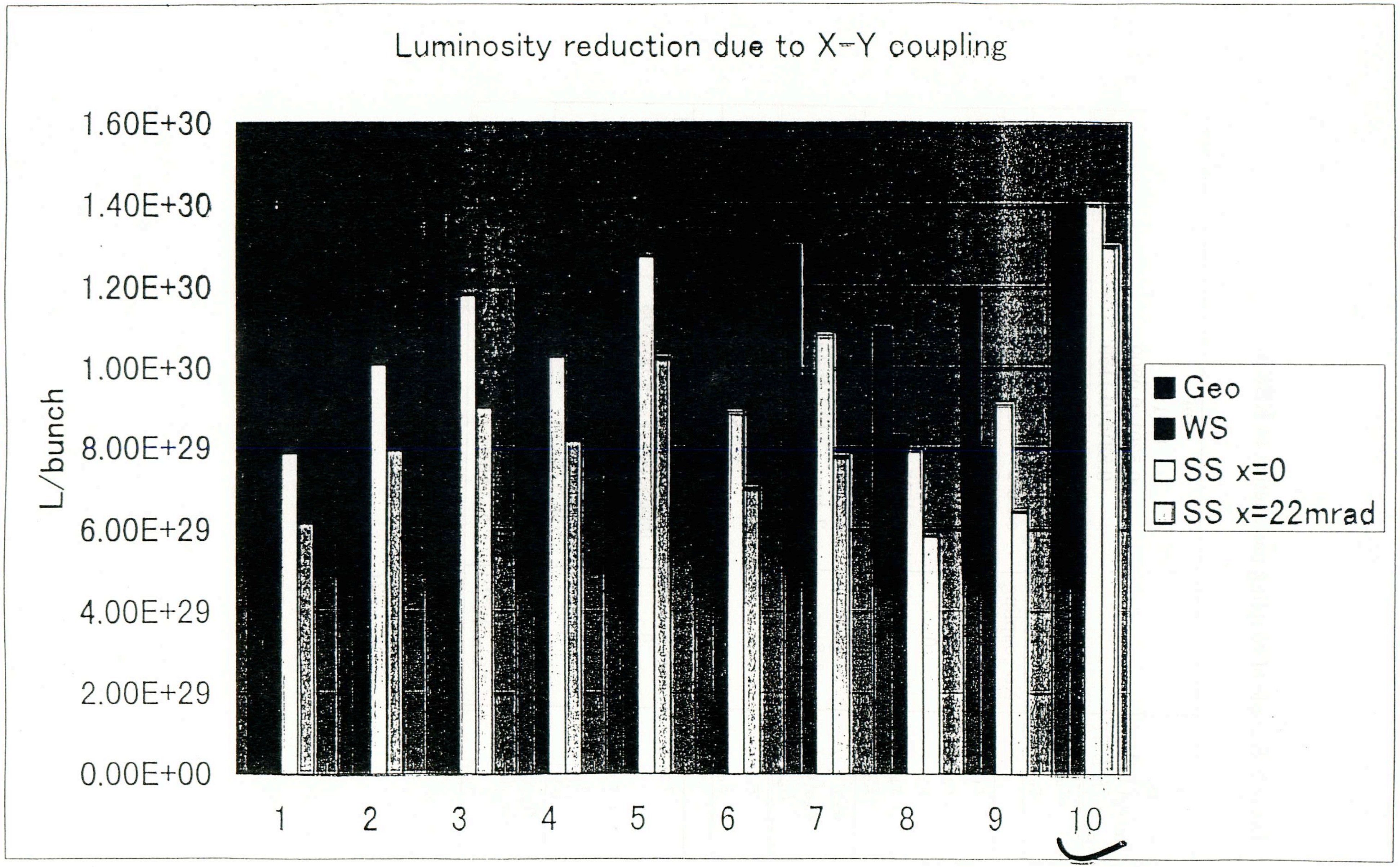
8.3 x-y coupling

Here we make samples of linear lattice with x-y coupling. Some quadrupole magnet on the x-y plane are rotated so as to produce the global coupling around 2%. Table 2 shows the linear lattices. With the same ε_Y, R is different, so σ_y and the geometrical luminosity L_{Geo} is different each other.

We show the results of the strong-strong simulation. The luminosity without the x-y coupling was almost the same as geometrical one. while those with x-y coupling in some examples were extremely reduced. Final luminosity depends on how we put the coupling. Not only σ_y but also σ_x of positron beam blow up, while those of electron beam do not blow up.

Table 3: Sample of coupling parameters at KEKB.

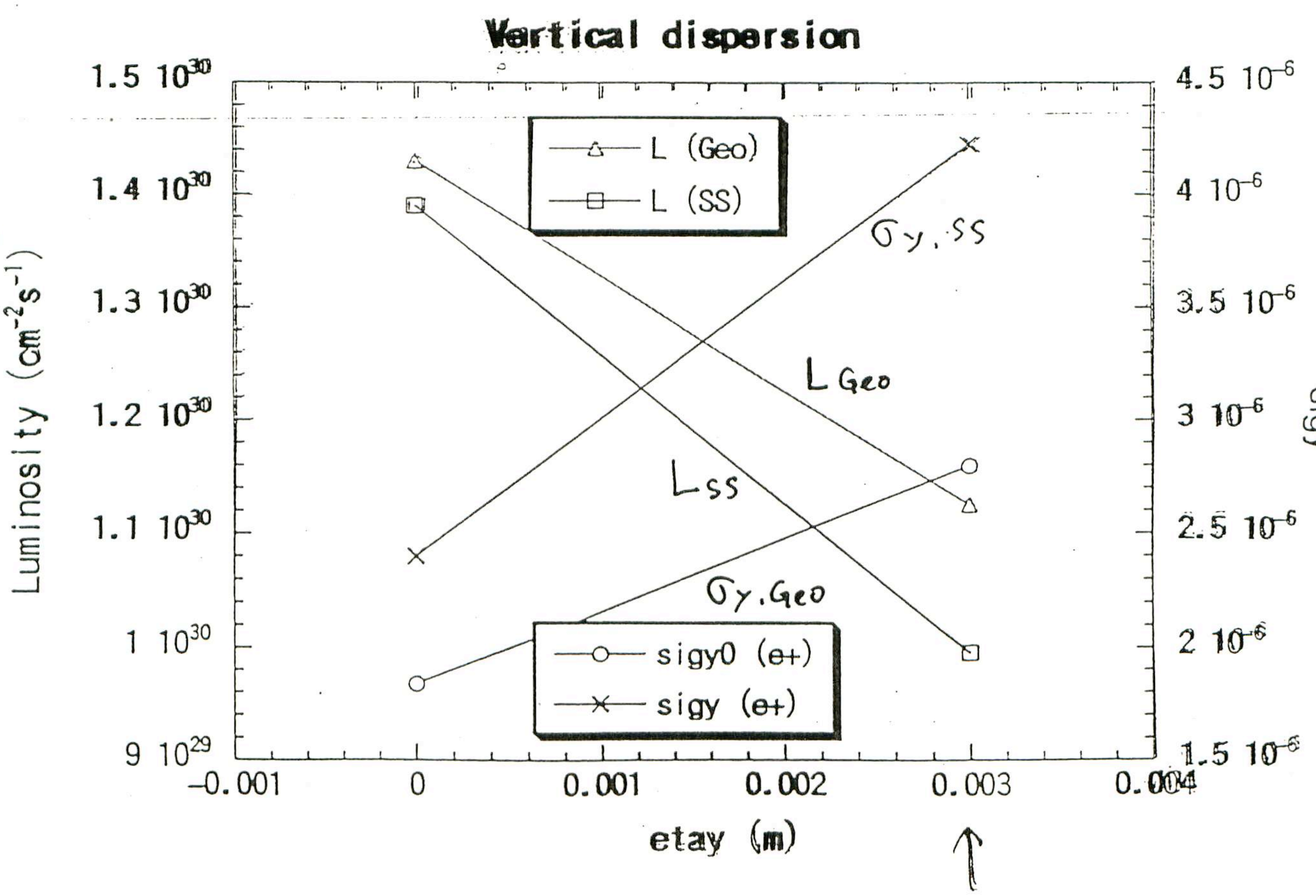
β_x	$1m$			
β_y	$0.01m$			
$\nu_x/\nu_y(LER)$	$0.5301/0.0809$			
$\nu_x/\nu_y(HER)$	$0.5311/0.1159$			
ε_u	1.65×10^{-8}			
ε_v	3.4×10^{-10}			
	No coupling	case 1	case 2	case 3
r_1	0	-0.004388	0.001828	-0.0005
r_2	0	0.01115	-0.008815	0.0104
r_3	0	0.2753	0.01696	0.2249
r_4	0	0.4997	0.1560	-0.6222
$\|R_2\|$	0	-5.3×10^{-3}	4.3×10^{-4}	-1.4×10^{-4}
$\sigma_{x0}(e^+)$	$128\mu m$	$129\mu m$	$128\mu m$	$128\mu m$
$\sigma_{y0}(e^+)$	$1.8\mu m$	$2.4\mu m$	$2.2\mu m$	$1.9\mu m$
L_{geo}	1.4×10^{30}	1.2×10^{30}	1.3×10^{30}	1.4×10^{30}
ε_u	1.65×10^{-8}			
ε_v	5.2×10^{-10}			
	No coupling	case 4	case 5	case 6
r_1	0	-0.004355	2.981×10^{-4}	$-8.493 \times 10-4$
r_2	0	0.005855	$-.002208$	.01076
r_3	0	0.3480	-0.1427	.2098
r_4	0	0.2263	0.3932	$-.3934$
$\|R_2\|$	0	-3.0×10^{-3}	-1.9×10^{-4}	-1.9×10^{-3}
$\sigma_{x0}(e^+)$	$128\mu m$	$128\mu m$	$128\mu m$	$128\mu m$
$\sigma_{y0}(e^+)$	$2.3\mu m$	$2.5\mu m$	$2.3\mu m$	$2.7\mu m$
L_{geo}	1.3×10^{30}	1.2×10^{30}	1.2×10^{30}	1.1×10^{30}


Luminosity reduction due to X-Y coupling
L/bunch
1.60E+30
1.40E+30
1.20E+30
1.00E+30
8.00E+29
6.00E+29
4.00E+29
2.00E+29
0.00E+00
1
2
3
4
5
6
7
8
9
10
Geo
WS
SS x=0
SS x=22mrad

w/o coupling

8.4 Dispersion and vertical crossing

We took account of the chromaticity and the transverse wake force.



$$\sqrt{\beta_y \varepsilon_x} \approx \eta_y \sqrt{\langle p_z^2 \rangle}$$

Luminosity Optimization

(1) Emittance

(2) Tunes

(3) Filling Pattern

(4) Beta Functions at the IP

(5) Bunch Length

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Beam-Beam Performance and Luminosity Optimization at KEKB

K. Akai, N. Akasaka, A. Enomoto, J. Flanagan, H. Fukuma, Y. Funakoshi*, K. Furukawa, J. Haba, S. Hiramatsu, K. Hosoyama, N. Huang†, T. Ieiri, N. Iida, T. Kamitani, S. Kato, M. Kikuchi, E. Kikutani, H. Koiso, M. Masuzawa, T. Matsumoto, S. Michizono, T. Mimashi, T. Nakamura, Y. Ogawa, K. Ohmi, Y. Ohnishi, S. Ohsawa, N. Ohuchi, K. Oide, D. Pestrikov‡, K. Satoh, M. Suetake, Y. Suetsugu, T. Suwada, M. Tawada, M. Tejima, M. Tobiyama, S. Uno, N. Yamamoto, M. Yoshida, S. Yoshimoto, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

The beam-beam performance of KEKB is summarized with an emphasis on methods of IP beam diagnostics and corrections which are important in double ring colliders. We also describe a method of parameter selection for luminosity optimization which is related to the beam-beam performance.

1 INTRODUCTION

The KEKB B-Factory is an electron-positron double ring collider aiming at the study of B meson physics with a design luminosity of $1 \times 10^{34}/\mathrm{cm}^2/\mathrm{sec}$. The high design luminosity comes from the requirements of B meson physics which studies very rare processes. Therefore, the luminosity is a parameter of overriding importance at B factory machines. Another significant feature of KEKB which distinguishes it from conventional electron-positron colliders is that it is an energy asymmetric collider. This feature is also required by physics motivations. The requirement of energy asymmetry inevitably leads us to a double ring collider. From the standpoint of machine design, this double ring feature enables a "high current-multibunch" approach like synchrotron light sources, which is vital to get to a higher luminosity. However, this feature also requires special care in luminosity tuning which is not encountered in conventional electron-positron colliders. Since the two rings are almost independent, we need careful tuning of the geometrical relationships between the two beams such as beam orbit offset at the IP, crossing angle, beam tilt at the IP, collision timing, waist points and others.

In this report, we summarize the beam-beam performance of KEKB with an emphasis on those methods of IP beam diagnostics and corrections which are especially important in double ring colliders. In addition, we also describe a method of parameter selection for luminosity optimization which is also related to the beam-beam performance.

2 BEAM-BEAM PERFORMANCE

As is mentioned above, the design luminosity of KEKB is $1 \times 10^{34}/\mathrm{cm}^2/\mathrm{sec}$. Other related parameters are: β_y^* of 1cm for both rings, total beam currents of 1.1A and 2.6A for the HER(High Energy Ring) and the LER(Low Energy Ring), respectively and a beam-beam limit of 0.05 for both rings. To realize this relatively high beam-beam parameter, we chose the natural bunch length to be 4mm for both rings in the design. KEKB has a horizontal crossing angle of ± 11mrad, which contributes to simplification of the IR design and avoids effects of parasitic collisions.

Beam-beam simulations showed that beam-beam parameters of 0.05 are attainable if there are no machine errors and if we choose operational tunes carefully[1]. In other words, it is important to correct machine errors which are relevant to beam-beam effects and choose tunes for higher beam-beam parameters.

2.1 *IP Beam Diagnostics and Corrections*

Collision Timing In double ring colliders, the collision point is shifted if the relative beam timing between the two rings changes. For beam timing tuning, we adjust the RF phase of the LER so that the two beams collide at the nominal collision point. The beam collision timing is measured by observing a signal from one of the electrodes of a BPM close to the IP with an oscilloscope under the condition that a single bunch is stored in each ring. The BPM is located at a position where it sees both beams. Since the resolution of the timing measurement is around 10 $\sim$ 20psec, the offset error of the collision point is considered to be less than 3mm. We have found that the relative timing between the LER and HER beams is rather stable and stays almost constant for several months.

IP Orbit Offset The tuning of the IP orbit offset is divided into two categories. One is a measurement of the offset and the other is a maintenance of the optimum collision condition once found.

Our method of offset measurement relies on a beam-beam scan with a measurement of the beam-beam deflection. There is some difference between the horizontal scanning procedure and the vertical one. In the horizontal beam-beam scan, the scan is done by changing the RF phase of the LER making use of the horizontal crossing angle of ± 11mrad. The vertical scan is done by changing the sizes of orbit bumps made around the IP in the HER.

In the horizontal (vertical) scan, the beam-beam deflection is detected by measuring orbit changes of the HER

* Email: yoshihiro.funakoshi@kek.jp
† visiting from IHEP, China.
‡ visiting from BINP, Russia.

(LER) at BPM's beside quadrupole magnets named "QC2" ("QCS") where the betatron phase advances from the IP are almost $\pi/2$. The beam-beam kick is approximated by the following expressions.

$$\Delta x' = \frac{\Delta x_{\mathrm{QC2R}}}{\sqrt{\beta_x^* \beta_{x\mathrm{QC2R}}}} + \frac{\Delta x_{\mathrm{QC2L}}}{\sqrt{\beta_x^* \beta_{x\mathrm{QC2L}}}}$$

$$\Delta y' = \frac{\Delta y_{\mathrm{QCSR}}}{\sqrt{\beta_y^* \beta_{y\mathrm{QCSR}}}} + \frac{\Delta y_{\mathrm{QCSL}}}{\sqrt{\beta_y^* \beta_{y\mathrm{QCSL}}}}$$

Here, L and R denote the left and right sides, respectively, of the rings viewed from the ring center. Asterisks denote values at the IP. As shown in the formula, we take the sum of these two BPM's to cancel out the effects of orbit drifts. A typical result of the horizontal (vertical) beam-beam scan is shown in Fig. 1 (Fig. 2). The deflection curve is fitted by using the Bassetti-Erskine formula[2] to get an offset. From the fit, we can also estimate the horizonal (vertical) beam size. The estimated beam sizes, however, do not agree very well with measurements by using synchrotron light interferometers. The discrepancy is now under study.

Once a horizontal or vertical offset is measured, it can be removed by making a horizontal or vertical orbit bump around the IP. In the vertical direction, this removal can be directly done by using the same steering magnets which are used in the vertical scan. In the horizontal direction, however, we sometimes need several iterations of scans and making bumps. This is because we need the translation from an offset in the RF phase, which is determined by the horizonal scan, to a horizonal bump height. As is seen in Figs. 1 and 2, the beam-beam kick is not zero at the center of the fitted curve where the offset should be zero. This offset of the beam-beam kick comes from the offsets of the BPM's. We have found that the offset of the beam-beam kick is relatively stable.

We constructed a feedback system by using steering magnets in the HER for the purpose of maintaining the optimum collision condition of zero orbit offsets. The steering magnets are dedicated to the IP orbit tuning and are called "iBump" magnets. There are eight iBump magnets in the HER: four in the horizontal direction and another four in the vertical. The vertical iBump magnets are used also in the vertical beam-beam scan. This iBump feedback system continuously makes bumps so that the value of the beam-beam kick is equal to that obtained from the beam-beam scan. In actual operations, we use the difference of the beam-beam kicks for two beams instead of that of either beam. By calculating this difference, it is expected that we can cancel out the effects of relatively parallel orbit shifts of the two beams around the IP which do not change the real IP offset but do change apparent (measured) value of the beam-beam kick. We have found that the zero offset value of the beam-beam kick is relatively stable and can be used as a target value of the feedback system. However, we sometimes have to change the target value, particularly when there is a big change in beam orbits for some reason.

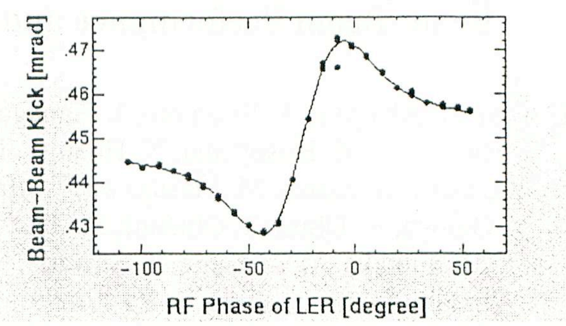

Figure 1: Horizontal Beam-beam scan.

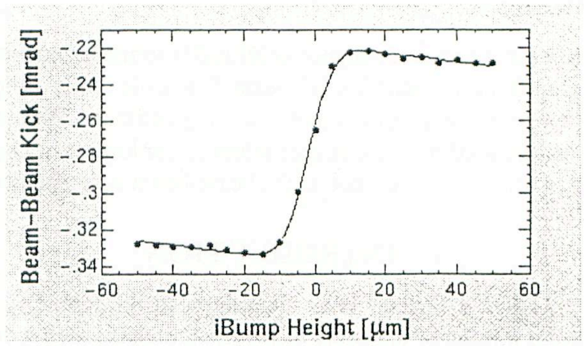

Figure 2: Vertical Beam-beam scan.

Crossing Angle The crossing angle is measured as a by-product of the horizontal (phase) scan. In the horizontal scan, the collision point is also changed together with the horizontal offset. The vertical offset is also changed in the horizontal scan, if there is a crossing angle. Therefore, the crossing angle can be detected by observing the vertical beam-beam deflection in the horizontal scan. Also when there is a vertical offset, one beam is deflected by the other beam. However, the deflection curve with a crossing angle can be distinguished from that with a vertical offset. Fig. 3 shows a typical deflection curve with a large crossing angle. As is seen in the figure, the curve has an asymmetric pattern with respect to the nominal collision phase. A typical deflection curve with a large vertical offset is shown in Fig. 4. In this case, the curve has a symmetric shape. If a vertical crossing angle is observed using this method, the crossing angle is compensated by making an asymmetric bump around the IP. Usually several iterations of scans and making bumps are needed until the deflection pattern becomes close to symmetrical. We do not have an orbit feedback system for the crossing angle so far. It has been expected that the fluctuation of the crossing angle can be corrected by the global orbit correction systems for both rings, which are working continuously during the beam operation and are called "CCC" (Continuous Closed orbit Correction). Even with the CCC system, however, orbit drifts can not be suppressed sufficiently. At present, we are suffering from a problem that the HER beam orbit fluctuates sinusoidally with a cycle of about 40 sec, which induces a fluctuation of the crossing angle with a size of ±0.1mrad

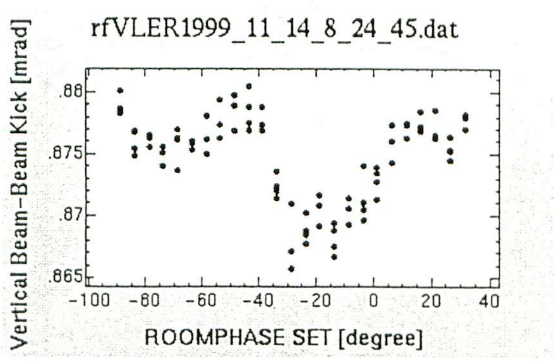

Figure 3: A typical vertical deflection curve in the horizontal scan with a large crossing angle.

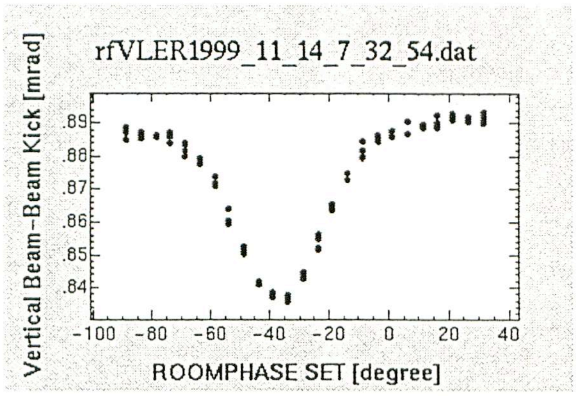

Figure 4: A typical vertical deflection curve in the horizontal scan with a large vertical offset.

and affects the luminosity by $\pm 5 \sim 10\%$.

Waist Point The waist search is a vital tuning procedure in the KEKB operation. The search for the vertical waist is done for each ring independently by shifting the waist point. The waist scan is done by changing the strength of quadrupole magnets near the IP where the betatron phase advance from the IP is almost $\pi/2$ (so that the modulation in the beta function is almost localized around the IP) and observing the luminosity and the beam sizes. A typical result of the waist scan in the LER is shown in Fig. 5. In this figure, specific luminosities from the CsI and EFC (Extremely Forward Calorimeter) luminosity monitors are shown. Also shown are the vertical beam size of the LER from the synchrotron light interferometers and the effective vertical beam size obtained from the vertical beam-beam scan. In this case, we set the LER waist point at +0.5cm according to the measurement. The luminosities and beam sizes in the figure show stronger dependence on the waist point than is expected from geometrical effects. This means that a beam blowup occurs with a small change of the waist point. This strong dependence of the beam-beam performance on the waist position is also reproduced by a beam-beam simulation. This makes the waist scan relatively easy. Conversely, precise adjustment of the waist is needed to

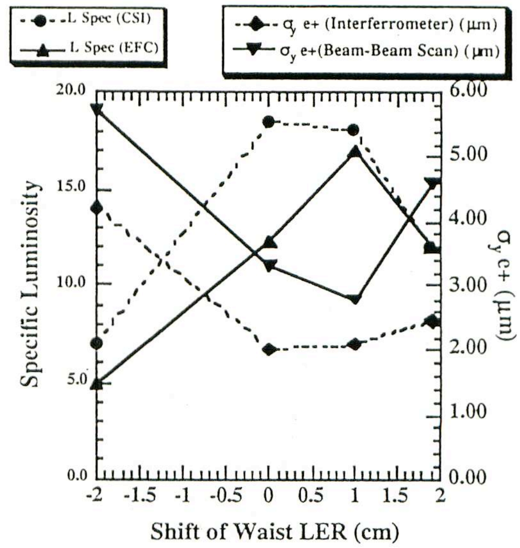

Figure 5: A typical result of LER waist scan.

prevent luminosity reduction. At KEKB, the waist search is done upon startup of the machine after a long shutdown. We have also found that sometimes after global optics correction of the beta functions[3], the waist point shifts significantly.

IP X-Y Coupling Beam-beam simulations show that the x-y coupling at the IP is harmful for the beam-beam effect and the luminosity, particularly in a machine with a large crossing angle[4]. Therefore, it is very important to remove any x-y coupling at the IP. For this purpose, development is under way of a coupling measurement system composed of single pass BPMs which is located near the IP and an exciter of betatron oscillations. Since we have not yet had definite values for the x-y coupling at the IP, the x-y coupling tuning is done in a trial and error manner by using an IP x-y coupling tool. This tool can make a localized x-y coupling around the IP by using skew quadrupole magnets. We have found that this tool is effective in some situations and can increase the luminosity by $10 \sim 20\%$. We should continue the effort to measure and correct the x-y coupling at the IP. The effect of the finite crossing angle can be removed by using a crab cavity system, the R & D for which is under way.

IP Dispersion The vertical dispersion at the IP is one of the sources of luminosity reduction. At KEKB, the IP dispersion is measured by a very conventional method of closed orbit measurement with different RF frequencies. We have found that the resolution of the measurement using this method is not high enough to estimate the IP dispersion with sufficient accuracy. There is some possibility that the accuracy may be improved by using BPMs near the IP which are now used for the x-y coupling measurement. We are also preparing an IP dispersion tool which can make a localized vertical dispersion around the IP.

2.2 *Tune Survey*

Since the beginning of commissioning, we have tried a larage number of betatron tunes. Usefulness of the tunes is evaluated from three viewpoints: injection efficiency, beam instabilities and beam-beam performance. In Figs. 6 and 7, we show a history of operational tunes in the LER. HER tunes were more or less the same as those of the LER. In the early days of KEKB commissioning, the rings were operated with horizontal tunes below the half integer as is seen in Fig. 6. In the figure, cross symbols mean tunes which gave a bad beam-beam performance where some beam loss occurred, mainly in the LER, on setting up the collision with nominal bunch currents. The tune with a circle symbol gave relatively good beam-beam performance. The tune with a triangle symbol gave a relatively good beam-beam performance but we could not inject beam into the HER with this tune. Since then we have found that beam injection performance is greatly improved by optics corrections in many cases[3]. Therefore, injection performance imposes almost no restriction on the choices of betatron tunes now. Although horizontal tunes above the half integer give better beam-beam performance in the beam-beam simulations, we used the tunes below the half integer at that time. This was because we could store higher beam currents with tunes below the half integer than we could above it where we were limited by beam instabilities. Subsequently, we found that bunch-by-bunch feedback systems and relatively large vertical chromaticities can suppress the instabilities.

After that we moved to tunes above the half integer. There, we tried three tune regions as shown in Fig. 7 where the beam-beam simulations predict good beam-beam performance. Of the three regions, the best luminosity so far is obtained in Region A where the beam-beam simulation shows the best result. The design tunes are located in this region. Broadly speaking, the beam-beam simulations agree with observations. However, the tunes which give the best beam-beam performance are not exactly the design tunes. In addition, we found that a very small change in tunes, by 0.003 for example, can make a very big change in the luminosity, by 30% for example in some cases. This too-sensitive tune dependence seems not to be reproduced by the usual beam-beam simulations, although we have not made a detailed comparison of simulations and experiments. These disagreements between simulations and observations might come from machine errors. The predictive power of the beam-beam simulations should also be confirmed. We are preparing a more extensive tune survey for better luminosity. We will be making more detailed comparisons between the experimental results and strong-strong simulations with machine errors.

2.3 *Beam-Beam Performance*

In this section, we show the present beam-beam performance. Tables 1 and 2 show a comparison of two different optics which were used in physics experiments. They are called "Normal Emittance Optics" and "High Emittance Optics" from the difference of design emittances. Motivations for these optics are discussed in the next section. In the tables, the luminosity and the beam sizes at the IP were measured by using a CsI luminosity monitor and a synchrotron light interferometer, respectively. The beam sizes at the IP are translated from measured values at observation points by using the design optics. In this translation, we have not considered the dynamic beta effect. In the tables, we also showed luminosities calculated from accelerator parameters. In the calculation of these luminosities and beam-beam parameters, we considered geometrical degradation factors which come from the crossing angle and the hour-glass effect. In the tables, values in parentheses denote

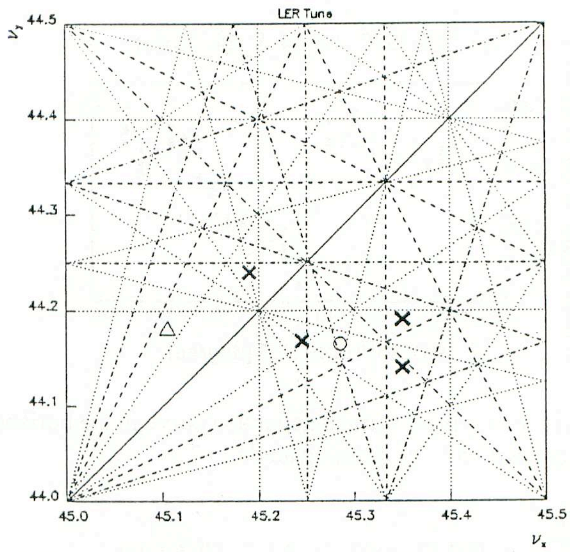

Figure 6: History of tune survey of the LER : the horizontal tunes are below the half integer resonance.

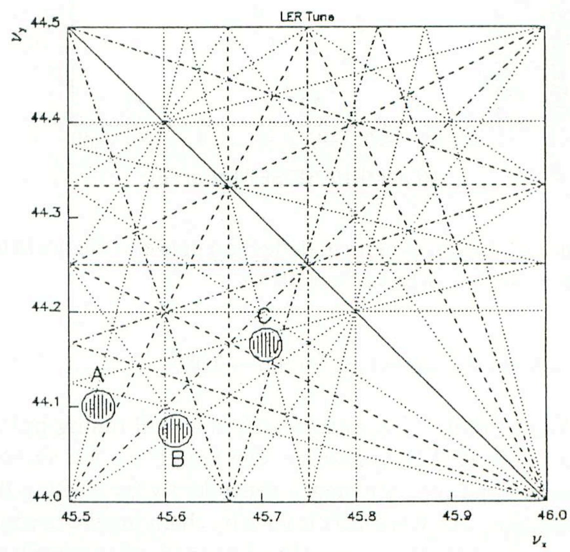

Figure 7: History of tune survey of the LER : the horizontal tunes are above the half integer resonance.

Table 1: Machine parameters related to the luminosity in the normal emittance optics.

	LER	HER	
Hor. Emittance	17	18	nm
β_x^*/β_y^*	1/0.01 (0.33/0.010)		m
Beam Current	270 (2600)	220 (1100)	mA
Bunches	872 (5000)	872 (5000)	
Bunch Current	0.30 (0.52)	0.25 (0.22)	mA
Trains	8	8	
Bunches/train	120	120	
σ_x^*/σ_y^*	140/2.8	140/2.2	
Emitt. Ratio $\varepsilon_y/\varepsilon_x$	4.0 (1.0)	2.5 (1.0)	%
Bunch Length (calculation)	4.8@9.0	3.4@5.0	mm@MV
ξ_x	0.039 (0.039)	0.021 (0.039)	
ξ_y	0.030 (0.052)	0.012 (0.052)	
ν_x	45.584 (45.52)	44.549 (44.52)	
ν_y	44.123 (44.08)	42.153 (42.08)	
Lifetime	130@300	280@240	mim@mA
Luminosity from above parameters	5.1×10^{32}		$/\text{cm}^2/\text{sec}$
Luminosity Belle CsI	5.2×10^{32} (1.0×10^{34})		$/\text{cm}^2/\text{sec}$

Table 2: Machine parameters related to the luminosity with the high emittance optics.

	LER	HER	
Hor. Emittance	30	30	nm
β_x^*/β_y^*	1/0.01 (0.33/0.010)		m
Beam Current	430 (2600)	270 (1100)	mA
Bunches	841 (2833)	841 (2833)	
Bunch Current	0.51 (0.87)	0.32 (0.37)	mA
Trains	32	32	
Bunches/train	29	29	
σ_x^*/σ_y^*	170/4.6	140/3.6	
Emitt. Ratio $\varepsilon_y/\varepsilon_x$	7.3 (1.0)	6.6 (1.0)	%
Bunch Length (calculation)	6.4@9.0	5.2@5.0	mm@MV
ξ_x	0.049 (0.039)	0.023 (0.039)	
ξ_y	0.023 (0.052)	0.010 (0.052)	
ν_x	45.526 (45.52)	44.537 (44.52)	
ν_y	44.131 (44.08)	42.114 (42.08)	
Lifetime	100@450	250@300	mim@mA
Luminosity from above parameters	5.7×10^{32}		$/\text{cm}^2/\text{sec}$
Luminosity Belle CsI	5.9×10^{32} (1.0×10^{34})		$/\text{cm}^2/\text{sec}$

design values.

Figs. 8 and 9 show the luminosity trends of the best fills in which the best peak luminosity was recorded with each set of optics. In the figures, thick(thin) lines denote values for the LER(HER). In the normal emittance optics, almost no beam blowup due to the beam-beam effect was observed, although some lifetime reduction was seen in the LER just after setting up the collision. In Fig. 8, we use design values for the horizontal beam sizes, since the interferometers in the horizontal direction had not been tuned up. The LER beam size depends on beam currents. This dependence is not due to the beam-beam effect but to a single beam instability[6] as is briefly mentioned below. The calculated beam-beam parameter for the HER is as low as 0.012. However, this value is not the limit in the sense that if we had been able to increase the bunch current of the LER, we might have obtained higher beam-beam parameters in the HER. The single beam blowup prevented us from increasing the bunch current of the LER. By using beams with fewer bunches, we can increase the bunch current and measure the beam-beam parameters. However, we have not yet done this kind of experiment.

Contrary to the case of the normal emittance optics, we observed a beam blowup in the HER due to the beam-beam effect with the high emittance optics as shown in Fig. 9. In this case, if we increase the bunch current of the LER, the HER beam is blown up further and the beam-beam parameter of the LER decreases. Therefore, with these optics the beam-beam limit seems to be around 0.01. We found later that the beam blowup of the HER is suppressed in some cases by manipulating the IP x-y coupling knob. However, when the beam blowup of the HER is suppressed in this way, the LER beam was blown up in turn and we could not reach a higher beam-beam parameter in the HER. Due to this beam-beam performance, worse than that of the normal emittance optics, the luminosity is not very high with the high emittance optics for much higher beam currents. We have not understood the reason for the worse beam-

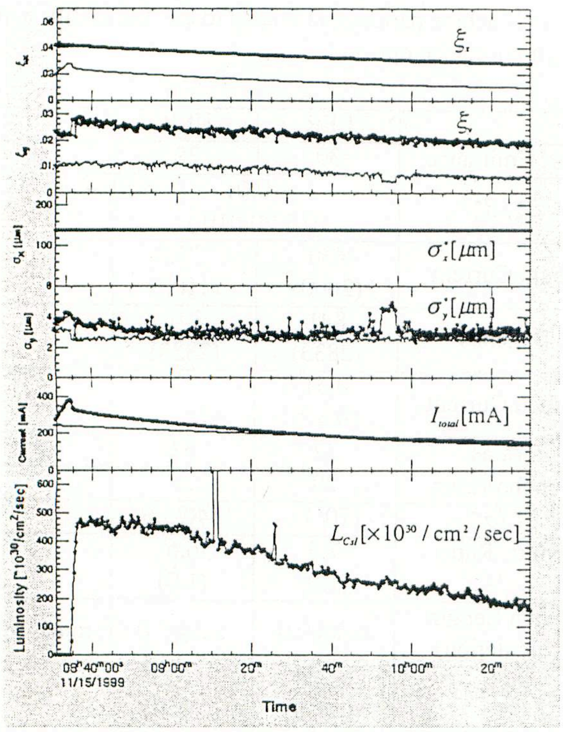

Figure 8: Luminosity trend with the normal emittance optics.

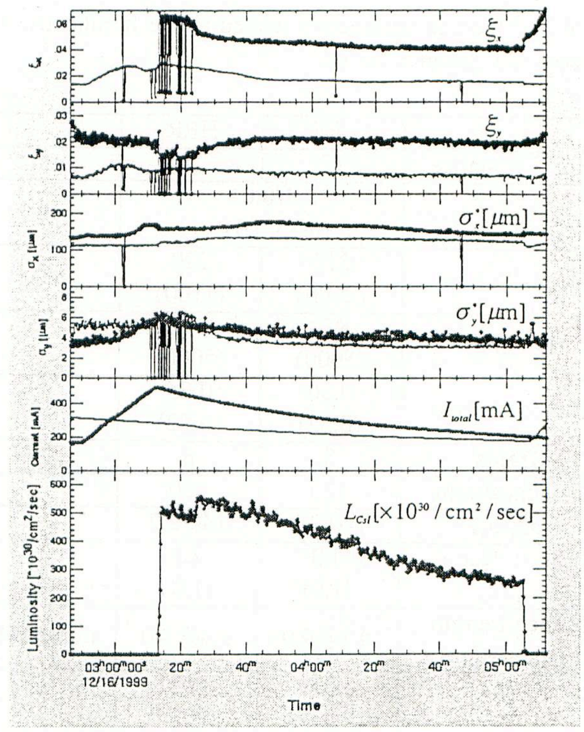

Figure 9: Luminosity trend with the high emittance optics.

beam performance of the high emittance optics. One possible explanation is that this difference is due to bunch length. As is mentioned blow, in high emittance optics, the momentum compaction factor was chosen so that the bunch length becomes longer compared to that of the normal emittance optics to prevent heating of some hardware components. We have found that the heating is within tolerable limits with the high emittance optics. We are preparing a machine study to investigate the beam-beam performance with shorter bunch length in the high emittance optics, although the beam-beam simulations do not predict a strong effect of the bunch length over the range in question on the beam-beam performance.

3 LUMINOSITY OPTIMIZATION

In this section, we describe how the present machine parameters of KEKB relevant to the luminosity have been chosen given several restrictions on the beam operation. We also discuss possible choices of the parameters in the future for a higher luminosity. In this paper, we restrict ourselves to a discussion of the peak luminosity. A discussion of the integrated luminosity, which is a more important parameter than the peak, is given in another paper[5].

The present KEKB luminosity is mainly limited by the following problems: (1) LER single beam blowup[6], (2) heating of masks used for suppressing Belle background, (3) beam blowup due to the beam-beam effect discussed in the previous section, (4) beam current limitation from the instabilities of the LER and HER and (5) Belle background. Of these items, the Belle background does not impose strong restrictions on the peak luminosity in the present operation, although we sometimes have to stop beam injections due to an increase of the Belle background from some beam instabilities.

3.1 Emittance

In the normal emittance optics, the main luminosity limitation comes from the LER single beam blowup, the heating of the movable masks and the beam current limitations from some other instabilities. As is mentioned above, if we had been able to increase the bunch current of the LER without beam blowup, we might have attained a higher luminosity. In reality, however, when we tried to increase the bunch current of the LER, we could not see an increase of the luminosity owing to the single beam blowup of LER. We found that the threshold current of the single beam blowup is roughly determined by the current line density: (bunch current)/(bunch spacing). We tried to increase the total beam currents by filling beams into bunch gaps that had been left for clearing ions. However, we failed to increase the beam currents due to some instabilities in the HER and the LER. We also tried to increase the number of bunches without filling the beams into the bunch gaps by changing the bunch spacing from every 4th RF bucket to every 3rd bucket. However, we failed due to the temperature rise of some vertical masks.

Considering this situation, we decided to move to the high emittance optics in December 1999. The motivations for these optics were: (1) to mitigate the effects of the single beam blowup of LER by increasing the (zero current) beam sizes, (2) to increase the total beam currents by increasing the bunch current without increasing the total number of bunches and (3) to get faster head-tail damping rates and to store more beam currents by increasing the bunch current. These aims have been achieved to some extent. As is seen in Figs. 8 and 9, we can store more currents with the high emittance optics. As for the single beam blowup in the LER, we have found that beam sizes after blowup do not depend on the zero current beam size. The effect of the blowup is relatively weaker with the high emittance optics with a larger nominal beam size, although we still observe severe blowups as shown in Fig. 9. In these optics, the beam blowup due to the beam-beam effect imposes a strong restrictions on the attainable luminosity, as is mentioned above.

3.2 *Tunes*

The present working points of KEKB were found out by trial and error around the design working point. We are preparing more detailed tune survey around the design working point (Region A in Fig. 7), as is described in the previous section. Another possible choice of the tunes is to move to a different region, Region C for example. The motivation for a big change in the tunes is to avoid effects of an integer or half-integer resonance. The present working points are unusually close to the half integer (and integer) resonances. We needed extensive optics corrections to narrow the stop band and operate the machine in Region A[3]. By going away from the resonances, it is expected that optics corrections, which are very time-consuming, become easier and more stable and the orbit drifts get smaller. Of course, a problem with this move might be the beam-beam performance. The beam-beam simulations showed that the tunes in Region C give a relatively good beam-beam performance but the good region is relatively narrow compared to the design tune region[1]. However, we can not deny the possibility that the beam-beam performance might be improved in Region C owing to the weaker effects of machine errors.

3.3 *Filling pattern*

The single beam blowup of the LER is sensitive to the filling pattern. The beam instabilities which are related to the maximum storable beam current and the heating of the masks also depend on the filling pattern. Their severity depends on the mask setting positions which can be changed as part of tuning of the Belle background. Although the situation is somewhat complicated, there is some possibility that we can manage to find some good filling pattern in the sense that we can store more beam current with less beam blowup. This kind of machine study is now in progress.

3.4 *Beta functions at the IP*

The present horizontal and vertical beta functions at the IP (β_x^*, β_y^*) are 1m and 1cm, respectively. The design value of the beta function is achieved in the vertical direction. In the horizontal direction, however, the present achieved value is three times larger than that of the design. From the viewpoint of the beam-beam interaction, in the event that the beam-beam parameters do not reach their limits, the luminosity could be increased by squeezing β_x^*. Other related issues for the beta functions are physical aperture around the IP, dynamic aperture, Belle background, injection efficiency and beam lifetime. In summer 1999, we tried to squeeze β_x^* to 0.5m. At that time, we terminated the trial due to an increase of the Belle background and a heavy beam blowup in the LER from the beam-beam effect. During the summer shutdown, we made some modifications for the background issues[7]. The beam-beam situation was also improved in the normal emittance optics by fine corrections mentioned above. We think that it is worth-while trying to squeeze β_x^* again in the normal emittance optics. In addition to the horizontal, we think that there still remains some room for squeezing β_y^* and attaining a higher luminosity without sacrificing other performances.

3.5 *Bunch Length*

From the viewpoint of the beam-beam effect, a shorter bunch length is favorable for both geometrical luminosity reduction and beam dynamics. As is mentioned above, we think that the longer bunch length in the high emittance optics might be a reason for the inferior beam-beam performance with these optics. We will be doing a machine study to investigate the beam-beam performance with a shorter bunch length using the high emittance optics in very near future.

4 CONCLUSION

It is important for a better beam-beam performance to continue the efforts for IP beam diagnostics and for error corrections. The corrections for the x-y coupling at the IP seem to be of particular importance. The R & D work for the crab cavity should be continued. The measurement of the beam-beam parameters with fewer number of bunches should be done. There is a possibility that some choice of machine parameters can help us achieve a higher luminosity. The parameter search should be continued.

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