Interplay of the beam-beam effect and the lattice nonlinearity

Demin Zhou
Accelerator laboratory, KEK, Japan

Acknowledgements:
K. Ohmi, K. Oide, M. Benedikt, F. Zimmermann

FCC Week 2016, Rome, Italy
Apr. 11-15, 2016
Outline

➤ Introduction
  ● Background
  ● Simulation codes
    ✴ BBWS (K. Ohmi): Weak-strong beam-beam(BB) + Ideal crab-waist(CW) map + Beamstrahlung(BS) + Linear one-turn map + Lumped radiation(RAD) damping/excitation
    ✴ SAD: Lattice[w/ or w/o CW] + Weak-strong BB + BS + Lumped or distributed radiation damping/excitation

➤ Beam-beam simulation results for FCC-ee
  ● $t\bar{t}$ threshold [175GeV]
  ● Z pole [45.6GeV]

➤ Summary
Outline

➤ Introduction
  ● Background
  ● Simulation codes
    ✴ BBWS (K. Ohmi): Weak-strong beam-beam(BB) + Ideal crab-waist(CW) map + Beamstrahlung(BS) + Linear one-turn map + Lumped radiation(RAD) damping/excitation
    ✴ SAD: Lattice[w/ or w/o CW] + Weak-strong BB + BS + Lumped or distributed radiation damping/excitation

➤ Beam-beam simulation results for FCC-ee
  ● $\bar{t}t$ threshold [175GeV]
  ● Z pole [45.6GeV]

➤ Summary
1. Introduction

➤ Luminosity of a lepton collider

\[ L = L_0 R_{H\theta} \]

\[ L_0 = \frac{N_e N_p f_0 N_b}{2\pi \sqrt{\sigma_{xe}^2 + \sigma_{xp}^2} \sqrt{\sigma_{ye}^2 + \sigma_{yp}^2}} \]

\[ R_{H\theta} \approx \frac{1}{\sqrt{1 + \frac{\sigma_{ze}^2 + \sigma_{zp}^2}{\sigma_{xe}^2 + \sigma_{xp}^2} \tan^2 \frac{\theta}{2}}} \]

➤ Trends of modern colliders

● To increase beam current
● To decrease emittance and/or to squeeze beam sizes at IP

➤ Growing demand for luminosity results in

● Stronger nonlinearity in beam-beam collision
● Stronger nonlinearity in lattice, especially in IR
1. Introduction

➤ Experiences of interplay of beam-beam effect and lattice nonlinearity (LN) in colliders
  ● Cubic nonlin. at DAΦNE [e.g. C. Milardi, EPAC2000]
  ● Chromatic coupling at KEKB [e.g. Y. Funakoshi, PTP 2009]
  ● Amplitude-dependent nonlin. at SuperKEKB [e.g. D. Zhou, IPAC’15]
  ● … …

➤ The motivation for FCC-ee
  ● Low emittance, large crossing angle, and small $\beta^*_x,y$
  ● Crab-waist lattice to mitigate beam-beam effects
  ● Unavoidable beamstrahlung effects
  ● Radiation effects
  ● Others … … [Ref. K. Oide, This conference]

➤ Evaluations via simulations are necessary
1. Introduction

➤ The idea via BBWS and SAD

- Simulation codes developed for KEKB and SuperKEKB
- One-turn map:

\[ M = M_{\text{RAD}} \circ M_{\text{BB}} \circ M_0 \]

- The IP-to-IP one-turn map \( M_0 \): linear matrix or realistic element-by-element maps from a design lattice w/ or w/o crab waist
- The beam-beam map \( M_{\text{BB}} \): Symplectic weak-strong model w/ or w/o beamstrahlung
- Radiation damping/excitation map \( M_{\text{RAD}} \): lumped or distributed

- Observables: luminosity, DA, beam tail, particle loss, etc.
## 1. Introduction: Machine parameters (for half ring)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>t¯t</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (km)</td>
<td>49990.9</td>
<td>49990.9</td>
</tr>
<tr>
<td>E (GeV)</td>
<td>45.6</td>
<td>175</td>
</tr>
<tr>
<td>Number of IPs</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>N_b</td>
<td>90300</td>
<td>78</td>
</tr>
<tr>
<td>N_p(10^{11})</td>
<td>0.33</td>
<td>1.7</td>
</tr>
<tr>
<td>Full crossing angle (rad)</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>ε_x (nm)</td>
<td>0.09</td>
<td>1.3</td>
</tr>
<tr>
<td>ε_y (pm)</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>β_x^* (m) [optional]</td>
<td>1 [0.5]</td>
<td>1 [0.5]</td>
</tr>
<tr>
<td>β_y^* (mm) [optional]</td>
<td>2 [1]</td>
<td>2 [1]</td>
</tr>
<tr>
<td>σ_z (mm)^SR</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>σ_δ(10^{-3})^SR</td>
<td>0.37</td>
<td>1.4</td>
</tr>
<tr>
<td>Fractional betatron tune ν_x/ν_y</td>
<td>.55/.57</td>
<td>.54/.57</td>
</tr>
<tr>
<td>Synch. tune ν_s</td>
<td>0.0075</td>
<td>0.0375</td>
</tr>
<tr>
<td>Damping rate/turn (10^{-2}) [x/y/z]</td>
<td>0.019/0.019/0.038</td>
<td>1.1/1.1/2.2</td>
</tr>
<tr>
<td>Lum./IP(10^{34}cm^{-2}s^{-1})</td>
<td>90</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Ref. F. Zimmermann, FCC-ee design meeting, Dec. 9, 2015, and K. Oide, this conference
Note: Minor difference from the latest parameter table
Outline

➤ Introduction
  ● Background
  ● Simulation codes
    ✴ BBWS (K. Ohmi): Weak-strong beam-beam(BB) + Ideal crab-waist(CW) map + Beamstrahlung(BS) + Linear one-turn map + Lumped radiation(RAD) damping/excitation
    ✴ SAD: Lattice[w/ or w/o CW] + Weak-strong BB + BS + Lumped or distributed radiation damping/excitation

➤ Beam-beam simulation results for FCC-ee
  ● $t\bar{t}$ threshold [175GeV]
  ● Z pole [45.6GeV]

➤ Summary
2. Simulations: BBWS: $\tt\bar{t}$

➤ Lum. tune scan \textit{w/o CW} \quad \textit{w/ BS}

- BB+BS: Coupled $x$-$y$-$z$ motions
2. Simulations: BBWS: $tt_{\bar{b}}$

- Lum. tune scan $w/ \ CW \ w/ BS$
- Optimal working point: $[.54,.57]/IP$
- CW's gains: not luminosity but beam-tail suppression

![Graphs showing luminosity (Lum.), $\sigma_x$, $\sigma_z$, and $\sigma_y$ as functions of fractional $v_x$ and $v_y$.](image-url)
2. Simulations: BBWS: $\text{tt}_{\text{bar}}$

➤ Beam distribution in $y$-$z$ plane w/ BS

- Working point: $[.54,.57]/\text{IP}$
- CW suppresses vertical beam-tail
- BS drives long. tail

$$A_y = \sqrt{2J_y/\epsilon_y}$$

$$A_z = \sqrt{2J_z/\epsilon_z}$$

$N_p = 0.01E11$ w/ CW

$N_p = 1.7E11$ w/o CW

$N_p = 1.7E11$ w/ CW
2. Simulations: SAD: $\texttt{tt}_{\text{bar}}$

- Luminosity for $\beta_x^*=1\text{m}, \beta_y^*=2\text{mm}$
  - Lattice ver. FCCee\_t\_65\_26\_1\_2
  - “Invisible” gain from CW
  - Small loss(order of a few percents) due to BB+LN

### Specific lum.

![Specific luminosity graph](image)

### Total lum.

![Total luminosity graph](image)
2. Simulations: SAD: $\tt_{\bar{t}}$

Beam distribution for $\beta_x^* = 1 \text{m}, \beta_y^* = 2 \text{mm}$

- Working point: $[.54,.57]/\text{IP}$
- CW suppresses vertical beam-tail
- BB+LN drives beam-tail and causes particle loss [next page]
2. Simulations: SAD: $\ttbar$

- **Particle losses in tracking**
  - Nominal $N_p=1.7\times10^{11}$, $\beta_x^*=1\text{m}$, $\beta_y^*=2\text{mm}$
  - “Instability” threshold observed
  - Loss rate depend on $\beta_{x,y}^*$ and DA
  - Above threshold particles continuously slip out of DA and RF bucket
2. Simulations: SAD: $tt_{\text{bar}}$

- Particle losses in tracking
  - Nominal $N_p=1.7E11$, $\beta_x^*=1\text{m}$, $\beta_y^*=2\text{mm}$
  - Translate loss rate into lifetime [No physical aperture for this calculation]
  - Likely CW improves lifetime via suppressing beam tail [Need more careful simulations]
2. Simulations: SAD: $\mathbf{t\bar{t}}_{\text{bar}}$

- Luminosity for $\beta_x^*=0.5\text{m}$, $\beta_y^*=1\text{mm}$
  - Lattice ver. FCCee_t_65_26
  - Small gain from CW
  - Small loss (order of a few percents) due to BB+LN
  - Allow lower beam current to achieve the same lum.

![Graphs of Specific and Total Luminosity](image-url)
Outline

➤ Introduction
  • Background
  • Simulation codes
  ✴ BBWS (K. Ohmi): Weak-strong beam-beam(BB) + Ideal crab-waist(CW) map + Beamstrahlung(BS) + Linear one-turn map + Lumped radiation(RAD) damping/excitation
  ✴ SAD: Lattice[w/ or w/o CW] + Weak-strong BB + BS + Lumped or distributed radiation damping/excitation

➤ Beam-beam simulation results for FCC-ee
  • $t\bar{t}$ threshold [175GeV]
  • Z pole [45.6GeV]

➤ Summary
3. Simulations: BBWS: Z

- Lum. tune scan w/o CW  w/ BS
  - BB+BS: Coupled x-y-z motions
  - Very small area for good luminosity

![Graphs showing lum., σx, σz, and σy](image-url)
3. Simulations: BBWS: Z

- Lum. tune scan w/ CW w/ BS
  - Optimal working point: [.55,.57]/IP
  - CW’s gains: both luminosity and beam-tail suppression
3. Simulations: BBWS: Z

- Beam distribution in y-z plane w/ BS
  - Working point: [.55,.57]/IP
  - CW suppresses vertical beam-tail
  - CW is a must for FCC-ee Z pole(?)

\[ A_y = \sqrt{\frac{2J_y}{\epsilon_y}} \]
\[ A_z = \sqrt{\frac{2J_z}{\epsilon_z}} \]
3. Simulations: SAD: Z

➤ Luminosity for $\beta_x^* = 1\text{m}, \beta_y^* = 2\text{mm}$

- Lattice ver. FCCee\_z\_65\_36
- Significant gain from CW
- Small loss (order of a few percents) due to BB+LN

![Graph showing specific and total luminescence]
3. Simulations: SAD: Z

➢ Beam distribution in for $\beta_x^* = 1\text{m}$, $\beta_y^* = 2\text{mm}$
  - Working point: [.55,.57]/IP
  - CW suppresses vertical beam-tail
  - BB+LN drives beam tail, but no particle loss observed

![Graphs showing beam distribution in Z-plane and Y-plane with different particle densities and operating points.](graph1.png)

- $N_p=0.01\text{E}11$
  - x-y plane, SAD, w/ CW
- $N_p=0.33\text{E}11$
  - z-y plane, BBWS, w/ CW
3. Simulations: SAD: Z

- Luminosity for $\beta_x^*=0.5\text{m}$, $\beta_y^*=1\text{mm}$
  - Lattice ver. FCCee_z_65_36_by1
  - Large gain from CW
  - Small loss (order of a few percents) due to BB+LN
  - Allow lower beam current to achieve the same lum.

**Specific lum.**

![](specific_lum.png)

**Total lum.**

![](total_lum.png)
Outline

➤ Introduction
  ● Background
  ● Simulation codes
    ✶ BBWS (K. Ohmi): Weak-strong beam-beam(BB) + Ideal crab-waist(CW) map + Beamstrahlung(BS) + Linear one-turn map + Lumped radiation(RAD) damping/excitation
    ✶ SAD: Lattice[w/ or w/o CW] + Weak-strong BB + BS + Lumped or distributed radiation damping/excitation

➤ Beam-beam simulation results for FCC-ee
  ● $t\bar{t}$ threshold [175GeV]
  ● Z pole [45.6GeV]

➤ Summary
4. Summary

➤ Crab waist
  • Work well for FCC-ee
  • Suppress vertical beam tail
  • Lum. gain at lower beam energy region

➤ BB+LN
  • Lum. loss in the order of a few percents given the present designs
  • Particle loss observed in tracking [beamstrahlung + DA + momentum
    acceptance], depending on optics designs and optimisations of DA
  • Not a concern for the latest designs

➤ \((\beta_x^*, \beta_y^*) \rightarrow (0.5, 0.001) [m]\)
  • No limit from BB+LN

➤ Simulations to be periodically updated with
  • Updates of machine parameters
  • Updates of optics designs
  • Updates of magnet designs, especially in the IR