Impedance and collective effects of CEPC

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Outline

• Impedance budget
• Single-bunch effects
• Multi-bunch effects
• Electron cloud instability
• Beam ion instability
## Main parameters of CEPC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol, unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E$, GeV</td>
<td>120</td>
</tr>
<tr>
<td>Circumference</td>
<td>$C$, m</td>
<td>54752</td>
</tr>
<tr>
<td>Beam current</td>
<td>$I_0$, mA</td>
<td>16.6</td>
</tr>
<tr>
<td>Bunch number</td>
<td>$n_b$</td>
<td>50</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$N_e$</td>
<td>$3.79 \times 10^{11}$</td>
</tr>
<tr>
<td>Natural bunch length</td>
<td>$\sigma_{l0}$, mm</td>
<td>2.65</td>
</tr>
<tr>
<td>Emittance (horz./vert.)</td>
<td>$\varepsilon_x/\varepsilon_y$, nm</td>
<td>6.12/0.018</td>
</tr>
<tr>
<td>RF frequency</td>
<td>$f_{rf}$, GHz</td>
<td>0.65</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>$h$</td>
<td>118800</td>
</tr>
<tr>
<td>Natural energy spread</td>
<td>$\sigma_{e0}$</td>
<td>1.63E-3</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>$\alpha_p$</td>
<td>3.36E-5</td>
</tr>
<tr>
<td>Betatron tune</td>
<td>$\nu_x/\nu_y$</td>
<td>179.08/179.22</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>$\nu_s$</td>
<td>0.18</td>
</tr>
<tr>
<td>Damping time (H/V/s)</td>
<td>$\tau_x/\tau_y/\tau_z$, ms</td>
<td>14/14/7</td>
</tr>
</tbody>
</table>
1. Impedance budget

- **RF cavities**
  - A five cell SC RF cavity structure with RF frequency of 650 MHz will be used.
  - Given a design accelerating gradient of 15.6 MV/m, 384 cavities are needed.
  - The wake of the RF cavities is calculated with ABCI.
  - Loss factor for one RF cavity is $k_l=2.332 \text{ V/pC}$.
  - We fit the bunch wake with the analytical model

\[
W(s) = -Rc\lambda(s) - Lc^2\lambda'(s)
\]

$L$ and $R$ are effective inductance and resistance, respectively.
- **Resistive wall**
  - Aluminum beam pipe is assumed. The beam pipe has an elliptical cross section with half height of \( a_x/a_y = 52/28 \) mm.
  - Resistive wall wake for a Gaussian bunch in a cylindrical beam pipe is calculated analytically

\[
W(s) = \frac{c l}{8\sqrt{2\pi}a} \frac{1}{\sigma_z^{3/2}} \sqrt{\frac{Z_0}{\sigma_c}} f(s/c)
\]

where \( f(x) = \sqrt{x^3} e^{-x^2/4} (I_{1/4} - I_{-3/4} \pm I_{-1/4} \mp I_{3/4})_x^2/4 \), and \( I_n(x) \) are the modified Bessel functions.

- Loss factor: \( k_f = 309.6 \) V/pC.
- Fitted parameter:
  \[ R = 9.7k\Omega, \quad L = 126.8nH \]
- CEPC ring wake and impedance budget

<table>
<thead>
<tr>
<th>Object</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R [kΩ]</td>
</tr>
<tr>
<td>Resistive wall (Al)</td>
<td>9.7</td>
</tr>
<tr>
<td>RF cavities (N=384)</td>
<td>28.1</td>
</tr>
<tr>
<td>Total</td>
<td>37.8</td>
</tr>
</tbody>
</table>

- The loss factor is dominated by the RF cavities.
- The imaginary part of the RF cavities is capacitive, the fitted \( L \) has no physical meaning.
- A more complete impedance budget will be obtained as the vacuum components are designed.

Longitudinal wake at nominal bunch length \((\sigma_z=2.65\text{mm})\)
2. Single-bunch effects

- Longitudinal microwave instability
  - The longitudinal microwave instability is estimated according to the Boussard or Keil-Schnell criterion:

  \[ I_{th} = \frac{\sqrt{2\pi}\alpha_p \frac{E}{e} \sigma_e^2 \sigma_l}{R |\frac{Z}{n}|_{eff}} \]

  - The threshold of the longitudinal impedance is \(|Z_{\parallel}/n| < 0.025 \, \Omega\).
  - LEP:
    Measurement: \(|Z_{\parallel}/n|_{th} = 0.03\,\Omega\) (B. Zotter, EPAC'92, p.273)
• Bunch lengthening
  - Steady-state bunch shape is obtained by numerically solving the Haissinski equation.
  - The Pseudo-Green function wake with bunch length of 0.5mm is used in the calculation.
  - Bunch is shortened due to the capacitive property of the RF cavities (Here, only resistive wall and RF cavities are considered)

Pseudo-Green function wake ($\sigma_z=0.5\text{mm}$)  
Steady-state bunch distribution
• Bunch lengthening with scaled SuperKEKB’s geometry wake
  • The scaling factor is \( \text{Cir (CEPC)/Cir(SuperKEKB)} \)
    - Scaled LER wake+RW+RF
    - Bunch is lengthened by 10.6%
    - Scaled HER wake+RW+RF
    - Bunch is lengthened by 20.9%

• Difference of the impedance models between SuperKEKB LER and HER:
  • There is ante-chamber in the LER, but not in the HER. Without ante-chamber, the SR masks, pumping ports, and bellows contribute more impedances.
• Simulation results with scaled wake of SuperKEKB LER/HER

![Energy spread with bunch current](image1)

![Bunch length with bunch current](image2)

• Scale SuperKEKB LER/HER:
  
  \[(\text{Geometric+RW impedance of SuperKEKB LER/HER}) \times \frac{\text{Cir(CEPC)}}{\text{Cir(SuperKEKB)}}\]

• The threshold for the longitudinal microwave instability is much higher than the design bunch population.

• The bunch lengthening at nominal bunch current are 10.9% (LER) and 18.5 (HER)
• Simulation with more careful scaling

- RF+RW+Scale SuperKEKB LER/HER:
  - Impedance data of CEPC RF+RW
  - Multiply Cir(CEPC)/Cir(SKEKB): bellows, flanges, pumping ports, SR masks, BPMs
  - No scaling: Feedback kicker, Longitudinal kicker
  - Scale by number of IP: collimators, IR duct

- The bunch lengthening are 2.9% (LER) and 13.3% (HER)

- CEPC should be safe from the microwave instability.
• Coherent synchrotron radiation (K. Bane, Y. Cai, G. Stupakov, PRST-AB, 2010)

- The beam is assumed to be moving in a circle of radius $\rho$ between two parallel plates at locations $y = \pm h$.
- The threshold of bunch population for CSR is given by

$$S_{th} = 0.50 + 0.12\Pi$$

$$S = \frac{r_e N_b \rho^{1/3}}{2\pi \nu_s \gamma \delta \sigma_z^{4/3}}, \quad \Pi = \frac{\sigma_z \rho^{1/2}}{h^{3/2}}$$

- For CEPC, $\sigma_z \rho^{1/2}/h^{3/2} = 15.6$ (=> CSR shielded)
- The CSR threshold in CEPC is $N_{b,\text{Th}} = 7.3 \times 10^{12} >> N_b = 3.79 \times 10^{11}$.

• Space charge tune shift

$$\Delta \nu_{x,y} = -\frac{r_e N_b}{(2\pi)^{3/2} \gamma^3 \sigma_z} \int \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)(\sigma_x(s) + \sigma_y(s))} ds$$

$$\Delta \nu_y = -1.9 \times 10^{-4}, \quad \Delta \nu_x = -5.8 \times 10^{-6}$$
• **Transverse mode coupling instability (TMCI)**

\[ |Z_\perp| \leq \frac{4\nu_s Eb}{eI_b R < \beta_\perp >} \]

- The threshold of transverse impedance is \( |Z_\perp| < 17.2 \ \text{M}\Omega/m \).
- The equivalent longitudinal impedance is 0.8 \( \Omega \), which is much higher than that of the longitudinal instability.

• **Eigen mode analysis**
  - Considering only resistive wall impedance
  - Beam current threshold:
    \( I_b^{th}=3.4\text{mA} \) (\( I_0^{th}=168\text{mA} \))
• Beam tilt due to the transverse wake fields
  • When a beam passes through a impedance with a transverse offset, the tail particles will receive transverse kicks
    \[
    \Delta y'(z) = \frac{Ne^2}{E} \int_0^\infty dz' \rho(z' + z)W_\perp(y_b, z')
    \]
  • This will lead to a transverse displacement of the bunch tail at IP
    \[
    \Delta y = \sqrt{0.5 \beta^*_y \beta_y \Delta y'}
    \]
• CEPC case:
  • Pretzel orbit of 5mm in horizontal
  • Closed orbit of 1mm in vertical
• Beam tilt due to the RF cavity wake

• Transverse wake for one RF cavity with $\sigma_z=0.5\text{mm}$

As there are 384 cavities located in 8 positions in the ring, the displacements at IP are

$\Delta x^* = 48\sqrt{8} \times 54.0\text{nm} = 7.3\mu\text{m}$

$\Delta y^* = 48\sqrt{8} \times 0.42\text{nm} = 0.057\mu\text{m}$

(beam size at IP: $\sigma_x^*/\sigma_y^* = 69.97/0.15\mu\text{m}$)
KEKB’s impedance model (D. Zhou, K. Ohmi, A. Chao, IPAC2011, p.601)

\[ \frac{\omega_r}{c} = 400 \text{m}^{-1} \]
\[ R_s^1 = 4 \times 10^8 \Omega/m^2 \]
\[ Q = 1 \]

\[ \Delta x' = 100.3 \mu \text{rad}, \quad \Delta x^* = 442.3 \mu \text{m} \]
\[ \Delta y' = 20.1 \mu \text{rad}, \quad \Delta y^* = 3.4 \mu \text{m} \]

**The impedance is assumed to be localized at one point in the ring → Distributed impedance will reduce this effect.**

LEP’s impedance model (B. Zotter, EPAC1992, p.273)

\[ \frac{\omega_{r1}}{c} = 42 \text{m}^{-1} \]
\[ R_s^1 = 5.9 \times 10^7 \Omega/m^2 \]
\[ Q = 1 \]

\[ \Delta x' = 58.1 \mu \text{rad}, \quad \Delta x^* = 256.2 \mu \text{m} \]
\[ \Delta y' = 11.6 \mu \text{rad}, \quad \Delta y^* = 2.0 \mu \text{m} \]

**Average beta function is used instead of that at the location of impedance → Smaller beta function can reduce this effect.**

**Transverse impedance should be carefully studied and well controlled.**
3. Multi-bunch effects

- Transverse resistive wall instability

\[
\frac{1}{\tau_\perp} = - \frac{n_b I_b c}{4\pi (E/e) v_{x,y}} \sum_{p=-\infty}^{\infty} e^{-(\omega_{pn} - \xi \omega_b / \alpha_p)^2 \sigma_t^2} \text{Re} Z_\perp(\omega_{pn})
\]

with \( \omega_{pn} = 2\pi f_{rev} \times (pn_b + n + \nu_{x,y}) \)

- The growth rate for the most dangerous instability mode is 3.4 Hz (\( \tau = 0.3 \)s) in the vertical plane with mode number of \( \mu = 20 \).

- The growth time is much higher than the transverse radiation damping time.
Smaller decimal tune is preferred to alleviate the transverse resistive wall instability.

The growth rate is not quite sensitive to the chromaticity.
- Coupled bunch instability induced by the RF HOM’s

<table>
<thead>
<tr>
<th>Monopole Mode</th>
<th>( f \text{ (GHz)} )</th>
<th>( R/Q(\Omega) ) *</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM011</td>
<td>1.173</td>
<td>84.8</td>
</tr>
<tr>
<td>TM020</td>
<td>1.427</td>
<td>54.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dipole Mode</th>
<th>( f \text{ (GHz)} )</th>
<th>( R/Q(\Omega/\text{m}) ) **</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE111</td>
<td>0.824</td>
<td>832.23</td>
</tr>
<tr>
<td>TM110</td>
<td>0.930</td>
<td>681.15</td>
</tr>
<tr>
<td>TE122</td>
<td>1.232</td>
<td>544.5</td>
</tr>
<tr>
<td>TM112</td>
<td>1.440</td>
<td>101.53</td>
</tr>
</tbody>
</table>

* \( k_{\parallel\text{mode}} = 2\pi f \cdot (R/Q)/4 \text{ [V/pC]} \)
** \( k_{\perp\text{mode}} = 2\pi f \cdot (R/Q)/4 \text{ [V/(pC \cdot m)]} \)
To keep the beam stable, the radiation damping time should be less than the rise time of any of the oscillation modes.

In the resonant condition, the threshold shunt impedances are

\[
R_L^{th} = \frac{2(E_0 / e)\nu_s}{f_L I_0 \alpha_p \tau_z} = \frac{11.1(G\Omega \cdot \text{GHz})}{f_L (\text{GHz})}
\]

\[
R_T^{th} = \frac{2(E_0 / e)}{f_{rev} I_0 \beta_{x,y} \tau_{x,y}} = 3.9(G\Omega / \text{m})
\]

Longitudinal impedance threshold
• Considering the whole RF system, there will be finite tolerances in the cavity construction.

• To find the total effects of all the RF cavities, we need to take into account the spread in the resonance frequencies of different cavities.

• For small frequency spread, this will result in an “effective” quality factor $Q$ of the whole RF system.

$f_R=1.173\text{GHz}, \ Q=2.54\times10^5, \ 384 \text{ RF cavities}$
4. Electron cloud instability

- The threshold value of the volume density of the electron cloud for the head-tail instability

\[
\rho_{e, \text{th}} = \frac{2\gamma v_s \omega_e \sigma_z / c}{\sqrt{3KQr_0\beta L}}
\]

\[K = \omega_e \sigma_z / c\]
\[Q = \min(Q_{nl}, \omega_e \sigma_z / c)\]
\[Q_{nl}\text{ depends on the nonlinear interaction}\]

- We take \(Q_{nl} = 7\) for analytical estimation, and get the threshold density for the single bunch instability is \(9.3 \times 10^{11} \text{ m}^{-3}\)

- For the multi-bunch instability, the electron cloud is considered as a rigid Gaussian with the chamber size. The characteristic frequency is

\[
\omega_{G,y}^2 = \frac{2\lambda_b r_e c^2}{(\sum x + \sum y) \sum y}
\]

- The phase angle between adjacent bunches is \(\omega_G L_{SP} / c = 32.3\), which means the electrons are not supposed to accumulate and the multipacting effects is low.
<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>SuperB</th>
<th>CEPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy $E$, GeV</td>
<td>3.5</td>
<td>4.0</td>
<td>6.7</td>
<td>120</td>
</tr>
<tr>
<td>Circumference $L$, m</td>
<td>3016</td>
<td>3016</td>
<td>1370</td>
<td>54752</td>
</tr>
<tr>
<td>Number of $e^+$/bunch, $10^{10}$</td>
<td>3.3</td>
<td>9</td>
<td>5.74</td>
<td>37.9</td>
</tr>
<tr>
<td>Emittance H/V $\varepsilon_x/\varepsilon_y$, nm</td>
<td>18/0.36</td>
<td>3.2/0.01</td>
<td>1.6/0.004</td>
<td>6.12/0.018</td>
</tr>
<tr>
<td>Bunch length $\sigma_z$, mm</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>2.88</td>
</tr>
<tr>
<td>Bunch space $L_{sp}$, ns</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3653</td>
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</table>

**Single bunch effect**

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>SuperB</th>
<th>CEPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron freq. $\omega_e/2\pi$, GHz</td>
<td>35.1</td>
<td>150</td>
<td>272</td>
<td>187.3</td>
</tr>
<tr>
<td>Phase angle $\omega_e\sigma_z/c$</td>
<td>2.94</td>
<td>18.8</td>
<td>28.5</td>
<td>10.6</td>
</tr>
<tr>
<td><strong>Threshold density</strong> $\rho_{e,th}, 10^{12}$ m$^{-3}$</td>
<td><strong>0.7</strong></td>
<td><strong>0.27</strong></td>
<td><strong>0.4</strong></td>
<td><strong>0.9</strong></td>
</tr>
</tbody>
</table>

**Multi-bunch effect**

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>SuperB</th>
<th>CEPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-e per meter $n_y$, p/(m)</td>
<td>5.0E8</td>
<td>1.5E9</td>
<td>3.6E9</td>
<td>1.1E10</td>
</tr>
<tr>
<td>Characteristic freq. $\omega_G$, MHz</td>
<td>62.8</td>
<td>87.2</td>
<td>69.6</td>
<td>8.8</td>
</tr>
<tr>
<td>Phase angle $\omega_G L_{sp}/c$</td>
<td><strong>0.13</strong></td>
<td><strong>0.35</strong></td>
<td><strong>0.28</strong></td>
<td><strong>32.3</strong></td>
</tr>
</tbody>
</table>

- Threshold density for the single bunch effect is considerable high.
- The phase angle for the multi-bunch effect is about two orders higher.
5. Beam ion instability

• Ion trapping
  – With uniform filling pattern, the ions with a relative molecular mass larger than $A_{x,y}$ will be trapped.

$$A_{x,y} = \frac{N_b r_p S_b}{2(\sigma_x + \sigma_y)\sigma_{x,y}}$$

The critical mass number is quite high, so the ions will not be trapped by the beam.

• Fast beam ion instability
  – The phase angle between adjacent bunches is $\omega_i L_{sep}/c=42$. So the ions will not accumulate due to the overfocus inside the bunch train.
The effect of pretzel on the instability

- In the pretzel scheme, there are two beams hosted in the same beam pipe.
- When a beam cross a resonator (e.g., RF cavity), the wake field excited by the beam will affect the other beam, i.e., the two beams will talk to each other.
- For the electron cloud instability, the electron beam will disturb the electron cloud accumulation. For the beam ion instability, the positron beam will affect the distribution of the ions in the beam pipe. In some point of view, both effects will be suppressed by the other counter rotating beam. (Discussion with K. Ohmi and G. Stupakov)
Summary

• With the impedance of resistive wall and RF cavities, the bunch length is reduced due to the capacitive property of the RF cavity. Analysis based on KEKB’s geometry impedance shows that bunch lengthening of 10% is expected.

• Bunch shape distortion due to the transverse wake is another potential restriction to the high luminosity. More detail analysis take into account impedance localization are needed.

• CEPC should be safe from microwave instability and transverse mode coupling instability.

• Coupled bunch instabilities are less important compare to the single bunch effects since the bunch spacing is large.

• Electron cloud and ion instability should not be a problem due to the overfocus inside the bunch train.

• The effect of pretzel on the beam instability will be studied in the future.
Thank you for your attention!