Beam-beam and electron cloud effects in FCC-ee

K. Ohmi (KEK)

Thanks to W. Chou, K. Oide, D. Shatilov, Y. Zhang, D. Zhou, F. Zimmermann
Introduction

• Beam-beam simulations
  • Strong-strong simulations for luminosity prediction
  • Coherent instability
  • Collective emittance growth

• Study of electron cloud effects
  • FCC-ee TLEP-Z,W,H,t

• Study of ion instability
  • FCC-ee TLEP-Z
### Parameters for FCC-ee’s; CEPC and TLEP

<table>
<thead>
<tr>
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<td>0.8</td>
<td>1.7</td>
</tr>
<tr>
<td>emittance εₓ (nm)/εᵧ (pm)</td>
<td>6.1/18</td>
<td>0.09/1</td>
<td>0.27/1</td>
<td>0.61/1.2</td>
<td>1.3/2.5</td>
</tr>
<tr>
<td>Beta at IP βₓ (m)/βᵧ (mm)</td>
<td>0.8/1.2-3</td>
<td>1/2</td>
<td>1/2</td>
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</tr>
<tr>
<td>Synchro. tune νₛ</td>
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<td>Bunch length σₓ₁₁₁ / σₓ₁₁₁ (mm)</td>
<td>2.3/2.6</td>
<td>2.7/5.0</td>
<td>2.0/3.0</td>
<td>2.0/2.4</td>
<td>2.1/2.5</td>
</tr>
<tr>
<td>Energy spread σₓ₁₁₁ / σₓ₁₁₁ (10⁻⁴)</td>
<td>13/15</td>
<td>3.7/6.8</td>
<td>6.5/10</td>
<td>10/12</td>
<td>14/17</td>
</tr>
<tr>
<td>Crossing angle φₖ (half angle)</td>
<td>-</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Piwinski angle φₖ σₓ₁₁₁ / σₓ</td>
<td>-</td>
<td>7.9</td>
<td>2.7</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Damping time τₓ₁₁₁ / T₀</td>
<td>40</td>
<td>1520</td>
<td>71</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Luminosity L (10³⁴ cm⁻²s⁻¹)</td>
<td>2</td>
<td>62</td>
<td>5.2</td>
<td>1.4</td>
<td></td>
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</table>

Luminosity is calculated by ws code BBWS.
Simulation of beam-beam collision

• Luminosity evaluation using simplified lattice, in which arc transformation is represented by 6x6 transfer matrix. Effect of lattice is discussed later.

• Weak-strong (WS) simulation
  • One (strong) beam is fixed charge distribution (Gaussian).
  • The other (weak) beam is represented by macro-particles.

• Strong-strong (SS) simulation
  • Two beams are represented by macro-particles.
  • Equilibrium charge distribution of two beams are determined self-consistently.
  • Coherent instability can be treated.
  • Noise due to statistics for macro-particle number. The statistical noise should be smaller than radiation excitation.

\[ N_{mp} \gg 2T_0/\tau_{x,y} \]
Strong-strong simulation using BBSS code

• Arbitrary beam distribution is treated using Particle In Cell Poisson solver.
• Available for very flat beam, using integrated Green function.
• Longitudinal slice and potential interpolation
• Beamstrahlung
• Shifted Green function for collision with large separation, collision between head of one beam and tail of the other beam.

• 50x50x4(TLEP-Z) collision solving Poisson equation per beam-beam crossing.

• Other choice for collision simulation: Gaussian approximation, combination of PIC and Gaussian collision
Shifted Green function
Beam distribution and potential

Neglect parallel translation to $x$

$\sigma_{z+} > \sigma_{z-}$

SuperKEKB
200 slices

Collision of 2nd x 2nd slices

Collision of 2nd x 199th slices
TLEP-t (strong-strong sim.)

- Evolution of Lum and beam sizes, $\sigma_y$, $\sigma_z$.

- No oscillation in $<xz>$. Dynamic $<xz>$ due to BB is seen.
**TLEP-H (strong-strong simulation)**

- Evolution of Lum and beam sizes, $\sigma_y$, $\sigma_z$.
- Fluctuations in Lum. and beam sizes are seen.
- Fluctuation of $\langle xz \rangle$ is the origin.
Coherent motion in $<xz>$ at tune $(\nu_x, \nu_y)=(0.54,0.61)$

- $<xz>$ oscillate in-phase ($\sigma(xz)$ mode) for $e^-$ and $e^+$ beam.

- Luminosity degradation is not very strong in H, but the motion is bad sign.

- Gaussian strong-strong gave similar results.
Coherent motion in $\langle x \rangle$ at tune $(v_x, v_y) = (0.51, 0.57)$

- $\langle x \rangle$ oscillate out-phase ($\pi(x)$ model) for $e^-$ and $e^+$ beam.

- Luminosity degradation is not very strong in $H$, but the motion is bad sign.
- Both of $\pi(x)$ and $\sigma(xz)$ modes are seen in $(0.52, 0.59)$.
- Gaussian strong-strong gave similar results.
Trials with several tune operating points

• The coherent motion is not recovered by choice of tune.

• The motion has not been seen in KEKB nor SuperKEKB simulations. \( \xi \sim 0.1 \) for finite crossing angle.

• Separation of \( v_x \) (0.53-0.54) did not work.

• \( \xi \sim 0.15 \) of TLEP may be too high.
TLEP-Z (strong-strong sim.)

- High Piwinski angle $\phi_c \sigma_{z,\text{tot}}/\sigma_x = 7.9$
- Shifted Green function is used for potential calculation for collision between separated slices
- The coherent motion is seen for TLEP-Z. Lum. is degraded by the motion

Simulation using shifted Green function and combination of ordinary Green function and complex error function ($\Delta x > 5 \sigma_x$)

- Coherent motion in $<xz>/\sigma_z \sim \sigma_x$ is seen.
Summary for beam-beam studies using strong-strong simulation

• Coherent motion (instability) is seen in H and Z, probably in W.
• Collision with crossing angle and high beam-beam parameter may induce the coherent motion.
• The coherent motion is bad sign.
• The coherent motion is not seen in simulations of KEKB and SuperKEKB.
Electron cloud effects in FCC-ee

- Photons are emitted by positron/electron beam.
  
  Number of photon per revolution \[ N_\gamma = \frac{5\pi}{\sqrt{3}} \alpha \gamma \]
  
  Critical energy \[ u_c = \frac{3h c}{2} \frac{\gamma^3}{\rho_{bend}} \]

- Electrons are produced at the chamber wall due to photo-emission. Quantum efficiency \( Y_1 = 0.1 - 0.2 \).

- Electron production by a bunch per m passage.
  
  \[ n_{e, pri} = N_\gamma Y_1 N_p \text{ (m}^{-1}\text{)} \]

- Secondary electron
Synchrotron radiation

- Number of photon per meter, proton
  \[ N_\gamma = \frac{5\alpha \gamma}{2\sqrt{3} \rho_{Bend}} \]
  \[ \rho_{bend} = 11.3\text{km}(\text{TLEP}),\ 6\text{km}(\text{CEPC}) \]
- Critical energy
  \[ E_c = \frac{3\hbar c \gamma^3}{2 \rho_{Bend}} \]
- Quantum efficiency of electron production, \( Y_1 = 0.1-0.2 \)
- Electron production by a bunch per m passage.
  \[ n_{e,\text{pri}} = N_\gamma Y N_p \ (\text{m}^{-1}) \]
- Chamber cross section 0.005 m\(^2\) (tentative)
- Electron density exceeds \( \rho_{e,\text{th}} = 7.8 \times 10^9 \text{ m}^{-3} \) even in a bunch passage.
- Antechamber and other cures are necessary.
Simulation of electron cloud build up in TLEP

TLEP-Z

TLEP-W

TLEP-H

TLEP-t
CEPC electron cloud build-up for partial double ring scheme

- Bunches are injected in 3000m area in circum. 50km. Bunch spacing is about 50m for 50 bunches.
- Electron cloud density for $\delta_{2\text{max}}=1.8$ and 2.2.

$\rho_e$ can be threshold $1\times10^{12}$ m$^{-3}$. 
Electron cloud effects in FCC-ee

- **TLEP-Z**
- \( N_b = 90300, \ L_{b-b} = 1.1 \text{m} \)
- \( N_p = 3.3 \times 10^{10}, \langle \beta \rangle = 100 \text{m}, \ \sigma_x = 95 \mu\text{m}, \ \sigma_y = 10 \mu\text{m} \)

\[
\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y (\sigma_x + \sigma_y)}}
\]

- \( \omega_e = 2\pi \times 127 \text{GHz}, \ \omega_e \sigma_x / c = 13 \)

\[
\rho_{e,th} = \frac{2\gamma \nu_s \omega_e \sigma_z / c}{\sqrt{3KQr_0/\beta L}} \quad K = \omega_e \sigma_z / c \\
Q = \min(\omega_e \sigma_z / c, 7)
\]

- \( \rho_{e,th} = 7.8 \times 10^9 \ \text{m}^{-3} \). Threshold is very weak density.

- KEKB 5×10^{11}, SuperKEKB 1×10^{11}
## Parameters related to EC instability

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<td>0.6</td>
<td>0.8</td>
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<td><strong>Beam l-density</strong> λ (10&lt;sup&gt;10&lt;/sup&gt;m&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.74</td>
<td>3.0</td>
<td>0.3</td>
<td>0.06</td>
<td>0.0013</td>
</tr>
<tr>
<td><strong>Beam size (av.)</strong> σ&lt;sub&gt;x&lt;/sub&gt;/σ&lt;sub&gt;y&lt;/sub&gt; (μm)</td>
<td>583/32</td>
<td>95/10</td>
<td>164/10</td>
<td>247/11</td>
<td>360/16</td>
</tr>
<tr>
<td><strong>Bunch length</strong> σ&lt;sub&gt;z,tot&lt;/sub&gt; (mm)</td>
<td>2.6</td>
<td>5.0</td>
<td>3.0</td>
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<td><strong>γ prod. rate</strong> N&lt;sub&gt;γ&lt;/sub&gt; (/m/e&lt;sup&gt;+&lt;/sup&gt;)</td>
<td>0.28</td>
<td>0.059</td>
<td>0.10</td>
<td>0.16</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>e&lt;sup&gt;-&lt;/sup&gt; prod. rate</strong> n&lt;sub&gt;e,prod&lt;/sub&gt; (10&lt;sup&gt;10&lt;/sup&gt;m&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>1.1</td>
<td>0.020</td>
<td>0.062</td>
<td>0.12</td>
<td>0.39</td>
</tr>
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<td><strong>Electron freq.</strong> ω&lt;sub&gt;e&lt;/sub&gt;/2π (GHz)</td>
<td>137</td>
<td>127</td>
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<td><strong>Thr. density</strong> ρ&lt;sub&gt;e,th&lt;/sub&gt; (10&lt;sup&gt;10&lt;/sup&gt;m&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>104</td>
<td>0.78</td>
<td>3.4</td>
<td>7.7</td>
<td>15</td>
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<tr>
<td><strong>Tune shift</strong> Δν at ρ&lt;sub&gt;e,th&lt;/sub&gt;</td>
<td>0.034</td>
<td>0.0025</td>
<td>0.0061</td>
<td>0.0092</td>
<td>0.012</td>
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Simulation for TLEP-Z

- Growth of emittance

Coherent motion in $y_+(z), y_-(z), \sigma_{y+}(z)$

Threshold is $\rho_{e,th} = 0.8 \times 10^{10} \, \text{m}^{-3}$, agree with the analytic formula $0.78 \times 10^{10}$. 
Ion instability in FCC-ee (TLEP-Z)

- $N_b = 90300$, $L_{sp} = 0.75\text{m}(2.5\ \text{ns})$
- $N_e = 3.3 \times 10^{10}$, $\langle \beta \rangle = 50\text{m}$, $\sigma_x = 67\mu\text{m}$, $\sigma_y = 7\mu\text{m}$
- Dispersion increases $\sigma_x$, assume $2^{1/2}$ times controlled by $\varepsilon_x$ in simulation.
- $\varepsilon_x = 0.09\text{nm}$, $\omega_i = 2\pi \times 103\text{MHz}$, $\omega_e L_{sp}/c = 1.61<- \text{critical for trap in the bunch train,}$
  $$\varepsilon_x = 0.18\text{nm}, \omega_i = 2\pi \times 88\text{MHz}, \omega_e L_{sp}/c = 1.38$$
- Ion production rate for CO, $n_i = 0.045\ \text{Ne P(Pa)}$,
  $$n_i (10^{-8}\ \text{Pa}) = 14.9 \ ((\text{m.e}^{-})).$$
Simulation results for $P=10^{-8}$ Pa

Ions are trapped partially for $\varepsilon_x=0.09\text{nm}$

Growth does not depend on train length.

Bunch-by-bunch Feedback $G=0.1(10\text{ turn})$ is necessary.
Coupled bunch instability observed in SuperKEKB

• SuperKEKB started from Feb. 2016. (no collision)
• \( I(e^+)=260\text{mA}, I(e^-)=200\text{mA} \) in early April.
• \( e^+ \) beam is unstable only in the early stage (Mar16), but is stable in Apr. *Antechamber works well.*
• Ion instability is observed in \( e^- \) beam. The growth becomes weak gradually.
Vertical beam size seems several times higher than the design at present.
Growth and mode change slightly day-by-day

- $\omega_i/\omega_0=140$ for the design beam size
- $\omega_i/\omega_0=70-80$ at present.
- $\omega_i \sim (\sigma_x \sigma_y)^{1/2}$. $\sigma_y$ is 4 times of design.
Summary

• Beam-beam effects and luminosity expectation have been studied for FCC-ee’s, CEPC and TLEP.
• Beamstrahlung and lifetime issue are evaluated.
• Design tools for beam-beam study are ready.
• Design parameters are achieved in weak-strong simulation, but are not in strong-strong simulations, because beam-beam coherent instability in \(<xz>\) is seen in H and Z.
• Electron cloud and ion instabilities in TLEP-Z are challenging issues.
• Threshold of electron density was given for FCCee’s.
• Required vacuum pressure and feedback power were given preliminary.
Thank you for your attention
Schematic view of the simulation
• Calculate trajectory interacting with colliding beam.
• Particles emit synchrotron radiation due to the momentum kick $dp/ds$.

\[ ds = \frac{z_i - z_{i+1}}{2} \]

\[ \langle \delta \rangle = dn_\gamma \langle u \rangle = \frac{2r_e \gamma^3}{3 \rho^2} ds \]

\[ \frac{1}{\rho_{x,y}} = \frac{dp_{x,y}}{ds} \]

\[ \langle \delta^2 \rangle = dn_\gamma \langle u^2 \rangle = \frac{55}{24\sqrt{3}} \frac{r_e \hbar \gamma^5}{mc\rho^3} ds \]