Beam Dynamics Issues in SuperKEKB

D. Zhou

With contributions from

KEK: T. Ishibashi, K. Ohmi, K. Oide, Y. Ohnishi, K. Shibata, H. Sugimoto, ...

Cornell Univ.: D. Sagan

IHEP: Y. Zhang

SLAC: Y. Cai

The 20th KEKB Accelerator Review Committee, Feb. 23, 2015
Outline

➤ Impedance issues - updates
➤ Interplay of beam-beam (BB) and lattice nonlinearity (LN)
➤ Space charge (SC) effects in LER
➤ Luminosity calculation for detuned lattices
➤ Benchmark of SAD
➤ Summary and Future plan
Outline

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➤ Benchmark of SAD
➤ Summary and Future plan
1. Impedance issues: LER

Clearing electrode

Grooved surfaces

From T. Ishibashi

Tested in KEKB

Ref. Y. Suetsugu et al., NIMA 598 (2009)  
Ref. Y. Suetsugu et al., NIMA 604 (2009)
1. Impedance issues: LER

➤ Pseudo-Green wake function

● $\sigma_z=0.5\text{mm}$

● Pumping ports and SR masks are negligible sources because of antechamber

● CSR and CWR (Wiggler radiation): CSRZ code with rectangular chamber
1. Impedance issues: LER

- Wake potential with nominal bunch length
  - $\sigma_z = 5$mm
  - Main sources: Collimators, Resistive wall, ARES cavity, Bellows, MO flanges, Clearing electrodes
  - CSR and CWR are not strong if no microbunching happens
1. Impedance issues: Impedance budget

- Impedance budget with $\sigma_z=5/4.9\text{mm}$:
  - Loss factors, resistance and inductance are calculated at nominal bunch lengths
  - Bellows, flanges and pumping ports contribute more impedance in HER than in LER

<table>
<thead>
<tr>
<th>Component</th>
<th>LER</th>
<th>HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>3016.25</td>
<td>3016.25</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>4</td>
<td>7.007</td>
</tr>
<tr>
<td>Bunch population ($10^{10}$)</td>
<td>9.04</td>
<td>6.53</td>
</tr>
<tr>
<td>Nominal bunch length (mm)</td>
<td>5</td>
<td>4.9</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.0244</td>
<td>0.028</td>
</tr>
<tr>
<td>Long. damping time (ms)</td>
<td>21.6</td>
<td>29.0</td>
</tr>
<tr>
<td>Energy spread ($10^{-4}$)</td>
<td>8.1</td>
<td>6.37</td>
</tr>
</tbody>
</table>

Table 2: Key parameters of SuperKEKB main rings for MWI simulations.

Ref. D. Zhou et al., IPAC14, TUPRI021
1. Impedance issues: MWI: LER

➤ Simulations with input of Pseudo-Green wake:

● Use Warnock-Cai’s VFP solver
● Collimators are important sources in bunch lengthening
● Simulated $\sigma_z \approx 5.9\text{mm}$ @Design bunch current
● Simulated MWI threshold is around $N_{P_{th}}=1.2E11$
● Interplay between CSR and conventional wakes?
1. Impedance issues: MWI: HER

- Simulations with input of Pseudo-Green wake:
  - Use Warnock-Cai’s VFP solver
  - Simulated $\sigma_z \approx 5.8\text{mm}$ @Design bunch current
  - Simulated MWI threshold is around $NP_{th} = 1.7E11$
  - Y. Cai’s comment: CSR should not be important in SuperKEKB (consider shielding and long bunch).
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➤ Summary and Future plan
2. BB+LN: LER: Simplified IR

➤ Simplified lattice (sler_simple001.sad) by H. Sugimoto
  ● No solenoid
  ● QC* magnets simplified: no offset, dipole and skew-quad correctors removed

➤ No significant lum. degradation at low current
➤ Solenoid and high-order terms in QC* are the main sources of lattice nonlinearity
2. BB+LN: Nonlin. X-Y coupling

➤ Realistic lattice
➤ Y. Zhang’s idea: Look at the nonlinear X-Y coupling

sher-5767 vs ler-1689 in X direction

From Y. Zhang
2. BB+LN: Nonlin. X-Y coupling

- Realistic lattice
- Poincare map in y direction as function of X offset
- Strong nonlinear X-Y coupling in LER

sher-5767 vs ler-1689 in Y direction

From Y. Zhang
2. BB+LN: Nonlin. X-Y coupling

➤ Simplified LER lattice (From H. Sugimoto)
➤ Confirm: solenoid and high-order terms in QC* magnets cause nonlinear X-Y coupling
2. BB+LN: Nonlin. X-Y coupling

Test by inserting a map of $H = K x^2 y$ into the LER lattice

```plaintext
GetMAIN["/ldata/SuperKEKB/Lattice/LER/sler_1689.sad"]; USE ASC;
b=ExtractBeamLine[];
b=Prepend[Drop[b,2],BeamLine[IP,BMBMP,SKEWSEXT]];

!!! Define external maps of skew sextupole (from Y. Zhang)
lambda=-66.6;
cosx = Cos[-1.571];
sinx = Sin[-1.571];
cosy = Cos[-1.351];
siny = Sin[-1.351];
ExternalMap["TRACK",LINE["POSITION","SKEWSEXT"],nt_,x_,y_]:=C

normalx = cosx * xx - sinx * px;
normalpx = sinx * xx + cosy * px;
normaly = cosy * yy - siny * py;
normalpy = siny * yy + cosy * py;
xx = normalx*Sqrt[32e-3];
px = normalpx*Sqrt[32e-3];
yy = normaly*Sqrt[0.27e-3];
py = normalpy*Sqrt[0.27e-3];
zz=x[[5]];
dd=x[[6]];
fl=x[[7]];
Return[{xx,px,yy,py,zz,dd,fl}];
```

Phase advance from IP
Normalized coordinates
Phase shift
skew-sext. kick

From Y. Zhang
2. BB+LN: Nonlin. X-Y coupling

➤ Test by inserting a map of $H=Kx^2y$ into the LER lattice
➤ COD and oscillation amplitude in $y$ are well suppressed as expected

From Y. Zhang
2. BB+LN: Luminosity: LER

- 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
2. BB+LN: Luminosity: LER

➤ Test by inserting a map of $H=Kx^2y$ into the LER lattice

➤ Skew-sext. map:
  - To cancel the nonlinear terms from solenoid and QC*
  - Work well at both low and high currents
  - Interplay of SC and lattice nonlin. also mitigated partially
2. BB+LN: LER: DA and lifetime

➡️ Test by inserting a map of $H=K^*x^2y$ into the LER lattice

➡️ Skew-sext. map:
  ● cause loss in DA and lifetime
  ● not perfect

From H. Sugimoto
2. BB+LN: Quasi-strong-strong simulation

Condition

• Assumption
  - Phase space distribution is upright during collisions.
    (i.e. alphax=0, alphay=0, etax=0, …)

• Fitting procedure
  - Gaussian fit is done for x, px, y, py, z, delta independently.
  - EMITX, EMITY, BX, BY, SIGZ, DP are obtained the fitting.

• The beambeam element is updated with the above 6 parameters.

• # of particles = 2000

• Case A: Update interval is 1000 turns
  Case B: Update interval is 10 turns, average of the last 10 turns
  Case C: Update interval is 1000 turns, exponentially weighted average of
    the all past data with damping rate of 1000 turns
  Case D: Case C with interval = 1 turn
  Case E: Case D with damping rate = 200 turns

From H. Sugimoto
2. BB+LN: Quasi-strong-strong simulation

From H. Sugimoto
2. BB+LN: Quasi-strong-strong simulation

From H. Sugimoto
2. BB+LN: Quasi-strong-strong simulation

Luminosity vs. Beam Current (LER)

- Done with the parameters of Case D.

From H. Sugimoto
2. BB+LN: Quasi-strong-strong simulation

Luminosity vs. Beam Current (HER)

- Done with the parameters of Case D.

From H. Sugimoto
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➤ Luminosity calculation for detuned lattices
➤ Benchmark of SAD
➤ Summary and Future plan
3. SC effects: LER

➤ FMA shows betatron tunes of particles at the beam core are close to half-integer with only SC considered.

From H. Sugimoto

4\textsuperscript{th} order
5\textsuperscript{th} order
6\textsuperscript{th} order
7\textsuperscript{th} order

Detailed Studies are now ongoing.
- Optics matching
- Checking simulation code including SAD code itself.

From H. Sugimot
3. SC effects: LER

- FMA with beam distribution: $10\sigma_x \times 10\sigma_y$

LN + SC

LN + SC + BB
3. SC effects: LER

- Luminosity: Tune scan w/ and w/o SC

**Hor. tune scan**

**Vert. tune scan**

![Graph of Hor. tune scan](image1)

![Graph of Vert. tune scan](image2)

![BBWS](image3)
3. SC effects: LER

➤ First try: optics matching w/o SC
➤ Compensate linear SC tune shift => Not successful
➤ Next try: optics matching w/ SC => Ongoing

![Graph showing specific lum. vs. product of bunch currents]

- BBWS
- w/ SC (no optics matching)
- w/ SC (optics matching w/o SC)
- Design

Specific Lum. $[10^{32} \text{cm}^{-2} \text{s}^{-1} \text{mA}^{-2}]$

$I_{bunch}(e^+) \times I_{bunch}(e^-)$ $[\text{mA}^2]$
3. SC effects: LER

Independent simulation (BBWS+SC) showed SC effects are not serious, but:

- No lattice nonlinearity
- Simple model for SC (Only consider tune spread due to SC)
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4. Lum. calculation: Detuned lattice

- Detuned lattice: sler_1689_d4-8/sher_5767_d4-8

<table>
<thead>
<tr>
<th>Parameters</th>
<th>symbol</th>
<th>Phase 2.x</th>
<th>Phase 3.x</th>
<th>unit</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>LER</td>
<td>HER</td>
<td>LER</td>
</tr>
<tr>
<td>Energy</td>
<td>E</td>
<td>4</td>
<td>7.007</td>
<td>4</td>
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<tr>
<td>#Bunches</td>
<td>(n_b)</td>
<td>2500</td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>Emittance</td>
<td>(\epsilon_x)</td>
<td>2.2</td>
<td>5.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Coupling</td>
<td>(\epsilon_y/\epsilon_x)</td>
<td>2</td>
<td>2</td>
<td>0.27</td>
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<tr>
<td>Hor. beta at IP</td>
<td>(\beta_x^o)</td>
<td>128</td>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>Ver. beta at IP</td>
<td>(\beta_y^o)</td>
<td>2.16</td>
<td>2.4</td>
<td>0.27</td>
</tr>
<tr>
<td>Beam current</td>
<td>(I_b)</td>
<td>1.0</td>
<td>0.8</td>
<td>3.6</td>
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<tr>
<td>Beam-beam</td>
<td>(\xi_y)</td>
<td>0.0240</td>
<td>0.0257</td>
<td>0.088</td>
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<tr>
<td>Hor. beam size</td>
<td>(\sigma_x^o)</td>
<td>16.8</td>
<td>22.8</td>
<td>10</td>
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<tr>
<td>Ver. beam size</td>
<td>(\sigma_y^o)</td>
<td>308</td>
<td>500</td>
<td>48</td>
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<tr>
<td>Luminosity</td>
<td>(L)</td>
<td>(1\times10^{34})</td>
<td>(8\times10^{35})</td>
<td></td>
</tr>
</tbody>
</table>

**LER**
- \(\beta_x\) at IP: 128 mm
- \(\beta_y\) at IP: 2.16 mm
- \(I_b\): 1 A
- \(n_b\): 2500
- \(\epsilon_x\): 1.75 nm
- \(\epsilon_y/\epsilon_x\): 2%

**HER**
- \(\beta_x\) at IP: 100 mm
- \(\beta_y\) at IP: 2.40 mm
- \(I_b\): 0.8 A
- \(n_b\): 2500
- \(\epsilon_x\): 4.5 nm
- \(\epsilon_y/\epsilon_x\): 2%

*From Y. Ohnishi*
4. Lum. calculation: Detuned lattice

➤ Assume: $\varepsilon_x = 1.75\text{nm}$, coupling = 2%
➤ Space-charge is not important
➤ Lattice nonlinearity is not very important
➤ $L=1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ is promising
➤ $L=10 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ is possible by increasing beam currents
4. Lum. calculation: Detuned lattice

➤ Assume: $\epsilon_x=1.75\text{nm}$, coupling = 2%
➤ Compare with the case of simplified IR
➤ Solenoid not to cause lum. loss
4. Lum. calculation: Detuned lattice

➤ Assume: $\varepsilon_x=1.75\text{nm}$, coupling = $1\%$
➤ Space-charge is not important at low currents
➤ Lattice nonlinearity is not very important
➤ Decreasing coupling => Lum. gain but beam-beam limit appears at lower beam currents
4. Lum. calculation: Detuned lattice

➢ LER: Tolerance for errors in various optics parameters at IP (Assume 10% of lum. loss)

<table>
<thead>
<tr>
<th>( \frac{\varepsilon_y}{\varepsilon_x} \beta_y^* )</th>
<th>2%, 2.2mm</th>
<th>1.5%, 1.1 mm</th>
<th>0.28%, 0.3 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta x ) (( \mu \text{m} ))</td>
<td>77</td>
<td>30</td>
<td>7.2</td>
</tr>
<tr>
<td>( \Delta y ) (( \mu \text{m} ))</td>
<td>0.35</td>
<td>0.2</td>
<td>0.025</td>
</tr>
<tr>
<td>R1 (mrad)</td>
<td>18</td>
<td>8.2</td>
<td>1.5</td>
</tr>
<tr>
<td>R2 (mm)</td>
<td>2.3</td>
<td>1.6</td>
<td>0.06</td>
</tr>
<tr>
<td>R3(( \text{m}^{-1} ))</td>
<td>50</td>
<td>7.9</td>
<td>4.9</td>
</tr>
<tr>
<td>R4(rad)</td>
<td>3.7</td>
<td>0.93</td>
<td>0.21</td>
</tr>
<tr>
<td>( \eta_y ) (mm)</td>
<td>0.33</td>
<td>0.23</td>
<td>0.017</td>
</tr>
<tr>
<td>( \eta'_y ) (mrad)</td>
<td>1</td>
<td>0.44</td>
<td>0.08</td>
</tr>
</tbody>
</table>

From K. Ohmi
Outline

➤ Impedance issues - updates
➤ Interplay of beam-beam (BB) and lattice nonlinearity (LN)
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➤ Luminosity calculation for detuned lattices
➤ **Benchmark of SAD**
➤ Summary and Future plan
5. Benchmark of SAD: sher_5764

Optics parameters at IP with $\delta=0$

- In general, Bmad agrees well with SAD

Bmad:
$\beta_x=0.02498209\text{m}$, $\alpha_x=-4.959\text{E}-5$, $\nu_x=45.5299896$,
$D_x=-4.\text{E}-8\text{m}$, $D'_x=-8.16\text{E}-6$,
$\beta_y=2.941\text{E}-4\text{m}$, $\alpha_y=-6.791\text{E}-5$, $\nu_y=43.56852721$,
$D_y=-4.55\text{E}-9$, $D'_y=-2.4\text{E}-7$,

SAD:
$\beta_x=0.025\text{m}$, $\alpha_x=-1.34\text{E}-12$, $\nu_x=45.53$,
$D_x=-1.03\text{E}-13\text{m}$, $D'_x=-3.11\text{E}-13$,
$\beta_y=3.\text{E}-4\text{m}$, $\alpha_y=-3.545\text{E}-13$, $\nu_y=43.57$,
$D_y=2.963\text{E}-15$, $D'_y=-1.616\text{E}-12$, 
5. Benchmark of SAD: sher_5764

➢ Optics parameters at IP with $\delta=0.002$

● In general, Bmad agrees well with SAD

**Bmad:**

$\beta_x=0.32635028E-01m, \alpha_x=0.65882408E-01, \nu_x=45.536646, \newline D_x=-0.47815350E-03m, D'_x=-0.11870747E-01, \newline \beta_y=0.31470442E-03m, \alpha_y=0.13545109E-01, \nu_y=43.577108, \newline D_y=0.64778741E-06, D'_y=0.23488780E-02,$

**SAD:**

$\beta_x=.032642757m, \alpha_x=.0658513493, \nu_x=45.536688655, \newline D_x=-.0004781727, D'_x=-.01190317, \newline \beta_y=.00032006m, \alpha_y=.01341448, \nu_y=43.57852356, \newline D_y=6.27523687e-07, D'_y=.0022601526,$
5. Benchmark of SAD: FMA: sler_1684

➤ X-Y space

- Bmad and SAD give similar DA in size
- Discrepancy is due to use of different maps for high-order nonlinear terms in elements such as solenoid
5. Benchmark of SAD: FMA: sler_1684

➤ Tune space
  - Discrepancy is due to use of different maps for high-order nonlinear terms in elements such as solenoid
5. Benchmark of SAD: luminosity calculation

➤ Compare with SCTR code (by K. Ohmi)
  • Test on simplified lattice (sler_simple001.sad)
  • Discrepancy observed
  • Need to compare in detail the nonlinear maps used in SAD, SCTR and Bmad.

From K. Ohmi
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➤ Luminosity calculation for detuned lattices
➤ Benchmark of SAD and Bmad
➤ **Summary and Future plan**
6. Summary

➤ Impedance issues
  ● Impedance model updated
  ● MWI simulation updated

➤ BB+LN
  ● Nonlinear amplitude-dependent X-Y coupling identified
  ● Solenoid and high-order terms in QC* magnets are the main sources of LN
    ● Mitigation methods to be investigated

➤ Space charge
  ● To be investigated
  ● Optics matching with SC (need to upgrade SAD?)

➤ Lum. calculation for detuned optics
  ● SC and LN likely not to cause lum. loss
  ● $L=1\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ is promising, $L=10\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ is possible

➤ Benchmark of SAD
  ● Successful and need more efforts
6. Summary

➢ Interplay of various issues
  - Luminosity <= Emittance <= Beam-beam, Lattice nonlinearity, Space charge, Impedances, Electron cloud, Intra-beam scattering, etc.
  - => Dynamic aperture and lifetime => Beam commissioning => Injection, Detector background, Alignments, etc. => Tolerance for hardwares => ...
7. Future plan

➤ Detailed analysis of lattice nonlinearity under an international collaboration program
  ● Cornell Univ.: D. Sagan (Bmad+PTC)
  ● SLAC: Y. Cai
  ● IHEP: Y. Zhang

➤ Collaboration with CEPC/FCC-ee teams

➤ High-priority tasks:
  ● Global or local correction schemes for latt. nonlin.
  ● SC compensation schemes
  ● Better understand beam-beam physics for nano-beam scheme
  ● More benchmark studies for SAD
  ● ... ...

➤ Recommendations are welcome!
Thanks for your attention!