Optics Correction
and
Low Emittance Tuning

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for SuperKEKB Optics&Commissioning Group
Optics correction and hardware calibration are iteratively repeated.
Some details of optics correction are reported in this talk.
Establish optics measurement and correction tools
- Optics and orbit servers to control the magnet system.
- Continuous Closed orbit correction
- Tune Changer
- Optics measurement and correction
- Local-bump control
- etc…

Hardware calibration and bug hunt
- Polarity check of the magnet using beam measurement.
- Check BPM system (e.g. cabling, aging effect)
- Beam based alignment (BBA)
- etc…

Others
- Check validity of the model lattice and correct the model if needed.

Low emittance tuning (LET)

Target vertical emittance is < 5-10 pm.
Measurement Method

• **Optics measurement with orbit response analysis**
  
  - Horizontal-vertical (XY) coupling:
    Vertical leakage orbits induced by horizontal kicks.
  
  - Dispersion:
    Response with RF frequency change.
  
  - Beta function:
    Orbit response analysis with steering kicks.

• ~60 BPMs (per ring) can be used with turn by turn (TBT) mode.
  
    - Results are preliminary and not presented this report.
Orthogonal Correctors

- **Skew quadrupole (SkewQ) coil of sextupole magnet**
  Symmetric / asymmetric excitation of skew-corrector pair can be used as orthogonal correctors for coupling and vertical dispersion. The orthogonality allows us to reduce size of the problem.
Beam Based Alignment (BBA)

- All quadrupole magnets have BPM. (~ 450 BPMs per ring)
- Calibrate BPM offset so that the beam passes through the magnetic center of the nearby magnet
- The measurement is carried out in spare moments from vacuum scrubbing.

**Benefit from BBA**

- **Before BBA:** Hit hardware limit of corrector strength.
- **After BBA:** Required corrector strength is remarkably reduced and allows us to further correction.
Beta and phase functions are extracted from orbit response. 12 orbit responses are used. (6 per each direction)

\[ \Delta \beta_x / \beta_x \% \]

\[ \Delta \beta_y / \beta_y \% \]

\[ \phi_{x \text{meas}} - \phi_{x \text{model}} \text{ [rad]} \]

\[ \phi_{y \text{meas}} - \phi_{y \text{model}} \text{ [rad]} \]

\[ (\Delta \beta_x / \beta_x)_{\text{rms}} \sim 19.5 \% \]

\[ (\Delta \beta_y / \beta_y)_{\text{rms}} \sim 20.5 \% \]

\[ \Delta \nu_x \sim -0.074 \]

\[ \Delta \nu_y \sim -0.141 \]
Beta-Beat after Correction

- Use quadrupole families distributed over the ring.

\[ \Delta \beta_x / \beta_x \; [\%] \]
\[ \Delta \beta_y / \beta_y \; [\%] \]
\[ \phi_x^{\text{meas}} - \phi_x^{\text{model}} \; [\text{rad}] \]
\[ \phi_y^{\text{meas}} - \phi_y^{\text{model}} \; [\text{rad}] \]

\[ (\Delta \beta_x / \beta_x)_{\text{rms}} \sim 2.0 \% \]
\[ (\Delta \beta_y / \beta_y)_{\text{rms}} \sim 2.9 \% \]
\[ \Delta \nu_x \sim 0.004 \]
\[ \Delta \nu_y \sim 0.001 \]
Horizontal Dispersion

- **Correction with horizontal orbital bumps at sextupoles.**
  Found that uncorrectable dispersion remains.
  The error source seems to be located in the Tsukuba straight section.

- **Quadrupoles in the Tsukuba section is additionally used.**
  A magnet name QLA2RP somehow shows the strongest corrector strength.

\[
\Delta \eta_x \ [\text{mm}] \\
\text{Horizontal bump} \ [\text{mm}] \\
\text{Quadrupole} \ [1/\text{m}]
\]

### Before Correction
- \((\Delta \eta_x)_{\text{rms}} = 49 \ [\text{mm}]\)

### After Correction
- \((\Delta \eta_x)_{\text{rms}} = 16 \ [\text{mm}]\)

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2016/06/13
The 21th KEKB Accelerator Review Committee
Horizontal Dispersion

- **Correction**
  - Found that uncorrectable dispersion remains.
  - The error source seems to be located in the Tsukuba straight section.

- **Quadrupole**
  - Quadrupoles in the Tsukuba section is additionally used.
  - A magnet name QLA2RP somehow shows the strongest corrector strength.

The most crowded region in the tunnel. Suspect Interference between magnets.

\[ \Delta \eta_x \text{ [mm]} \]

**Horizontal bump [mm]**

**Quadrupole [1/m]**

QLA2RP

LER

HER Bend

LER

HER
XY-Coupling Measurement

- Not so easy to extract optical coupling parameters $R_{1-4}$ from closed orbit response.
- Measure vertical leakage orbits induced by 6 steering kicks.
XY-Coupling Correction

- Use the orthogonal correctors.
- The presented correction scheme effectively works, but...

V. orbit by H. steering

\[ \text{LER} \]

\[ \text{LER} \]

\[ \text{LER} \]

\[ \text{LER} \]

\[ \text{LER} \]

\[ \text{LER} \]

\[ \text{LER} \]

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\[ \text{LER} \]

\[ \text{LER} \]
XY-Coupling Correction

- Use the orthogonal correctors.
- The presented correction scheme effectively works, but…

Uncorrectable XY-coupling remains.
Leakage Field from Lambertson Septum

- A Lambertson septum is used to deliver aborted beam to a beam dump.
- This magnet creates unexpected leakage field to stored beam line.
Historical Background

• The problem was founded at the previous KEKB commissioning already.
  - They installed permanent magnets to cure this problem (04/2000)

• The leakage field gets stronger in SuperKEKB.
  - The vacuum chamber is replaced by an anti-chamber.
  - A magnetic shielding system gets less effective due to clearance problem of the wider aperture.  

A note from the previous KEKB commissioning

Tunnel survey@03/17/2016

Series of permanent magnets
Cure to the Leakage Field

- Activate two SkewQ coils installed in SF magnets using standby PS.
Correction with the Additional SkewQ

- The vertical leakage orbit is reduced.

Before

After
For Further Improvement

- A hardware group proposes a permanent SkewQ using Ferrite magnets.
- Installed it last Wednesday (June 8).

Ferrite magnets

\[ B \sim 0.07 \, [T] \]
Measurement before & after Installation

- Further improvement in the vertical leakage orbit.
Vertical Dispersion after Installation

- A sharp peak of vertical dispersion is vanished.
- As a result RMS residual is reduced from 6 mm to 4 mm.

Residual V. dispersion

\[ \Delta \eta_y \ [\text{mm}] \]

Corrector strength

\[ K_1 \ [1/\text{m}] \]

Strong corrector field is vanished owing to the permanent SkewQ.
Vertical Emittance

LER

WER X-Ray Beam Profile Monitor

\[ \beta_y = 67 \text{ m} \]

\[ \varepsilon_y \sim 12 \text{ pm} \]

HER

Estimation with beam size measurement

\[ \varepsilon_y \sim 120 \text{ pm} \]

Estimation with measured optics

\[ \varepsilon_y \sim 10 \text{ pm} \]

Flanagan-san’s talk?

The exact value is still under discussion.
• Measure Betatron tune with changing RF frequency.

Horizontal

\[ \nu_x \]\n
\[ \xi_x \sim 10.6 \]

\[ \xi_x \sim 9.8 \]

\[ \Delta p/p_0 \% \]

Measurement

Model

Vertical

\[ \nu_y \]

\[ \xi_y \sim 9.6 \]

\[ \xi_y \sim 9.5 \]

\[ \Delta p/p_0 \% \]

• Good agreement between the real and model lattice.
• Measure Betatron tune with changing RF frequency.

**Horizontal**

\[ \nu_x \]

**Measurement**

\[ \xi_x \approx 5.2 \]

**Model**

\[ \xi_x \approx 3.1 \]

\[ \Delta p/p_0 \text{ [%]} \]

**Vertical**

\[ \nu_y \]

**Measurement**

\[ \xi_y \approx 5.2 \]

\[ \xi_y \approx 9.6 \]

\[ \Delta p/p_0 \text{ [%]} \]

• **Large discrepancy compared with that of HER.**

• Off-momentum beta and phase are measured and analyzed. No big error sources are founded so far.

• Need more study to clarify the source of the discrepancy.
Error of the linear chromaticity in LER is still mystery.

The exact value of vertical emittance is still unknown.
Establish optics measurement and correction tools.
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Hardware calibration and bug hunt.
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Mystery of tune chromaticity in LER

Low emittance tuning (LET)

Reached ~10pm?, the exact value is still under discussion.
Thank you for listening
### Machine Parameters in Phase I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LER</th>
<th>HER</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>4.000</td>
<td>7.007</td>
<td>GeV</td>
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<tr>
<td>Beam current</td>
<td>910</td>
<td>830</td>
<td>mA</td>
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<tr>
<td># of bunches</td>
<td>1576</td>
<td>1576</td>
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<tr>
<td>Bunch current</td>
<td>0.58</td>
<td>0.52</td>
<td>mA</td>
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<tr>
<td>Hor. emittance</td>
<td>1.8</td>
<td>4.6</td>
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<tr>
<td>Momentum compaction</td>
<td>$2.45 \times 10^{-4}$</td>
<td>$4.44 \times 10^{-4}$</td>
<td></td>
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<tr>
<td>Energy spread</td>
<td>$7.5 \times 10^{-4}$</td>
<td>$6.3 \times 10^{-4}$</td>
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</tr>
<tr>
<td>Total $V_c$</td>
<td>7.56</td>
<td>12.45</td>
<td>MV</td>
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<tr>
<td>Bunch length</td>
<td>4.6</td>
<td>5.3</td>
<td>mm</td>
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<tr>
<td>$\nu_s$</td>
<td>-0.019</td>
<td>-0.025</td>
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</tr>
<tr>
<td>Tune $\nu_x/\nu_y$</td>
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<td>45.57/43.61</td>
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<tr>
<td>$U_0$</td>
<td>1.76</td>
<td>2.43</td>
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<tr>
<td>$\tau_{x,y}/\tau_x$</td>
<td>46/23</td>
<td>58/29</td>
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## Machine Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LER</th>
<th>HER</th>
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<tr>
<td>E</td>
<td>4.000</td>
<td>7.007</td>
<td>GeV</td>
</tr>
<tr>
<td>I</td>
<td>3.6</td>
<td>2.6</td>
<td>A</td>
</tr>
<tr>
<td>Number of bunches</td>
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<tr>
<td>Bunch Current</td>
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<td>εx/εy</td>
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<td>4.6(4.4)/12.9(1.5)</td>
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<td>σδ</td>
<td>8.10(7.73)x10^-4</td>
<td>6.37(6.30)x10^-4</td>
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<tr>
<td>Vc</td>
<td>9.4</td>
<td>15.0</td>
<td>MV</td>
</tr>
<tr>
<td>σz</td>
<td>6.0(5.0)</td>
<td>5(4.9)</td>
<td>mm</td>
</tr>
<tr>
<td>Vs</td>
<td>-0.0244</td>
<td>-0.0280</td>
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<tr>
<td>Vx/Vy</td>
<td>44.53/46.57</td>
<td>45.53/43.57</td>
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<tr>
<td>U0</td>
<td>1.86</td>
<td>2.43</td>
<td>MeV</td>
</tr>
<tr>
<td>Τx,y/Τs</td>
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<td>58.0/29.0</td>
<td>msec</td>
</tr>
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<td>0.0012/0.0807</td>
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</tr>
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<td>Luminosity</td>
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<td>cm^{-2}s^{-1}</td>
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