

# Correction of Beam-Optical Functions in the KEKB Storage Rings

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for the KEKB Commissioning Group

February 10, 2000

Topics:

- Correction of  $\beta$  function
- Correction of  $x$ - $y$  coupling
- Correction of dispersion

# Introduction

The KEKB storage rings, the LER (3.5 GeV,  $e^+$ ) and the HER (8 GeV,  $e^-$ ), have been operated with  $\beta_y^*/\beta_x^* = 0.01\text{m}/1\text{m}$ .

To achieve large dynamic apertures, the noninterleaved chromaticity correction scheme has been adopted. In each ring, 56 pairs of sextupole magnets connected with the pseudo  $-I$  transformer are installed. In addition, only in the LER, two vertical pairs are placed in the interaction region (IR) for the local chromaticity correction.

$$\begin{pmatrix} -1 & 0 \\ & -1 \end{pmatrix}$$

It is important for the commissioning to measure optical functions such as  $\beta$ -functions, dispersions and  $x$ - $y$  couplings and to correct them in the suitable way.

In the KEKB rings, most of beam position monitors (BPMs) give only the average orbit in seconds. Therefore special methods represented here have been devised to derive the optical function without turn-by-turn information.

Two kinds of knobs are utilized in the corrections:

(A) correction factors (*fudge factors*) for power supplies of quadrupole magnets, and

(B) local bumps at sextupole pairs.

All calculations have been done with SAD developed at KEK.

# Measurement of $\beta$ function

The  $\beta$  functions can be measured by analyzing single-kick orbits at two different source points ( $a$  and  $b$ ). As it is well known, an orbit at  $i$ -th BPM kicked by a steering at  $a$  is given as

$$x_{ia} = \frac{\theta_a}{2} \frac{\sqrt{\beta_a}}{\sin \pi \nu} \sqrt{\beta_i} \cos(\pi \nu - |\mu_i - \mu_a|), \quad (1)$$

and an alternate formula is

$$\begin{aligned} x_{ia} &= \frac{\theta_a}{2} M_{12}(i, a) (1 + \cot \pi \nu \cot |\mu_i - \mu_a|) \\ &\equiv F(i, \theta_a, \mu_a), \end{aligned} \quad (2)$$

where  $\theta$  is the kick angle,  $M_{12}$  is the 12-element of the transfer matrix,  $\nu$  is the betatron tune, and  $\mu$  is the betatron phase advance. Assuming that  $M_{12}$  and  $\mu_i$  can be replaced by the model values, the kick angles ( $\theta_{af}$  and  $\theta_{bf}$ ) and the betatron phases ( $\mu_{af}$  and  $\mu_{bf}$ ) are evaluated by minimizing a function

$$\sum_{j=a,b} \sum_i (x_{ij} - F(i, \theta_{jf}, \mu_{jf}))^2, \quad (3)$$

where  $x_{ij}$  is the measured orbit.

Using the fitting results and Eq.(1), the ratio of  $\beta$  functions at the kick points is estimated by

$$\sqrt{\frac{\beta_{bf}}{\beta_{af}}} = \left\langle \frac{x_{ib} \theta_{af} \cos(\pi \nu - |\mu_i - \mu_{af}|)}{x_{ia} \theta_{bf} \cos(\pi \nu - |\mu_i - \mu_{bf}|)} \right\rangle_{\text{ave.}} \quad (4)$$

Values  $\beta_{af}$  and  $\beta_{bf}$  are obtained respectively, assuming again that the transfer matrix  $M_{12}$  between the kick points is given by the model optics, *i.e.*,

$$\sqrt{\beta_{bf}\beta_{af}} = \frac{\sin \Delta\mu}{M_{12}}, \quad (5)$$

where

$$\Delta\mu \equiv |\mu_{af} - \mu_{bf}|. \quad (6)$$

Once  $\beta_{af}$ ,  $\beta_{bf}$ ,  $\theta_{af}$ ,  $\theta_{bf}$ ,  $\mu_{af}$  and  $\mu_{bf}$  are determined, the  $\beta$  function at each BPM is obtained as

$$\beta_i = (X_{ia}^2 + X_{ib}^2 - 2X_{ia}X_{ib} \cos \Delta\mu) / \sin^2 \Delta\mu \quad (7)$$

where

$$X_{ia,b} \equiv x_{ia,b} \frac{2 \sin \pi\nu}{\theta_{a,bf} \sqrt{\beta_{a,bf}}}. \quad (8)$$



In the KEKB operation, the  $\beta$  functions are measured by two sets of kicks with  $\Delta\mu \sim \pi/2$ , both in the Oho and the Nikko straight sections, which are opposite regions to each other.

Usually 20 BPMs around the kicks are used in the fitting procedure. Note that it is necessary to subtract contributions of the dispersion at the kick point, if exists.

In most cases, residuals of the fitting were sufficiently small and two measurements in Oho and Nikko agreed well each other at all ( $\sim 450$ ) BPMs attached to quadrupole.

Only in the case of  $\beta_x$  in the LER, however, the fitting sometimes did not converge enough and two measurements gave inconsistent results.

It may be because of error fields induced by "C-Yoke" permanent magnets, which were attached in LER to cure the blowup of the vertical beam size.

## Correction of $\beta$ function

We introduce fudge factors for power supplies of quadrupoles to correct  $\beta$  functions.

However, 6 out of 7 power supplies of the quadrupoles in  $2.5\pi$  unit cells are not changed to keep the pseudo  $-I$  transformation between noninterleaved sextupoles and to keep the momentum compaction factor constant.

For a series of quadrupoles connected to a single power supply, error of each magnet can not be corrected since its trim coils are only equipped with a small numbers of common power supplies.

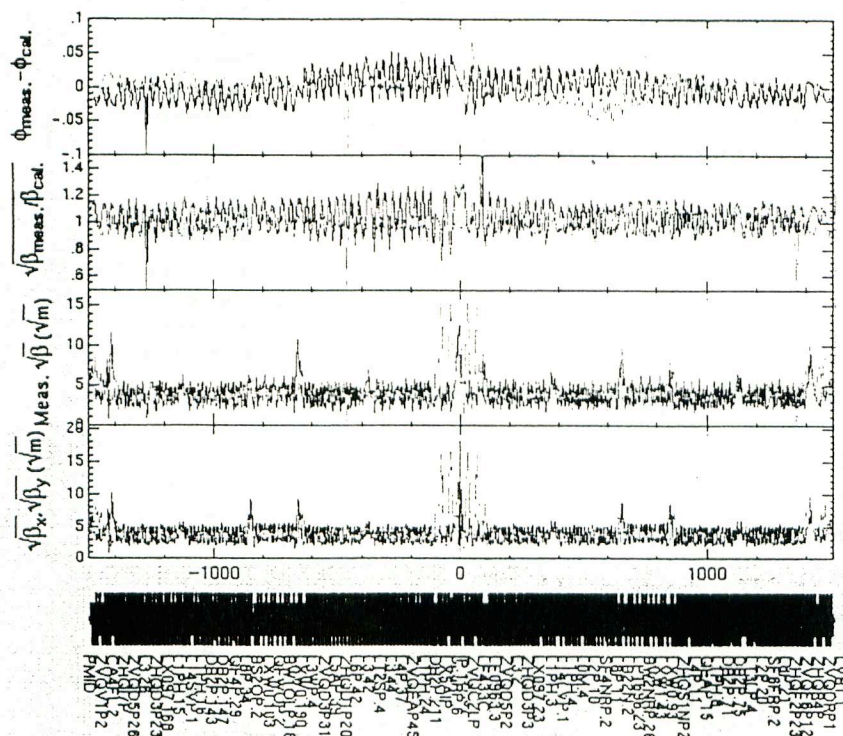
The magnitudes of the fudge factors are calculated with analytic responses based on the model lattice. When two measurements were consistent, the  $\beta$  functions were successfully corrected to be  $\Delta\sqrt{\beta}/\sqrt{\beta_{model}} \leq 0.1$  and  $\Delta\phi \leq 4^\circ$  by iteration of a few times.

After the corrections, the  $\beta$  functions at IR quadrupoles were confirmed by measurements of the tune shift changing the strength of each magnet.



## LER (before correction)

Set Reference Here

vx,vy Dispersion Chromaticity IR  $\beta$  function Ring  $\beta$  function X-Y coupling

## Measurement

Change corrector located at:

Oho Nikko Fuji

## Horizontal

Steering 1: ZHQFWOP2

Steering 2: ZHQFWOP3

Kick angle [mrad]: .050

## Vertical

Steering 1: ZVQDWOP2

Steering 2: ZVQDWOP3

Kick angle [mrad]: .025

No. of BPMs for  $\beta$ @st: 10

Weight of SX: 1

☒ use design phase☒ use fudge around kick point

RECALC

GO

SAVE

READ

## Correction

Threshold 1: -.5

Threshold 2: .5

Tolerance: .01

Damping Factor: 1

Use for  $\beta$  correction:

Oho Nikko Fuji

Phase Correction

☒ QCS

CALC

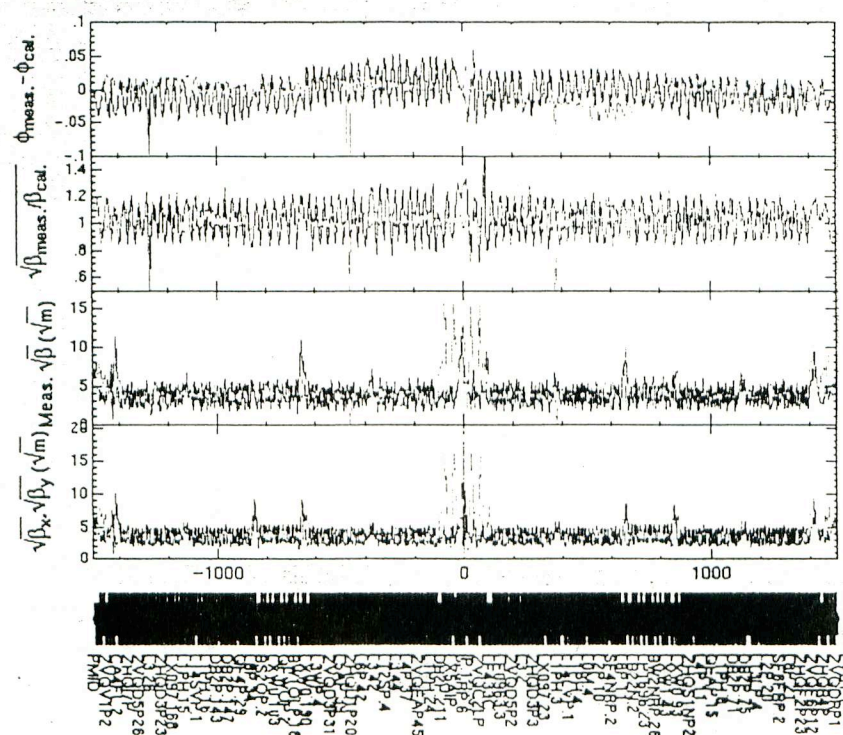
SET

LOAD

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## LER

Set Reference Here

vx,vy Dispersion Chromaticity IR  $\beta$  function Ring  $\beta$  function X-Y coupling

## Measurement

Change corrector located at:

Oho Nikko Fuji

## Horizontal

Steering 1: ZHQFWNP1

Steering 2: ZHQFWNP2

Kick angle [mrad]: .050

## Vertical

Steering 1: ZVQDWNP1

Steering 2: ZVQDWNP2

Kick angle [mrad]: .025

No. of BPMs for  $\beta$ @st: 10

Weight of SX: 1

☒ use design phase☒ use fudge around kick point

RECALC

GO

SAVE

READ

## Correction

Threshold 1: -.5

Threshold 2: .5

Tolerance: .01

Damping Factor: 1

Use for  $\beta$  correction:

Oho Nikko Fuji

Phase Correction

☒ QCS

CALC

SET

LOAD

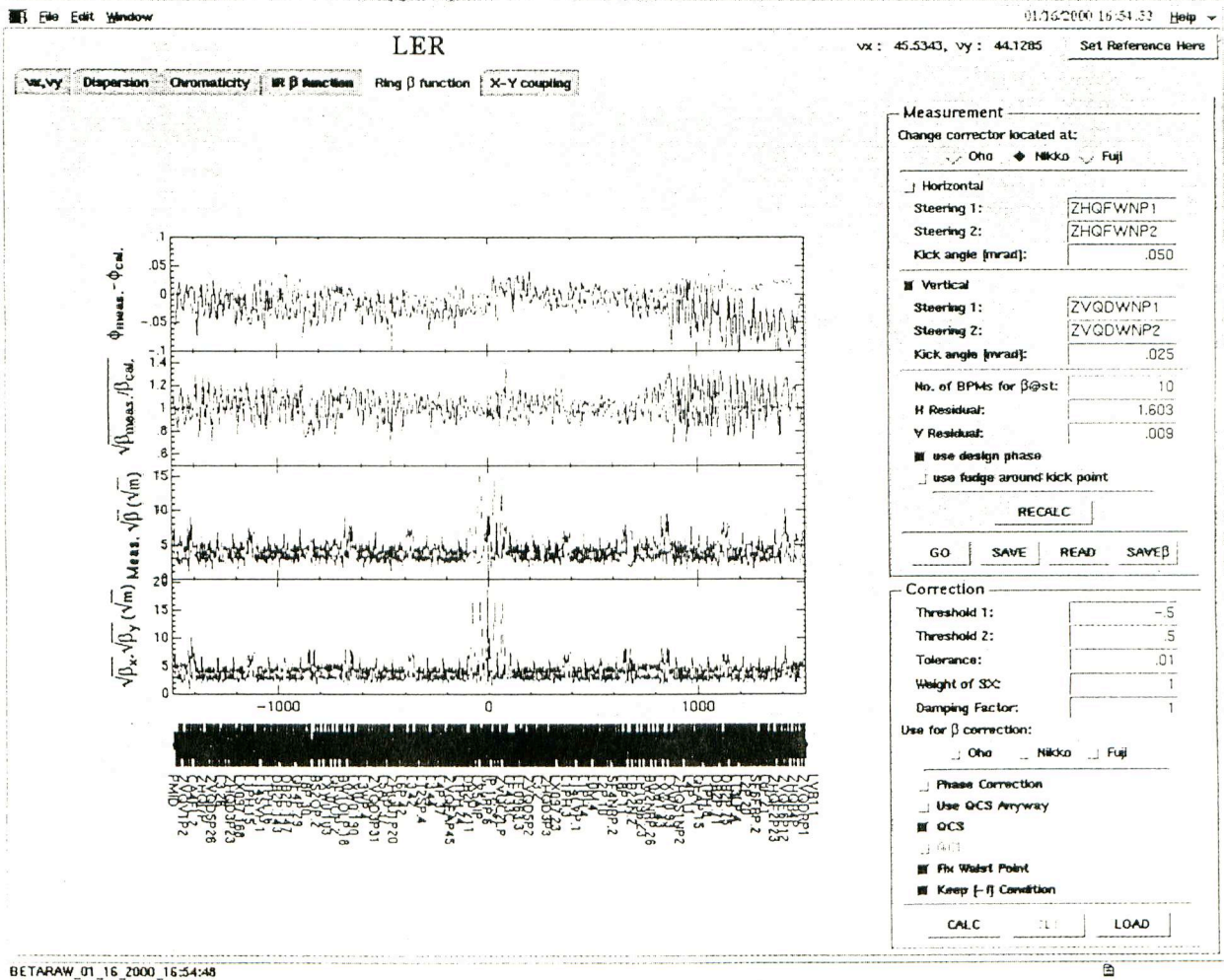
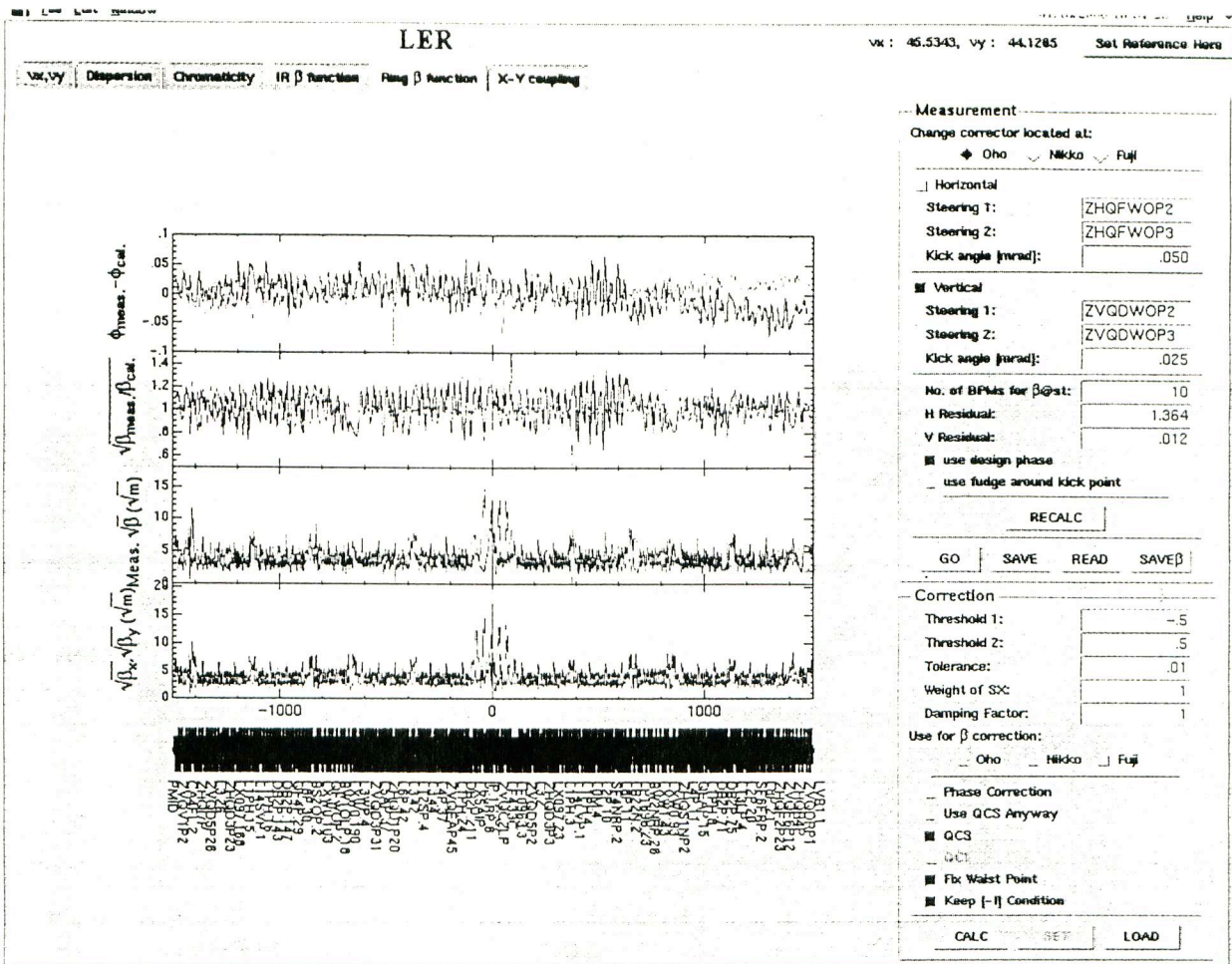
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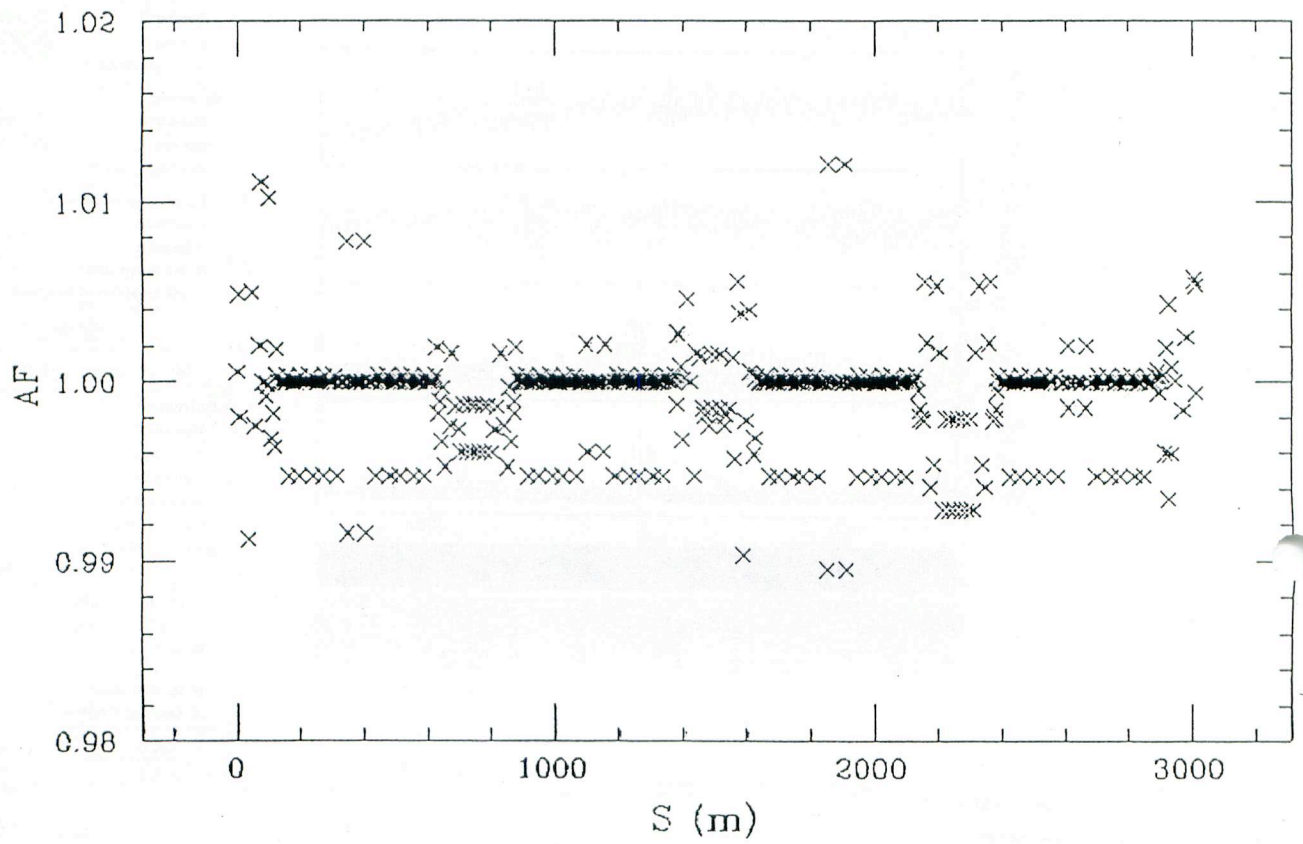


1/16





HER Temp02\_10\_2000\_02:47:35



An example of fudge factors  
in the HER

## Correction of $x$ - $y$ coupling

The  $x$ - $y$  couplings are measured by observing the vertical leakage orbits associated with horizontal single-kick orbits.

Skew quadrupole components produced by symmetric vertical bumps at SD sextupole pairs are used as correctors. Because of the pseudo  $-I$  transformation between the noninterleaved sextupoles, the symmetric bumps mainly produce the  $x$ - $y$  coupling with cancellation of the vertical dispersion.

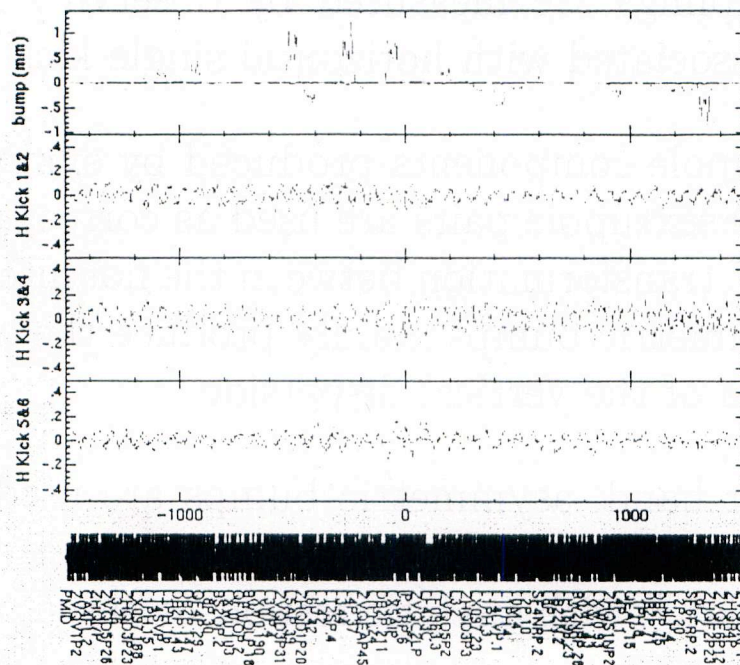
On the other hand, asymmetric bumps are used in the dispersion correction discussed in the next section. Heights of the bumps are calculated with analytic responses based on the model lattice.

Usually vertical leakage orbits by horizontal kicks of  $50\ \mu\text{ rad}$  at six different points (two in each of Oho, Nikko and Tsukuba) were measured and were reduced to  $\Delta y_{rms} \leq 20\ \mu\text{m}$ . This method corrects the  $x$ - $y$  coupling globally, thus reduces the vertical emittance.

The local coupling at the IP, however, should be measured and corrected in other methods using special BPMs (OctoPos) between the final quadrupoles (QCSs) and skew quadrupoles.

## LER (before correction)

Set Reference Here

vx,vy Dispersion Chromaticity IR  $\beta$  function Ring  $\beta$  function X-Y coupling

## Measurement

Steering H1:	ZHQFWNP1
Steering H2:	ZHQFWNP2
Steering H3:	ZHQFWOP1
Steering H4:	ZHQFWOP2
Steering H5:	ZHQA2LP
Steering H6:	ZHQA2RP
Kick angle (mrad):	.050
cy1 (μm):	47.7
cy2 (μm):	53.8
cy3 (μm):	87.8
cy4 (μm):	61.6
cy5 (μm):	22.3
cy6 (μm):	57.0
average (μm):	55.0
<input type="checkbox"/> display x	

GO SAVE READ

## Correction

<input type="checkbox"/> skew	
Skew Weight:	1
Tolerance:	.01
Damping Factor:	1

CALC SET

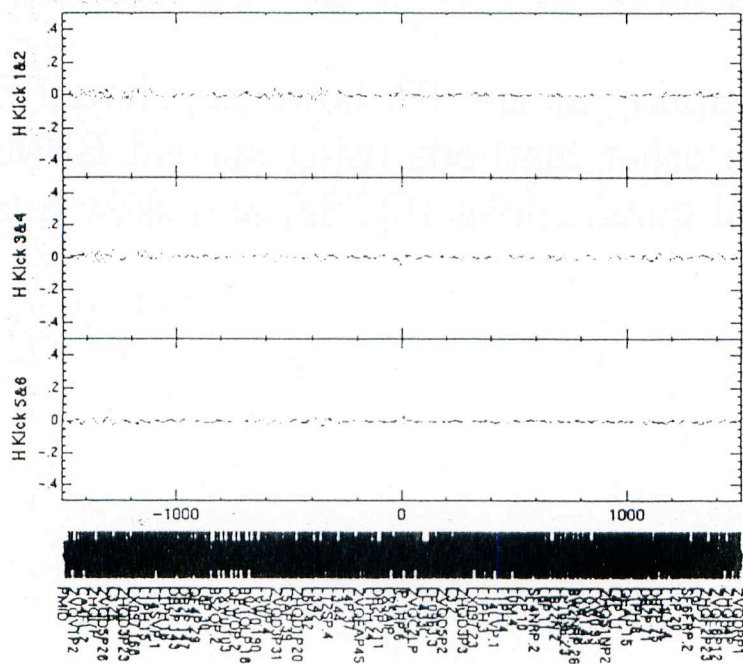
Fudge

LOAD

raw data saved to COD\_12\_06\_1999\_19:32:20

## LER (after correction)

Set Reference Here

vx,vy Dispersion Chromaticity IR  $\beta$  function Ring  $\beta$  function X-Y coupling

## Measurement

Steering H1:	ZHQFWNP1
Steering H2:	ZHQFWNP2
Steering H3:	ZHQFWOP1
Steering H4:	ZHQFWOP2
Steering H5:	ZHQA2LP
Steering H6:	ZHQA2RP
Kick angle (mrad):	.050
cy1 (μm):	13.6
cy2 (μm):	11.9
cy3 (μm):	15.2
cy4 (μm):	11.0
cy5 (μm):	9.6
cy6 (μm):	8.3
average (μm):	11.6
<input type="checkbox"/> display x	

GO SAVE READ

## Correction

<input type="checkbox"/> skew	
Skew Weight:	1
Tolerance:	.01
Damping Factor:	1

CALC SET

Fudge

LOAD



## Correction of dispersion

The vertical (horizontal) dispersions are corrected by asymmetric bumps at SD(SF) pairs in the vertical (horizontal) plane.

Bump heights are calculated with responses obtained by simulations with the model lattice.

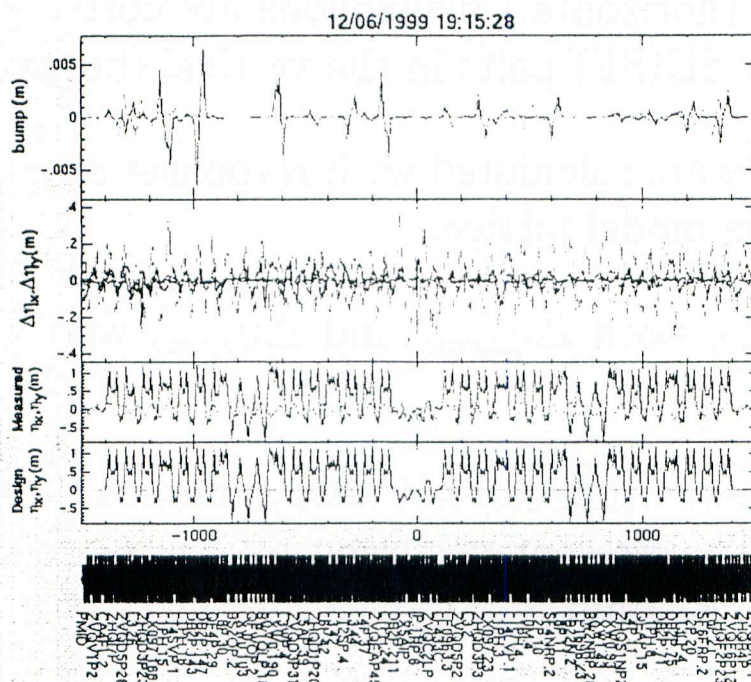
In most cases, both  $\Delta\eta_{x,rms}$  and  $\Delta\eta_{y,rms}$  were corrected to be less than 2 cm.

This global correction can not always reduce the vertical dispersion at IP. The present accuracy of  $\Delta\eta_{y,IP}$  remains at the insufficient level,  $\leq 1\text{mm}$ .

More precise corrections will be critical.

## LER (before correction)

Set Reference Here

vx,vy Dispersion Chromaticity IR  $\beta$  function Ring  $\beta$  function X-Y coupling

## Control

lower frequency (Hz): -100  
upper frequency (Hz): 100  
 $\Delta f$  per step (Hz): 20

GO

Cancel

## Result

$\Delta \eta$  threshold (m): 1  
 $\Delta \eta_x$  (m): 0.055  
 $\Delta \eta_y$  (m): 0.135  
 $\eta_x^*$  (m): 0.0047

## Correction

Tolerance: .01  
Damping Factor (H): .5  
Damping Factor (V): 1

READ

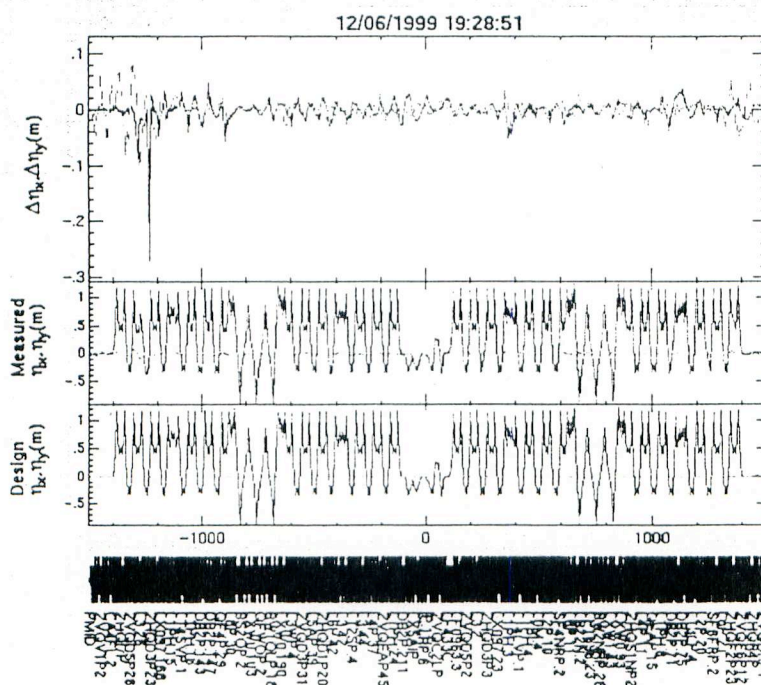
CALC

SET

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## LER (after correction)

Set Reference Here

vx,vy Dispersion Chromaticity IR  $\beta$  function Ring  $\beta$  function X-Y coupling

## Control

lower frequency (Hz): -100  
upper frequency (Hz): 100  
 $\Delta f$  per step (Hz): 20

GO

Cancel

## Result

$\Delta \eta$  threshold (m): 1  
 $\Delta \eta_x$  (m): 0.019  
 $\Delta \eta_y$  (m): 0.019  
 $\eta_x^*$  (m): 0.0032

## Correction

Tolerance: .01  
Damping Factor (H): .5  
Damping Factor (V): 1

READ

CALC

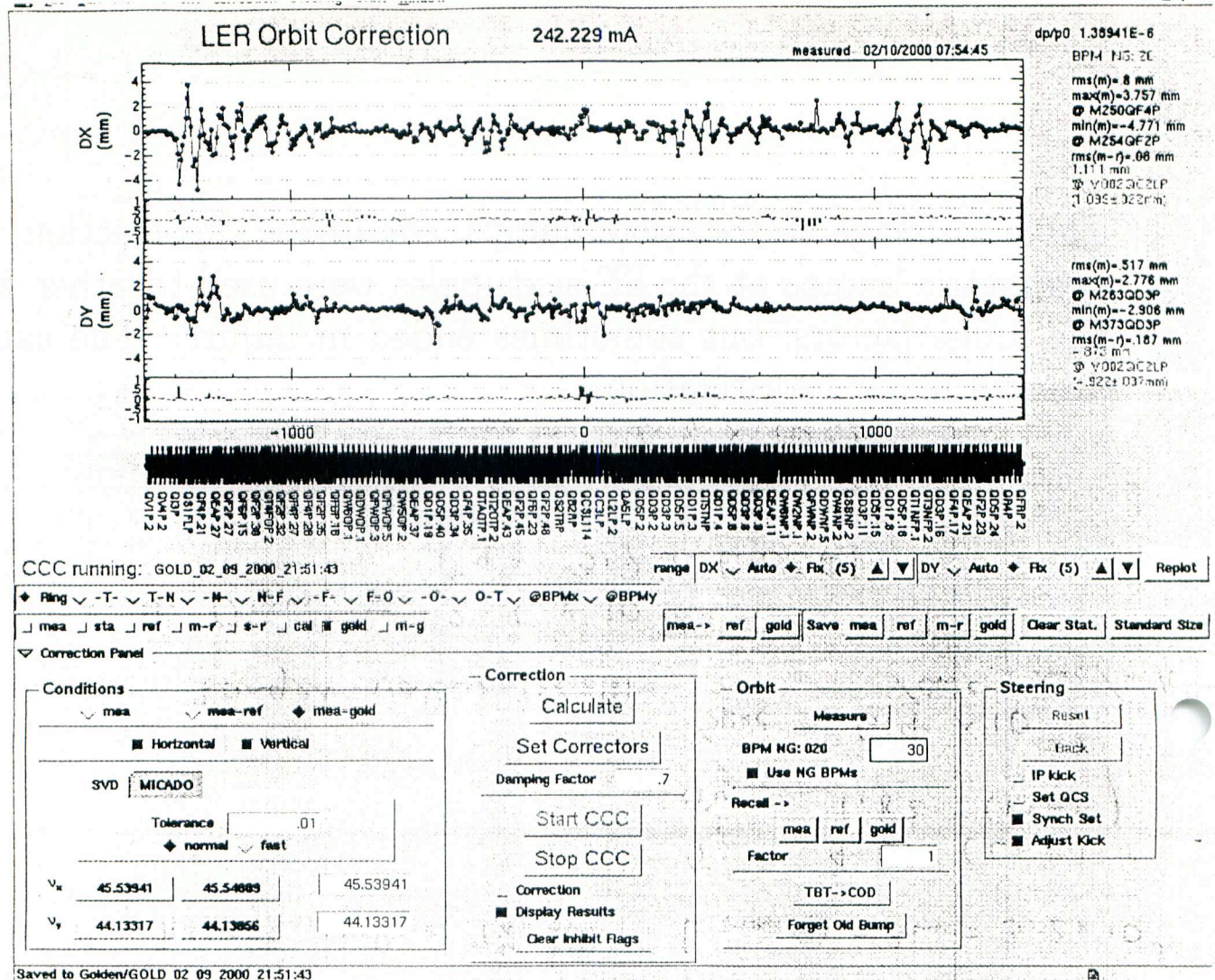
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Table 1: Usage of sextupole bumps. (\*) In the  $\beta$  correction, the symmetric bumps at the SF sextupoles were used together with the fudge factors, but sometimes ended in failure. The causes are still under investigation.

sextupole	plane	symmetric	asymmetric
SD	$x$	$x$ - $y$ coupling	$\Delta\eta_y$
SF	$y$	$\Delta\beta$ (*)	$\Delta\eta_x$



An example of LER orbit  
after optics correction

# Summary

The global optical functions have been successfully corrected with the three kinds of corrections in both rings. The local bumps at the sextupoles are fully utilized in the corrections.

Although these corrections are, in principle, affected each other, the interference among them are not so big. Thus the corrections converge well in sequential repetitions of several times.

After the correction, the vertical-to-horizontal emittance ratio was reduced to less than 1% in both rings, where the vertical beam size was measured by the synchrotron light interferometer.

The corrections mentioned here are the global ones, so the optical functions at the IP should be corrected locally in more dedicated ways.

Actually, the waist point of each ring needs to be searched by readjusting the fudge factors of QCSs and/or QC1s (the second final-focusing quadrupoles only in the HER) every time after the  $\beta$  correction.

Practical methods for the local correction of the dispersion and the  $x$ - $y$  coupling are under development.

Efforts to identify true sources of machine imperfections should also be continued.



# CORRECTION OF OPTICAL FUNCTIONS IN THE KEKB RINGS

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## Abstract

This paper describes methods of beam-optical corrections in the KEKB storage rings.

## 1 INTRODUCTION

The KEKB storage rings[1], the LER (3.5 GeV,  $e^+$ ) and the HER (8 GeV,  $e^-$ ), have been operated with  $\beta_y^*/\beta_x^* = 0.01\text{m}/1\text{m}$ [2]. To achieve large dynamic apertures, the noninterleaved chromaticity correction scheme[1,3] has been adopted. In each ring, 56 pairs of sextupole magnets connected with the pseudo  $-I$  transformer are installed. In addition, only in the LER, two vertical pairs are placed in the interaction region (IR) for the local chromaticity correction. It is important for the commissioning to measure optical functions such as  $\beta$ -functions, dispersions and  $x$ - $y$  couplings and to correct them in the suitable way. In the KEKB rings, most of beam position monitors (BPMs) give only the average orbit in seconds. Therefore special methods represented here have been devised to derive the optical functions without turn-by-turn information. Two kinds of knobs,

- correction factors (*fudge factors*) for power supplies of quadrupole magnets, and
- local bumps at sextupole pairs,

are utilized in the corrections. All calculations have been done with SAD[4] developed at KEK.

## 2 CORRECTION OF $\beta$ FUNCTION

### 2.1 Measurement

The  $\beta$  functions can be measured by analyzing single-kick orbits at two different source points ( $a$  and  $b$ ). As it is well known, an orbit at  $i$ -th BPM kicked by a steering at  $a$  is given as

$$x_{ia} = \frac{\theta_a}{2} \frac{\sqrt{\beta_a}}{\sin \pi\nu} \sqrt{\beta_i} \cos(\pi\nu - |\mu_i - \mu_a|), \quad (1)$$

and an alternate formula is

$$\begin{aligned} x_{ia} &= \frac{\theta_a}{2} M_{12}(i, a) (1 + \cot \pi\nu \cot |\mu_i - \mu_a|) \\ &\equiv F(i, \theta_a, \mu_a), \end{aligned} \quad (2)$$

where  $\theta$  is the kick angle,  $M_{12}$  is the 12-element of the transfer matrix,  $\nu$  is the betatron tune, and  $\mu$  is the betatron phase advance. Assuming that  $M_{12}$  and  $\mu_i$  can be replaced by the model values, the kick angles ( $\theta_{af}$  and  $\theta_{bf}$ ) and the

betatron phases ( $\mu_{af}$  and  $\mu_{bf}$ ) are evaluated by minimizing a function

$$\sum_{j=a,b} \sum_i (x_{ij} - F(i, \theta_{jf}, \mu_{jf}))^2, \quad (3)$$

where  $x_{ij}$  is the measured orbit.

Using the fitting results and Eq.(1), the ratio of  $\beta$  functions at the kick points is estimated by

$$\sqrt{\frac{\beta_{bf}}{\beta_{af}}} = \left\langle \frac{x_{ib}}{x_{ia}} \frac{\theta_{af}}{\theta_{bf}} \frac{\cos(\pi\nu - |\mu_i - \mu_{af}|)}{\cos(\pi\nu - |\mu_i - \mu_{bf}|)} \right\rangle_{\text{ave.}} \quad (4)$$

Values  $\beta_{af}$  and  $\beta_{bf}$  are obtained respectively, assuming again that the transfer matrix  $M_{12}$  between the kick points is given by the model optics, i.e.,

$$\sqrt{\beta_{bf}\beta_{af}} = \frac{\sin \Delta\mu}{M_{12}}, \quad (5)$$

where

$$\Delta\mu \equiv |\mu_{af} - \mu_{bf}|. \quad (6)$$

Once  $\beta_{af}$ ,  $\beta_{bf}$ ,  $\theta_{af}$ ,  $\theta_{bf}$ ,  $\mu_{af}$  and  $\mu_{bf}$  are determined, the  $\beta$  function at each BPM is obtained as

$$\beta_i = (X_{ia}^2 + X_{ib}^2 - 2X_{ia}X_{ib} \cos \Delta\mu) / \sin^2 \Delta\mu \quad (7)$$

where

$$X_{ia,b} \equiv x_{ia,b} \frac{2 \sin \pi\nu}{\theta_{a,bf} \sqrt{\beta_{a,bf}}}. \quad (8)$$

In the KEKB operation, the  $\beta$  functions are measured by two sets of kicks with  $\Delta\mu \sim \pi/2$ , both in the Oho and the Nikko straight sections, which are opposite regions to each other. Usually 20 BPMs around the kicks are used in the fitting procedure of Eq.(3). Note that it is necessary to subtract contributions of the dispersion at the kick point, if exists.

In most cases, residuals of the fitting were sufficiently small and two measurements in Oho and Nikko agreed well each other at all ( $\sim 450$ ) BPMs attached to quadrupoles. Only in the case of  $\beta_x$  in the LER, however, the fitting sometimes did not converge enough and two measurements gave inconsistent results. It may be because there are large horizontal dispersions at kick points in addition that the horizontal tune (0.52) is very close to the half-integer.

### 2.2 Correction

We introduce fudge factors for power supplies of quadrupoles to correct  $\beta$  functions. (The usage of the local bumps will be mentioned later.) However, 6 out of 7

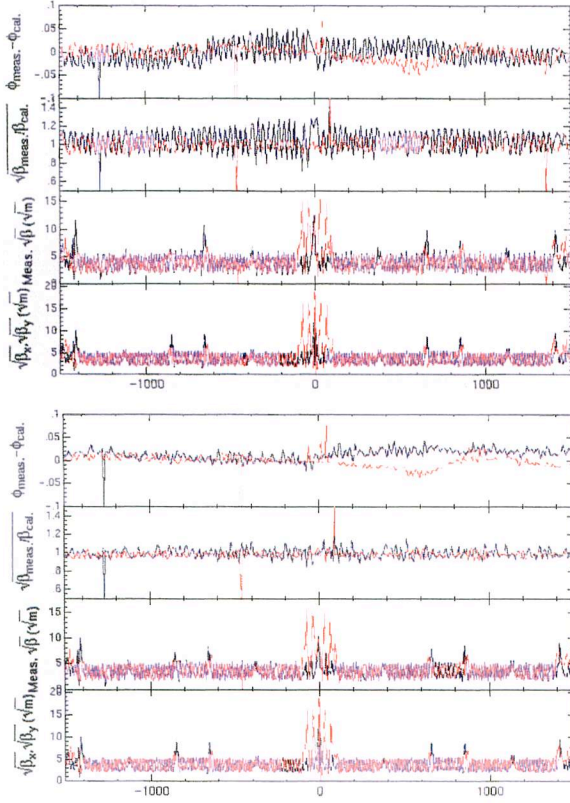


Figure 1: An example of the  $\beta$  correction in the LER, before (upper) and after (lower) the correction. Each of which shows the betatron phase difference  $\Delta\phi$ , the ratio of  $\sqrt{\beta}$ , the measured  $\sqrt{\beta}$ , and the design  $\sqrt{\beta}$ , from top to bottom. The solid (dashed) lines show the vertical (horizontal) data. The IP is located at  $s = 0$ .

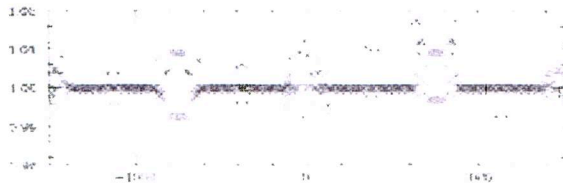


Figure 2: An example of fudge factors in the LER.

power supplies of the quadrupoles in  $2.5\pi$  unit cells are not changed to keep the pseudo  $-I$  transformation between noninterleaved sextupoles and to keep the momentum compaction factor constant. For a series of quadrupoles connected to a single power supply, error of each magnet can not be corrected since its trim coils are only equipped with a small numbers of common power supplies.

The magnitudes of the fudge factors are calculated with analytic responses based on the model lattice. When two measurements were consistent, the  $\beta$  functions were successfully corrected to be  $\Delta\sqrt{\beta}/\sqrt{\beta_{model}} \leq 0.1$  and  $\Delta\phi \leq 4^\circ$  by iteration of a few times, as shown in Fig.1. Af-

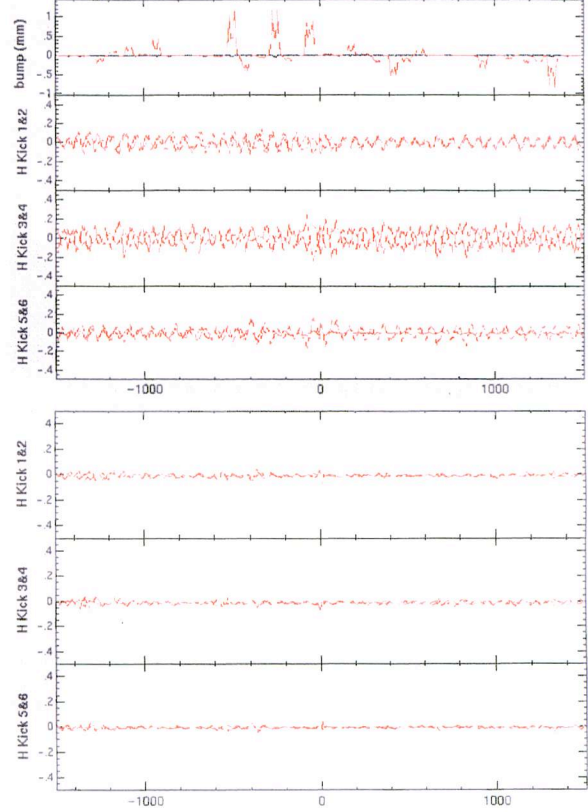


Figure 3: An example of the  $x$ - $y$  coupling correction in the LER, before (upper) and after (lower) the correction. The top graph shows bumps required for the correction.  $\Delta y_{rms}$  reduced from 55 to 12  $\mu\text{m}$ .

ter the corrections, the  $\beta$  functions at IR quadrupoles were confirmed by measurements of the tune shift changing the strength of each magnet.

### 3 CORRECTION OF X-Y COUPLING

The  $x$ - $y$  couplings are measured by observing the vertical leakage orbits associated with horizontal single-kick orbits. Skew quadrupole components produced by symmetric vertical bumps at SD sextupole pairs are used as correctors. Because of the pseudo  $-I$  transformation between the non-interleaved sextupoles, the symmetric bumps mainly produce the  $x$ - $y$  coupling with cancellation of the vertical dispersion. On the other hand, asymmetric bumps are used in the dispersion correction discussed in the next section. Heights of the bumps are calculated with analytic responses based on the model lattice.

Usually vertical leakage orbits by horizontal kicks of 50  $\mu$  rad at six different points (two in each of Oho, Nikko and Tsukuba) were measured and were reduced to  $\Delta y_{rms} \leq 20\mu\text{m}$ . This method corrects the  $x$ - $y$  coupling globally, thus reduces the vertical emittance. The local coupling at the IP, however, should be measured and corrected in other



methods using special BPMs (OctoPos[5]) between the final quadrupoles (QCSs) and skew quadrupoles.

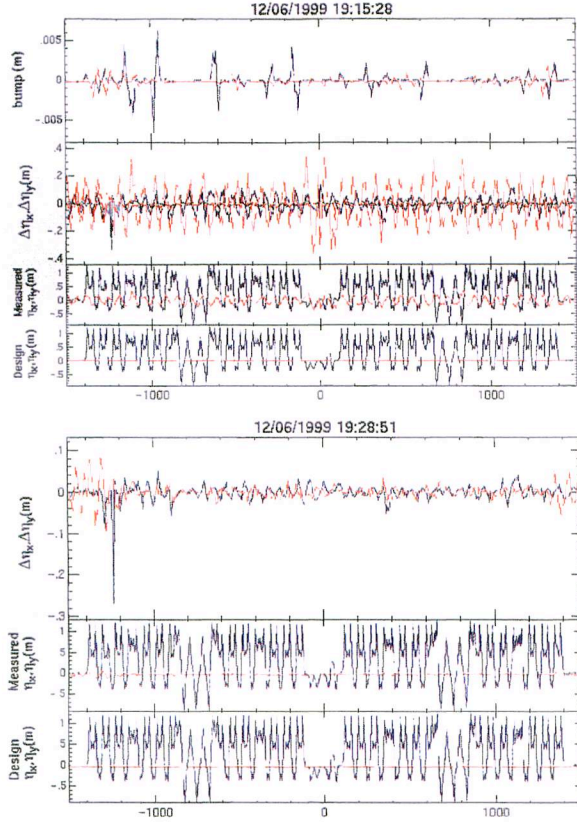


Figure 4: An example of the dispersion correction in the LER, before (upper) and after (below) the correction. The top graph shows the local bumps required for the correction.  $\Delta\eta_{y,rms}$  ( $\Delta\eta_{x,rms}$ ) reduced from 0.135 (0.055) to 0.019 (0.019) m.

#### 4 CORRECTION OF DISPERSION

The vertical (horizontal) dispersions are corrected by asymmetric bumps at SD(SF) pairs in the vertical (horizontal) plane. Bump heights are calculated with responses obtained by simulations with the model lattice. In most cases, both  $\Delta\eta_{x,rms}$  and  $\Delta\eta_{y,rms}$  were corrected to be less than 2 cm. This global correction can not always reduce the vertical dispersion at IP. The present accuracy of  $\Delta\eta_{y,IP}$  remains at the insufficient level,  $> 1\text{mm}$ . For more accurate correction, precise measurements using OctoPos will be critical.

#### 5 SUMMARY

The global optical functions have been successfully corrected with the three kinds of corrections in both rings. The local bumps at the sextupoles are fully utilized as summarized in Table 1. Although these corrections are, in principle, affected each other, the interference among them are

not so big. Thus the corrections converge well in sequential repetitions of several times. After the correction, the vertical-to-horizontal emittance ratio was reduced to less than 1% in both rings, where the vertical beam size was measured by the synchrotron light interferometer[6].

Table 1: Usage of sextupole bumps. (\*) In the  $\beta$  correction, the symmetric bumps at the SF sextupoles were used together with the fudge factors, but sometimes ended in failure. The causes are still under investigation.

sextupole	plane	symmetric	asymmetric
SD	$x$	$x$ - $y$ coupling	$\Delta\eta_y$
SF	$y$	$\Delta\beta$ (*)	$\Delta\eta_x$

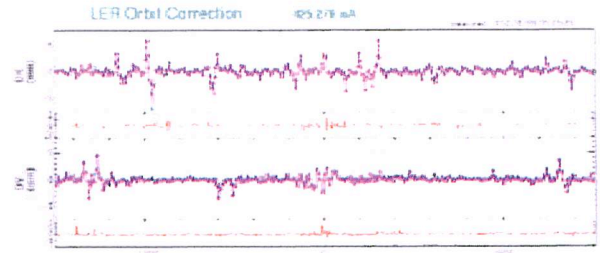


Figure 5: An example of the orbit of the LER after the correction.

The corrections described here are the global ones, so the optical functions at the IP should be corrected locally in more dedicated ways. Actually, the waist point of each ring needs to be searched by readjusting the fudge factors of QCSs and/or QC1s (the second final-focusing quadrupoles only in the HER) every time after the  $\beta$  correction. As for the local correction of the dispersion and the  $x$ - $y$  coupling, simulation studies have been done[7] and practical methods are under development. Efforts to identify true sources of machine imperfections should also be continued.

The authors thank all the members of the KEKB accelerator group, machine operators and the Belle Collaboration for supporting the commissioning.

#### 6 REFERENCES

- [1] KEKB B-Factory Design Report, KEK-Report 95-7(1995).
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