Optics aberration at IP and Beam-beam effects

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Introduction

• How to get the target luminosity
• Optics aberration degrade luminosity in beam-beam simulations.
• Optics correction at IP was one of key issues, since starting KEKB.
• The optics aberration is serious in SuperKEKB.
• The aberration is related to QCS mainly and also to other lattice magnets.

1. Design stage

2. Starting Phase II

3. Toward Phase III
Study in the design stage of SuperKEKB

• Weak-strong beam-beam simulation using SAD.
• Luminosity degradation has been seen from low bunch current.
• Interplay of beam-beam effect with lattice nonlinearity
• Skew sextupole component degrade luminosity (Y. Zhang).
• Where is the source of the nonlinearity.
• Focusing to QCS.
IR magnets and their nonlinearity

• There are many nonlinear field components in IR magnets.
• Chromatic coupling

➤ Realistic lattice: lum. drops at low beam currents
➤ Crab-waist:
  • To cancel beam-beam driven resonances
  • Work well at high currents, but not well at low currents

D. Zhou,
SKEKB MAC
2015

BBWS : arc expressed by simple transfer matrix
SAD: complex lattice structure
Y. Zhang’s (IHEP) work at KEK

• Vertical orbit is induced by a large horizontal betatron oscillation.

• Skew sextupole term at IP, $x^2y$, is suspected for the luminosity degradation.

Nonlinear aberration at IP

From Y. Zhang
QCS superconducting magnet system

QCS-L Cryostat

QCS-R Cryostat

N. Ohuchi et al.
Overview of IR magnets

- Compensation solenoids [ESL, ESR1, ESR2 and ESR3]

In the left cryostat, one solenoid (12 small solenoids) is overlaid on QC1LP and QC1LE.

In the right cryostat, the 1st solenoid (15 small solenoids) is overlaid on QC1RP, QC1RE and QC2RP.
- The 2nd and 3rd solenoids on the each beam line in the QC2RE vessel.
Evaluation of nonlinear term

• Focus on skew sextupole component.
• Reference axes in solenoid is chosen as a straight line with half crossing angle.
• Magnet components are defined on the reference orbit.
• Beam orbit deviate from the reference orbit.
• Skew sextupole component is induced by Skew sextupole and octupole with a vertical orbit.
C_{10} from SK2 and K3+yCOD

- Contribution to SK2 is coming from explicit Skew Sext SK2_0 and octupole, K3+COD
- No contribution from higher order than K3.

There are 10 skew components.

\[ y^3, y^2p_y, yp_y^2, p_y^3, x^2y, x^2p_y, xp_xy, xp_xy, p_x^2y, p_x^2p_y \]

\[ H = c_{10}p_x^2p_y \]

- Skew sextupole coming from higher order nonlinearity is small.
Luminosity for $H = c_{10} p_x^2 p_y$

- The luminosity degradation due to $c_{10}$ is weaker than that of beam-beam simulation with SAD.
- There may be still unknown nonlinearity?
Commissioning of SuperKEKB

$\beta^*$ is squeezed step-by-step

- $c_{10}=0.072$ m is kept for $\beta^*$ change, because IR magnets are fixed in SuperKEKB.
- For normalized coordinates, $P_i = \sqrt{\beta_i} p_i$, $X_i = x_i/\sqrt{\beta_i}$

$$C_{10} = \frac{c_{10}}{\beta^*_x \sqrt{\beta^*_y}} \quad H = c_{10} p_x^2 p_y \quad H_N = C_{10} P_x^2 P_y$$

- $C_{10}=136.9$ m$^{-1/2}$ for $\beta^*_x=3.2$ cm, $\beta^*_y=0.27$ mm
- Normalized $C_{10}$ directly affects the beam dynamics. $\Delta Y = C_{10} P_x^2$

$$\Delta Y = C_{10} P_x^2 \approx 136.9 \varepsilon_x \approx 0.15 \sqrt{\varepsilon_y} \quad \text{for} \quad \beta^*_x=3.2 \text{ cm}, \beta^*_y=0.27 \text{ mm}$$

- The effect is reduced by Detune of $\beta^*$.
- $C_{10}$ is 4.4% for 8x8, 8.8% for 4x8.

- This nonlinearity does not affect commissioning stage. (MAC2018)
Phase II commissioning stage

• Collision starts the end of April 2018.
• Beta was squeezed to 8->6->4->3mm. Clear luminosity gain did not have the first 1.5 month of the beam-beam commissioning. Rather it worsened.
• Collision tools (offset, optics/emittance, waist, x-y coupling ...) are developed during the period.
• Many works were done simultaneously
  • Develop machine protection interlock.
  • Injection tuning. Linac tuning. Back ground.
  • Beam current increase.
  • ......................
Lspec at June 10, 2018

Observations

- 0mA, $\sigma_{y_0}=0.3\,\mu\text{m}, 0.4\,\mu\text{m}$, $L_{sp}=35$
- 200x80mA, $\sigma_{y_0}=0.5\,\mu\text{m}, 0.6\,\mu\text{m}$, $L_{sp}=23$
- 285x340mA, $\sigma_{y_0}=1.5\,\mu\text{m}, 0.6\,\mu\text{m}$, $L_{sp}=11$

$L_{sp}$ agrees with geo value at high current

$L_{peak}=1.2\times10^{33}\,\text{cm}^{-2}\text{s}^{-1}$, 285x340mA, $N_b=788$

Blow-up of e- beam was serious.

$$L_{sp} = \frac{1}{2\pi\sigma_{xc}\sigma_{yc}e^2f_0}$$

$$\sigma_{yc} = \sqrt{\sigma_{y+}^2 + \sigma_{y-}^2}$$
Luminosity in a weak-strong simulation

- BBWS, strong e- beam 5% coupling 285mA, $\beta_x=200\text{mm}$, $\beta_y=4\text{mm}$, early stage of parameters
  weak  e+ beam 1% coupling 340mA

Even in very conservative condition of the simulation, measured luminosity was half of simulation.
R scan in the simulation

- Required tuning range $R_1 \sim \text{O(mrad)}$, $R_2 \sim \text{O(mm)}$, $R_3 \sim \text{O(1m}^{-1})$, $R_4 \sim \text{O(0.1)}$
- $R_2$ scanned $\sim \text{O(0.01-0.1mm)}$
- Lack of tuning range especially in $R_2$.
IP coupling and beam distribution at IP

\[\sigma_y^2(s = 0) \approx \sigma_{y,0}^2 + \sigma_x^2 \left[ \frac{R_2^2}{\beta_x^2} + R_1^2 \right] + (\eta_y \sigma_\delta)^2\]

We do not change IR magnets for squeezing \(\beta^*\), R2 is kept. Effect of R2 is enhanced for squeezing \(\beta^*\).
Beam shape at IP with IP coupling

low current
• R1

high current
• R2

Discrepancy from L calculated by the measured beam size
Better agreement with L calculated by the measured beam size

• In either case, luminosity better agree with that given by the measured beam size at high current,
• Emittance growth is remarkable for beam with coupling.
HER R2 scan in June 15, 2018

Increase tuning range of R2, R2 correction scheme is changed so using sextupole bump as is done in KEKB, although there are side effects.

- $R2 = -3.9\text{mm}$
- $I+ = 340\text{mA}$
- $I- = 285\text{mA}$
- 789 bunch
- no inj

\[ \Delta \sigma_y = \frac{R_2}{\beta_x} \sigma_x = 0.8\mu\text{m} \]
\[ = 2\sigma_y \]
Relation of R and skew strength of QC1 in a simple model

- Transformation of $R_2$,

- Assume $\pi/2$ for phase difference between IP to both QC1.

- Skew quad at QC1 is $B'L/B\rho=R_2$, which is independent of $\beta^*$.

- Deviation from $\pi/2$ induces $R_3$.

- Control of inside of $\pi$ section is hard from outside. It should be corrected by both side of skew. (like waist correction)

- We do not change IR magnets for squeezing $\beta^*$, $R_2$ is kept.

- Effect of $R_2$ is enhanced for squeezing $\beta^*$.
Skew Q component at QC1

\[ M_{\text{rev}}(k_{1L}, k_{1R}) = T_{1R} K_{1R} T_{1R}^{-1} M_0 T_{1L}^{-1} K_{1L} T_{1L} \]

\[ M_{\text{rev}}(R) = R M_0 R^{-1} \]

Solve \[ M_{\text{rev}}(k_{1L}, k_{1R}) = M_{\text{rev}}(R), \{R\} \]

Focus off-diagonal 2x2 matrix

\[ M_{\text{rev},R}(k_{1L}, k_{1R}) = M_0 T_{1L}^{-1} K_{1L} T_{1L} T_{1R} K_{1R} T_{1R}^{-1} \]

\[ R_{1-4,L} \] are also given. \[ R_{1-4,L} \]
Skew correction at realistic IR

• $\beta_x^* = 0.1, \beta_y^* = 0.003$, (MKS)
• $\beta_{x1} = 4.46, \alpha_{x1} = -7.52, \phi_{x1} = 0.236, \beta_{y1} = 329, \alpha_{y1} = -12.3, \phi_{y1} = 0.2495$

• $R_1 = -14.9 k_{L1} - 14.9 k_{R1}, R_2 = -0.716 k_{L1} + 0.716 k_{R1},$
• $R_3 = -487 k_{L1} + 487 k_{R1}, R_4 = -1156 k_{L1} - 1156 k_{R1}$

• For $k_{L1} = k_{R1} = 0.0021, R_1 = R_4 = 0, R_2 = 0.003, R_3 = -2.05.$
• $R_3$ leaks outside of IR due to the deviation of betatron phase from $\pi/2$.  
• Correct x-y coupling due to the leakage of $R_3$ globally.
• Detailed values are determined by SAD (Ohnishi).
June 30, 2018

Observations

- 0 mA, $\sigma_y^0=0.25\,\mu m$, $0.25\,\mu m$, $L_{sp}=49$
- 200 x 160 mA, $\sigma_y^0=0.4\,\mu m$, $0.6\,\mu m$, $L_{sp}=24.4$
- 285 x 340 mA, $\sigma_y^0=0.6\,\mu m$, $0.6\,\mu m$, $L_{sp}=20.7$

$L_{sp}$ agrees with geo value at every current

$L_{peak}=2.5\times10^{33} \, cm^{-2}s^{-1}$, (2 times higher)

285 x 340 mA, $N_b=788$

$L_{sp} = \frac{1}{2\pi \sigma_x \sigma_y e^2 f_0}$

$10^{30} \, cm^{-2}s^{-1}/mA^2$

$\sigma_y = \sqrt{\sigma_{y+}^2 + \sigma_{y-}^2}$

6/29 21:00- R2 using QCS corrector

Blow-up of e+ beam was serious.
TbT measurement

- y motion in X mode.

\[
x = RBX
\]

\[
R = \begin{pmatrix}
  r_0 & 0 & r_4 & -r_2 \\
  0 & r_0 & -r_3 & r_1 \\
  -r_1 & -r_2 & r_0 & 0 \\
  -r_3 & -r_4 & 0 & r_0
\end{pmatrix}
\]

\[
B = \begin{pmatrix}
  B_x & 0 \\
  0 & B_y
\end{pmatrix}
\]

\[
B_X = \begin{pmatrix}
  \sqrt{\beta_x} & 0 \\
  -\alpha_x/\sqrt{\beta_x} & 1/\sqrt{\beta_x}
\end{pmatrix}
\]

\[r_1: \text{cos component of } y \text{ for } x \text{ betatron motion}, r_2: \text{sin component}\]

\[y = -r_1x - r_2p_x = -r_1a \cos \phi(s) + r_2\left[\frac{a}{\beta} \sin \phi(s) + \frac{\alpha}{\sqrt{\beta}} a \cos \phi(s)\right]\]

\[= c \cos(2\pi n v_x + \phi_y)\]

\[\frac{c}{a} \cos(\phi_y - \phi_x) = \left(-r_1 + r_2 \frac{\alpha}{\sqrt{\beta}}\right)\]

\[\frac{c}{a} \sin(\phi_y - \phi_x) = r_2 \frac{\alpha}{\beta}\]

\[r_3: \text{cos component of } y \text{ for } p_x \text{ betatron motion}, r_4: \text{sin component}\]

\[p_y = r_3x - r_4p_x = r_3a \cos \phi(s) + r_4\left[\frac{a}{\beta} \sin \phi(s) + \frac{\alpha}{\sqrt{\beta}} a \cos \phi(s)\right]\]

\[= d \cos(2\pi n v_x + \phi_q)\]

\[\frac{d}{a} \cos(\phi_q - \phi_x) = \left(r_3 + r_4 \frac{\alpha}{\sqrt{\beta}}\right)\]

\[\frac{d}{a} \sin(\phi_q - \phi_x) = -r_4 \frac{\alpha}{\beta}\]
FFT of BPM data

- Small $y_{IP}$, but enough $p_{yIP} = q_{IP}$. 
HER

\[ r_1 = 1.0 + 137\delta \]

\[ r_2 = \text{Data} \]

\[ r_3 = \text{Data} \]

\[ r_4 = -0.073 + 23.3\delta \]
LER

\[ r_3 = 0.24 + 338\delta \]

\[ r_4 = -0.15 + 8.9\delta \]
Toward Phase III

- Squeezing beta*, Luminosity increase is not trivial at all without IP optics tuning.

Luminosity is half at $I_+I_- = 0.4 \text{mA}^2$.

Design $1.5 \text{mA}^2$. $\beta_y^* \approx 1/10$
Beam-beam simulation considering optics aberrations at IP

- Linear
- Nonlinear
- Chromatic

- Recent operation showed e+ beam is weaker than e- beam. Weak(e+)-strong(e-) simulation is performed.
Weak(e+)-strong(e-) simulation with errors

• Error strengths of R3 and R4 are much larger than measurement. Discard.

• R1 and R2 were already scanned and given optimum.

• We cleared linear aberrations in Phase-II.
Nonlinear aberrations

- $p_x^2 p_y$ term was studied before commission.
- $p_x^2 p_y$ term well reproduces measured $L_{sp}$.
- The strength is **100 times larger** than the value given by design of QCS. $c_{10} = c(p_x^2 p_y) = 0.07$.  

![Graph showing nonlinear aberrations](image)
Chromatic coupling

- $R_3'$ and $R_4'$ were measured to be $R_3' = 300$, $R_4' = 20$.
- The behaviors for $R_1'$ and $R_2'$ are plausible.
- $R_1'$ and $R_2'$ are hard to be measured in the present monitor. $R_1' \sim -10$ in measurement?

![Graph showing the relationship between $L_{\text{spec}}$ (in $10^{30} \text{cm}^{-2}\text{s}^{-1}/\text{mA}^2$) and $I_+I_-$ (in mA$^2$), with four different lines corresponding to $R_1' = 12$, $R_2' = 3$, $R_3' = 35000$, and $R_4' = 1500$.]}
Summary

• SuperKEKB is squeezing $\beta^*$ step-by-step in the commissioning.

• Luminosity increase proportional to $\beta_\gamma^*$ is not trivial at all.

• High Luminosity is only achieved, when the optics aberration at IP are perfectly corrected.

• QCS as error source and corrector is key component.

• Errors induced at QCS are enhanced for squeezing $\beta^*$.

• Correction of nonlinear aberration is next target in Phase-III commissioning.

• Final target, $L_{sp}=220 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}\text{mA}^{-2}$. 
Thank you for your attention
Transfer matrix, \( M \)

\[
M = RBUB^{-1}R^{-1} = RM_{2 \times 2}R^{-1}
\]

- Matrix transformation for \( R \).

\[
R = \begin{pmatrix}
    r_0 & 0 & r_4 & -r_2 \\
    0 & r_0 & -r_3 & r_1 \\
    -r_1 & -r_2 & r_0 & 0 \\
    -r_3 & -r_4 & 0 & r_0
\end{pmatrix}
\]

\[
B = \begin{pmatrix}
    B_x & 0 \\
    0 & B_y
\end{pmatrix}
\]

\[
\bar{y} = r_0 y - r_1 x - r_2 p_x
\]

\[
\bar{p}_y = r_0 p_y - r_3 x - r_4 p_x
\]

- Corresponding canonical transformation for \( R \).

\[
G_2(x, \bar{p}_x, y, \bar{p}_y) = xp_x + yp_y + axy + b\bar{p}_x y - cx\bar{p}_y - d\bar{p}_x \bar{p}_y
\]

\[
\bar{y} = \frac{\partial G_2}{\partial \bar{p}_y} = y - cx - d\bar{p}_x
\]

\[
p_y = \frac{\partial G_2}{\partial y} = \bar{p}_y + ax + b\bar{p}_x
\]

\[
\bar{x} = \frac{\partial G_2}{\partial \bar{p}_x} = x + by - d\bar{p}_y
\]

\[
p_x = \frac{\partial G_2}{\partial x} = \bar{p}_x + ay - c\bar{p}_y
\]

\[
c(\delta) \approx r_1(\delta) \quad d(\delta) \approx r_2(\delta) \quad a(\delta) \approx r_3(\delta) \quad b(\delta) \approx r_4(\delta)
\]
6D transfer map for chromatic coupling

- 4D transfer for \( a(\delta), b(\delta), c(\delta), d(\delta) \)

\[
R = \begin{pmatrix}
1 + \frac{ad}{1 + bc} & \frac{bd}{1 + bc} & b \left( 1 - \frac{ad}{1 + bc} \right) & -\frac{d}{1 + bc} \\
-\frac{1 + bc}{ac} & 1 & \frac{1}{1 + bc} & b \\
-c \left( 1 - \frac{ad}{1 + bc} \right) & -\frac{d}{1 + bc} & 1 + \frac{ad}{1 + bc} & \frac{cd}{1 + bc} \\
-\frac{a}{1 + bc} & -\frac{1 + bc}{b} & \frac{ab}{1 + bc} & \frac{1}{1 + bc}
\end{pmatrix}
\]

\[
\bar{p}_x = \frac{p_x - ay + cp_y + acx}{1 + bc}
\]

or

\[
\bar{p}_y = p_y - ax - b\bar{p}_x
\]

\[
\bar{x} = x + by - d\bar{p}_y
\]

\[
\bar{y} = y - cx - d\bar{p}_x
\]

- Z transfer

\[
\bar{z} = \frac{\partial G_2}{\partial \bar{p}_z} = z + a'xy + b'\bar{p}_x y - c'x\bar{p}_y - d'\bar{p}_x \bar{p}_y
\]

\[
c(\delta) \approx r_1(\delta) \quad d(\delta) \approx r_2(\delta)
\]

\[
a(\delta) \approx r_3(\delta) \quad b(\delta) \approx r_4(\delta)
\]
• Take Fourier transformation of the BPM position data.

- Take Fourier transformation of $x_{\text{IP}}$. 
- Evaluate Twiss parameters.
HER
Beam motion at Interaction Region (IR)

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0.6m  1.3m
0.53m  2.25m
Betatron phase, betatron tune

- **Beam position variation**
  
  \[ x_n = a \cos(2\pi n v_x + \phi_x) \]

  \( \phi_x \): Initial betatron phase at a position.

- **Fourier transformation of beam position**
  
  \[ x_v = \sum_{n=0}^{N} x_n \exp(2\pi i n v) \]
  
  \[ x_v = \frac{a}{2} \exp(-i \phi_x) \]

- **Betatron amplitude and phase**
  
  \[ a = \sqrt{\beta W} = 2|x_v| \]
  
  \[ \phi_x = -\tan^{-1}\left(\frac{\text{Im } x_v}{\text{Re } x_v}\right) \]

- **\( \alpha, \beta \)** are determined by Fourier transformation of \( p_x \).
  
  \[ p_n = -\frac{\beta}{\alpha} \sin(2\pi n v_x + \phi_x) - \sqrt{\beta} a \cos(2\pi n v_x + \phi_x) \]

  \[ p_v = \frac{b}{2} \exp(-i \phi_p) = \frac{a}{2} \left( -\frac{i}{\beta} + \frac{\alpha}{\sqrt{\beta}} \right) \exp(-i \phi_x) \]

  \[ \beta = \frac{a}{b \sin(\phi_p - \phi_x)} \]

  \[ \alpha = \frac{a \sqrt{\beta}}{b} \cos(\phi_p - \phi_x) \]
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• No dependence in R3