Low emittance and luminosity tuning in SuperKEKB

K. Ohmi (KEK)
Beam test and commissioning of
Low Emittance storage rings,
18-20 Feb, 2019,
Karlsruhe, Germany

Thanks to Y. Funakoshi, K. Hirosawa, H. Koiso, A. Morita, Y. Ohnishi, H. Sugimoto, D. Zhou
SuperKEKB

- Asymmetric $e^+e^-$ collider with energy 4 and 7 GeV.
- Collision with large Piwinski angle, $\phi_c \sigma_z / \sigma_x = 26$.
- Arc design ~ Very high current 3$^{rd}$ generation light source
- Interaction Point: Extremely low $\beta^*$, 3cmx0.3mm.
- Very large chromaticity and local correction in the Interaction Region.
## Machine Parameters

<table>
<thead>
<tr>
<th></th>
<th>LER</th>
<th>HER</th>
<th>unit</th>
</tr>
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<td>2011/July/20</td>
<td></td>
<td></td>
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<tr>
<td>E</td>
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<td>7.007</td>
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<tr>
<td>I</td>
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<td>$\sigma_\delta$</td>
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<td>6.37(6.31)x10^{-4}</td>
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<td>$\nu_c$</td>
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<td>$\sigma_z$</td>
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<td>Luminosity</td>
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<td>cm^{-2}s^{-1}</td>
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</table>
X-y coupling

- Eigenvector to resolve x-y coupling, $R$.

\[ x = R B X \]

\[ x(s + C) = U X(s) \]

\[ U = \begin{pmatrix} U_x & 0 \\ 0 & U_y \end{pmatrix} \quad U_x = \begin{pmatrix} \cos \mu_x & \sin \mu_x \\ -\sin \mu_x & \cos \mu_x \end{pmatrix} \]

\[ x(s + C) = M(s) x(s) \]

\[ M(s) = R(s) B(s) U B^{-1}(s) R^{-1}(s) \]

- $R(s)$ as Twiss parameters

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

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

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

\[ r_0 = \sqrt{1 - r_1 r_4 + r_2 r_3} \]

- Beam envelope matrix

\[ \langle X(s) X^t(s) \rangle = \begin{pmatrix} \varepsilon_x & 0 & 0 & 0 \\ 0 & \varepsilon_x & 0 & 0 \\ 0 & 0 & \varepsilon_y & 0 \\ 0 & 0 & 0 & \varepsilon_y \end{pmatrix} \]

\[ \langle x(s) x^t(s) \rangle = R(s) B(s) \langle XX^t \rangle B^t(s) R^t(s) \]

\[ x^t = (x, x', y, y') \]

\[ \langle yy \rangle = \sigma_y^2 \]
Normal mode X,Y and emittance

• Normal mode with eigenvalues, \( \exp(\pm i\mu_{X,Y}) \).
• Betatron motion, oscillation with frequency, \( \mu_{X,Y} \).
• Emittance rms of the normal mode amplitude, \( \varepsilon_X = \langle |X|^2 \rangle, \varepsilon_Y = \langle |Y|^2 \rangle \).
• Emittance is determined by radiation excitation and damping along the normal mode.

\[
\varepsilon_Y \propto \int \frac{\gamma_Y \eta_Y^2 + 2\alpha_Y \eta_Y \eta_Y' + \beta_Y \eta_Y'^2}{\rho^3} \, ds
\]

\( \eta_{X,Y}(s) = R^{-1}(s)\eta_{x,y}(s) \)

• To reduce \( \varepsilon_Y \), X-y coupling in bend should be suppressed.
• Global coupling determines vertical emittance.
Local x-y coupling and beam size

• Beam size at location given Twiss parameters.

\[
\sigma_y^2(s) \approx \sigma_Y^2 + \sigma_X^2 \left[ \frac{r_2^2}{\beta_x^2} + r_1^2 \right] + (\eta_y \sigma_\delta)^2
\]

\[
\sigma_Y^2(s) = \beta_Y(s) \varepsilon_Y \quad \sigma_X^2(s) \approx \sigma_X^2(s) = \beta_X(s) \varepsilon_X
\]

• Local vertical beam size consists of the vertical emittance and local x-y coupling R(s).

• x-y coupling at IP enhances emittance growth due to the beam-beam interaction.

• Beam size at Interaction Point determines luminosity performance.
Local coupling and beam distribution

\[ R1 \]

\[ R2, \eta \]

\[ \sigma_y^2(s) \approx \sigma_{y,0}^2 + \sigma_x^2 \left[ \frac{r_2^2}{\beta_x^2} + r_1^2 \right] + (\eta_y \sigma_\delta)^2 \]

R3 and R4 are explained by the same picture for \( p_y \).
X-y coupling correction in SuperKEKB

• Exciting 6 horizontal steerings one by one, measure closed orbit distortion in each.

• Vertical orbit is corrected by skew quads or vertical bump of sextupoles.

Before correction

• r1 and r2 at every s is corrected, r3 and r4 are corrected as the result.
• X-y coupling in LER is somewhat worse than HER.
# Optics Correction Summary

<table>
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<tr>
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<th>Phase 1</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>LER</td>
</tr>
<tr>
<td>$(\Delta \beta_{x,y} / \beta_{x,y})^{\text{rms}}$ [%]</td>
<td>3 / 3</td>
</tr>
<tr>
<td>$(\Delta y)^{\text{rms}} / (\Delta x)^{\text{rms}}$</td>
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<tr>
<td>$(\Delta \eta_{x,y})^{\text{rms}}$ [mm]</td>
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<tr>
<td>$\Delta \xi_{x,y}$</td>
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</table>

<table>
<thead>
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<th>Phase 2</th>
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</thead>
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<td>LER</td>
</tr>
<tr>
<td>$(\Delta \beta_{x,y} / \beta_{x,y})^{\text{rms}}$ [%]</td>
<td>2 / 4</td>
</tr>
<tr>
<td>$(\Delta y)^{\text{rms}} / (\Delta x)^{\text{rms}}$</td>
<td>0.014</td>
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<td>$(\Delta \eta_{x,y})^{\text{rms}}$ [mm]</td>
<td>10 / 4</td>
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<tr>
<td>$\Delta \xi_{x,y}$</td>
<td>2 / 3</td>
</tr>
</tbody>
</table>

**HER** $(\beta_x^*, \beta_y^*) = (100 \text{ mm}, 3 \text{ mm})$

**LER** $(\beta_x^*, \beta_y^*) = (200 \text{ mm}, 3 \text{ mm})$
Vertical Emittance in Phase 2

• Emittance of HER is improved compared with Phase 1.
• Emittance of LER is larger than that of Phase 1.
  
  Note: Residual of XY coupling is larger compared with Phase 1.

\[ \varepsilon_x = 3 \text{nm} \]

\[ \varepsilon_x = 5 \text{nm} \]

\[ \sigma_y = 40 \mu \text{m} \quad \beta_y = 69 \text{ m} \]

\[ \sigma_y = 16 \mu \text{m} \quad \beta_y = 28 \text{ m} \]

\[ \varepsilon_y \sim 23 \text{ pm} \]

\[ \varepsilon_y \sim 9 \text{ pm} \]
Beam size measurement using XRM

Masks: ~20 μm Au on 600 μm CVD diamond substrate

HER X-Ray Beam Profile Monitor

LER X-Ray Beam Profile Monitor

X-ray beam line under construction at LER
Beam life time vs vertical emittance

Touschek effect can be observed in LER.

\[ I_b = 1 \text{mA/bunch} \rightarrow N_e = 6 \times 10^{10} / \text{bunch} \]
SuperKEKB as a low emittance collider

• Compatibility of low emittance, beam-beam tune shift and luminosity

• Collision with Large crossing angle to avoid large horizontal tune shift.

• Extreme small $\beta_y$.

• Small $x$-$y$ coupling for keeping vertical beam-beam tune shift

\[
\Delta \nu_x = \frac{N_e r_e}{2\pi \gamma_p} \frac{\beta_x}{\sigma_x (\sigma_x + \sigma_y)} \\
\Delta \nu_y = \frac{N_e r_e}{2\pi \gamma_p} \frac{\beta_y}{\sigma_y (\sigma_x + \sigma_y)}
\]

\[
L = \frac{N_e N_p}{4\pi} \frac{f_{col}}{\sigma_x \sigma_y} = \frac{N_p \gamma_p \Delta \nu_y}{2r_e \beta_y} f_{col}
\]

Effective horizontal beam size

\[
\sigma_x = \sqrt{\beta_x \varepsilon_x + (\phi_c \sigma_z)^2}
\]

$\phi_c$: half crossing angle
Commissioning of SuperKEKB, Phase I

• Low emittance operation
  • X-y coupling, vertical dispersion correction.
  • X-ray beam size monitor using coded aperture.
  • Global X-y coupling <1% is achieved.
  • $I_+ = 1\text{A}$ and $I_- = 0.7\text{A}$ achieved without emittance growth.

• Check electron cloud instability, and other instabilities.
  • EC Instability was observed early stage, but suppressed by winding solenoids in bellow section not coated by TiN.
  • Beam size blow-up due to electron cloud is suppressed by 1A at least. $N_{\text{bunch}} = 1500$.

1mA/bunch=$6 \times 10^{10}$/bunch, C=3016m
Commissioning of SuperKEKB, Phase II

- $\beta$ squeezing
5.55 x 10^{33}/cm^2/s (β_y*3mm, LER: 800mA, HER: 780mA, 1576 bunches/beam July 5^th)
2.29 x 10^{33}/cm^2/s (β_y*3mm, LER: 270mA, HER: 225mA, 394 bunches/beam July 3^rd)
Observations

- 0 mA, $\sigma_y=0.3\mu m, 0.4\mu m$, $L_{sp}=35$
- 200x80 mA, $\sigma_y=0.5\mu m, 0.6\mu m$, $L_{sp}=23$
- 285x340 mA, $\sigma_y=1.5\mu m, 0.6\mu m$, $L_{sp}=11$

$L_{sp}$ agrees with geo value at high current $L_{sp}=20$ was at lowest current, 0.01 mA x 0.01 mA.

$L_{peak}=1.2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, 285x340 mA, $N_b=788$

Blow-up of e-beam was serious.

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

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

1 mA/bunch = $6 \times 10^{10}$/bunch
Optics aberration and tuning at IP

- In early stage of Phase II, luminosity of very low current contradict with the measured emittance.
- Luminosity did not increase for squeezing beta.
- Local coupling R2 at IP could be suspected.

\[
\sigma_y^2 \approx \sigma_Y^2 + \sigma_x^2 \left[ \frac{R_2^2}{\beta_x^2} + R_1^2 \right] + (\eta_y \sigma_\delta)^2
\]

\[
\sigma_Y^2(s) = \beta_Y(s) \epsilon_Y \quad \sigma_X^2(s) \approx \sigma_X^2(s) = \beta_X(s) \epsilon_X
\]

- R2 can be induced by skew rotation of both side of QCS.
- Induced R2 does not change for squeezing of $\beta^*$. 
- However effect of R2 is enhanced for squeezing $\beta^*$.

$$\Delta \phi = \frac{\pi}{2}$$

$\beta \beta^* \sim 1m^2$
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.

- Linear and nonlinear correction coils including skew are wound in QC1-2.
- R2 was corrected by a1 (skew Q) correction coil of QC1.
• R2 is changed 7mm in July 15-30, corresponding QCS rotation is ~7mrad.
June 30, 2018

Observations

- **0 mA, \( \sigma_{y0} = 0.25 \mu m \), \( 0.25 \mu m \), \( L_{sp} = 49 \)
- **200x160 mA, \( \sigma_{y0} = 0.4 \mu m \), \( 0.6 \mu m \), \( L_{sp} = 24.4 \)
- **285x340 mA, \( \sigma_{y0} = 0.6 \mu m \), \( 0.6 \mu m \), \( L_{sp} = 20.7 \)

\( L_{sp} \) agrees with geo value at every current

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

\( 10^{30} \) cm\(^{-2}\)s\(^{-1}\)/mA\(^2\)

\[ \sigma_{yc} = \sqrt{\sigma_{y+}^2 + \sigma_{y-}^2} \]

6/29 21:00 - R2 using QCS corrector

\( L_{peak} = 2.5 \times 10^{33} \) cm\(^{-2}\)s\(^{-1}\), (2 times higher)

285x340 mA, \( N_b = 788 \)

Blow-up of e+ beam was serious.
Beam-beam tune shift was saturated at $\Delta v_y (e^-) = 0.02$ due to $e^+$ beam blow-up.

Specific luminosity dropped at very low current.

$$L_{sp} = \frac{L}{n_b I_+ I_-} = \frac{1}{4\pi (\sigma_x \phi_x) e^2 f_0 \sigma_y} \frac{1.25 \times 10^{25}}{\sigma_y} \left[ cm^{-2} s^{-1} / mA^2 \right]$$

$L_{sp}$ at very low current is consistent with beam size measurement.

$$L_{sp} = 4 \times 10^{31} \rightarrow \sigma_y^* = 300 \text{ nm} \ (\varepsilon_y = 30 \text{ pm})$$
$$\leftrightarrow \varepsilon_y = 23 \text{ pm} \quad \text{Single beam measurement (LER)}$$

Achieved: $L_{sp} = 15 \times 10^{30} \text{ cm}^{-2} \text{s}^{-1} \text{mA}^{-2}$ at $0.4 \text{mA}^2$, $\Delta v_y = 0.02$ at $\beta_y = 3\text{mm}$

Final goal: $L_{sp} = 220 \times 10^{30} \text{ cm}^{-2} \text{s}^{-1} \text{mA}^{-2}$ at $1.5 \text{mA}^2$, $\Delta v_y = 0.08$ at $\beta_y = 0.3\text{mm}$

$1\text{mA/bunch} = 6 \times 10^{10} / \text{bunch}$
TbT measurement of x-y coupling at IP

• y motion in X mode.

\[ x = RBX \]

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

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

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

r1: cos component of y for x betatron motion , r2: sin component

\[ y = -r_1 x - r_2 p_x = -r_1 a \cos \phi(s) + r_2 \left[ \frac{a}{\beta} \sin \phi(s) + \frac{\alpha}{\sqrt{\beta}} a \cos \phi(s) \right] \]

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

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

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

r3: cos component of y for px betatron motion , r4: sin component

\[ p_y = r_3 x - r_4 p_x = r_3 a \cos \phi(s) + r_4 \left[ \frac{a}{\beta} \sin \phi(s) + \frac{\alpha}{\sqrt{\beta}} a \cos \phi(s) \right] \]

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

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

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

• \(x_L, y_L\) left side and \(x_R, y_R\) right side monitor of IP.

• Small \(y_{IP}\), but enough \(p_{y_{IP}} = q_{IP}\). R1 and R2 is hard to measure compare with R3, R4.
LER

$r_3 = 0.24 + 338\delta$

$r_4 = -0.15 + 8.9\delta$
Toward Phase III (start Mar. 2019)

• 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 $1.5 \text{mA}^2$. $\beta_y * 1/10$
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.

\[ 1 \text{mA/bunch}=6\times10^{10}/\text{bunch} \]
Nonlinear aberrations

\[ M = \exp(\pm c_{10} p_x^2 p_y^2) = \exp(\pm c_{10} x^2 y) \]

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

![Graph showing the relationship between \( L_{spec} \) and \( I_\text{bunch} \)](image)

1 mA/bunch = 6x10^{10} / bunch
Chromatic coupling

\[ M = \exp(\pm: R_2' p_x^* p_y^* \delta: \pm: R_1' x^* p_y^* \delta:) = \exp(\pm: R_2' x y \delta: \pm: R_1' p_x y \delta) \]

- R3’ and R4’ were measured to be R3’=300, R4’=20.
- The behaviors for R1’ and R2’ are plausible.
- R1’ and R2’ are hard to be measured in the present monitor. R1’ ~-10 was measured. Reliable?

1mA/bunch=6x10^{10}/bunch
Summary

• Phase II commissioning was done by July 2018.
• Collision with $\beta^*_x=0.1m(e^-), 0.2m(e^+), \beta^*_y=3\text{mm}$ was established.
• Luminosity gain squeezing $\beta^*$ is not trivial, considering various errors.
• $L=5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ was achieved. Beam-beam tune shift is limited to be $\Delta \nu_y(e^-)=0.02$ due to $e^+$ beam blow-up.
• Electron cloud instability seems to be managed well.
• Phase III commissioning starts Mar. 2019.
• $\Delta \nu_y(e^{+-})=0.04$ is minimum target. Final goal 0.06-0.08.
• We expect nonlinear/chromatic aberration at IP as sources of the luminosity degradation.
• The correction can be done skew sextupoles and QCS nonlinear coils.
• Otherwise our luminosity tuning may become deadlock.
HER

\[ F_0 = 100 \text{kHz} \]

\[ r_2 (\text{MQC1}) \]

\[ r_3 (\text{MQC1}) \]

\[ r_4 (\text{MQC1}) \]

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

\[ r_3 = 1.0 + 137\delta \]
QCS superconducting magnet system

• R2 was corrected by a1 correction coil of QC1.