Mitigation of Coherent Beam Instabilities in CEPC

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Outline

• Introduction
• Impedance modeling
• Impedance-induced instabilities
• Two-stream instabilities with ions and electron cloud
• Interaction with beam-beam
• Summary
Introduction to CEPC

- Double ring collider with 2 Ips.
- The Z mode shows the most critical restriction on the beam instabilities.

<table>
<thead>
<tr>
<th>Parameter [unit]</th>
<th>Higgs</th>
<th>W</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>120</td>
<td>80</td>
<td>45.5</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>17.4</td>
<td>87.9</td>
<td>461.0</td>
</tr>
<tr>
<td>Bunch Population [$10^{10}$]</td>
<td>15</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$1.1\times10^{-5}$</td>
<td>$1.1\times10^{-5}$</td>
<td>$1.1\times10^{-5}$</td>
</tr>
<tr>
<td>Emittance (H/V) [nm]</td>
<td>1.21/0.0031</td>
<td>0.54/0.0016</td>
<td>0.18/0.0016</td>
</tr>
<tr>
<td>Natural energy spread</td>
<td>1.0E-3</td>
<td>6.6E-4</td>
<td>3.8E-4</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.065</td>
<td>0.039</td>
<td>0.028</td>
</tr>
<tr>
<td>Radiation damping [ms]</td>
<td>46/46/23</td>
<td>157/157/78</td>
<td>843/843/436</td>
</tr>
</tbody>
</table>
Potential restrictions from collective beam instabilities

• Beam current threshold
  – Collective beam instabilities which can induce beam losses
  – Parasitic power dissipation on vacuum components => heat load

• Beam quality degradations
  – Bunch lengthening and beam energy spread increase
  – Synchrotron and betatron tune shifts
  – Emittance blow-up
Impedance modeling

• Dominate impedance contributors are identified
  – Components with large impedance contributions
    • Resistive wall, RF cavities, Electro-separators, Vacuum transitions, IP chambers
  – Components with small impedances in large numbers
    • Flanges, Bellows, Pumping ports, BPMs

• The impedances of the components are carefully designed and optimized
  – Reduce parasitic power dissipation
  – Increase beam instability threshold
Resistive wall impedance

- NEG coating is adopted on the copper beam pipe for vacuum pumping and electron cloud mitigation.
- The effect of different coating thickness on the longitudinal and transverse impedance is studied => Impedance is reduced with thinner NEG coating.
the effective impedance are calculated to identify the influence of the coating thickness on the impedance

In the frequency range of interest, the NEG coating has

- Significant effect on the imaginary part of the effective impedance
  => bunch lengthening and tune shift
- Less effect on the real part of the impedance
  => beam energy spread or instability growth rate
- The result is dependent on $\sigma_z$ and pipe radius.
- RF shielding adopted for cavity structures

![One cylindrical cavity: width = 1mm depth = 1mm](image)

SSRF or BEPCII design

- Taper transitions of 1/10 are adopted at aperture discontinuities

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Aperture1 [mm]</th>
<th>Aperture2 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF taper</td>
<td>112</td>
<td>78</td>
<td>28</td>
</tr>
<tr>
<td>IP chamber taper1</td>
<td>4</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>IP chamber taper2</td>
<td>4</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>E-seperator taper</td>
<td>44</td>
<td>55</td>
<td>28</td>
</tr>
</tbody>
</table>

- HOM damping are considered for resonant structures
  - RF cavities
  - IP chambers
  - Electro-separators
• Impedance budget (@$\sigma_z=3\text{mm}$)

| Components        | Number | $Z_{||}/n$, mΩ | $k_{\text{loss}}$, V/pC | $k_y$, kV/pC/m |
|-------------------|--------|----------------|--------------------------|----------------|
| Resistive wall    | -      | 6.2            | 363.7                    | 11.3           |
| RF cavities       | 240    | -1.0           | 225.2                    | 0.3            |
| Flanges           | 20000  | 2.8            | 19.8                     | 2.8            |
| BPMs              | 1450   | 0.12           | 13.1                     | 0.3            |
| Bellows           | 12000  | 2.2            | 65.8                     | 2.9            |
| Pumping ports     | 5000   | 0.02           | 0.4                      | 0.6            |
| IP chambers       | 2      | 0.02           | 6.7                      | 1.3            |
| Electro-separators| 22     | 0.2            | 41.2                     | 0.2            |
| Taper transitions | 164    | 0.8            | 50.9                     | 0.5            |
| **Total**         |        | **11.4**       | **786.8**                | **20.2**       |

• The broadband impedances are dominated by the RW, flanges and bellows.
• The loss factor is mainly contributed by the resistive wall and the RF cavities.
• More components, such as the collimators, absorbers and kickers, should be included.
Impedance-induced instabilities

• Single-bunch effects
  – Microwave instability and bunch lengthening
  – Transverse mode coupling instability

• Multi-bunch effects
  – Transverse resistive wall instability
  – HOMs
• Microwave instability and bunch lengthening
  – The microwave instability will rarely induce beam losses, but may reduce the luminosity
due to the deformed beam distribution and increasing of the beam energy spread.
  – With the impedance model developed, the microwave instability and bunch lengthening
are simulated with the code Elegant => the design bunch intensity is just above the
threshold, and turbulent distributions are observed above the threshold.
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are simulated with the code Elegant => the design bunch intensity is just above the
threshold, and turbulent distributions are observed above the threshold.
  – To mitigate the effect:
    • Impedance reduction
    • Beam parameter optimization

Keil-Schnell criterion: \( I_{th} = \frac{\sqrt{2} \frac{E}{p} \frac{e_0}{e} \frac{E}{e_0}}{R | \frac{Z_{||}}{n} |_{eff}} \)
• Transverse mode coupling instability
  – The threshold for the TMCI is estimated using both analytical formula and Eigen mode analysis.
    \[ I_{0}^{th} = \frac{2Q_s}{e} E / e \]
  – When considering bunch lengthening due to the impedance or beamstrahlung, the transverse effective impedance decreases due to its dependence on the bunch distribution => TMCI threshold increases.

Threshold is comparable with the design current without considering bunch lengthening.

Larger safety margin obtained when considering bunch lengthening effects.
• Transverse resistive wall instability
  – The coupled bunch instability can be driven by the resonance at zero frequency of the transverse resistive wall impedance.
  – The most dangerous mode has a growth time of ~4.3ms (~12 turns), which is much faster than the radiation damping (~843ms).

⇒ An effective feedback system is required.
⇒ A nonzero chromaticity can also help to shift the sampled impedance frequencies.

  – NEG coating has little effect on this instability.
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  – 120 2-cell SC RF cavities (650MHz) will be used for Z mode. The CBI driven by the sum of the RF HOMs is faster than the radiation damping or even feedback damping.
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  - 120 2-cell SC RF cavities (650MHz ) will be used for Z mode. The CBI driven by the sum of the RF HOMs is faster than the radiation damping or even feedback damping.
  - When consider the whole RF system, HOM frequency spread due to the actual tolerances of the cavity construction can further relax the instability.
  - The measured HOM frequency shift among 650MHz 2cell RF cavities is around 0.5MHz~1MHz.
  - With a frequency spread of 1MHz, the shunt impedance can be reduced by a factor of 10.
• **RF HOMs**
  - 120 2-cell SC RF cavities (650MHz) will be used for Z mode. The CBI driven by the sum of the RF HOMs is faster than the radiation damping or even feedback damping.
  - Taking into account the HOM frequency spread, the impedance is well below the threshold determined by feedback damping.
Fast beam ion instability

• The beam ion instability for the electron beam can be serious due to high beam current and small emittance in order to reach high luminosity.
  – Emittance blow-up
  – A positive tune shift along the bunch train

• Mitigations adopted:
  – Low vacuum level
  – Multi-train filling pattern
  – Transverse feedback system
• The build-up of the ions and the instability growth rate are investigated.
• An efficient transverse feedback is required to damp the instability.
• More detailed simulation studies are underway.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{sep} \omega_{ion}/c_0$</td>
<td>1.4</td>
</tr>
<tr>
<td>$\rho_{ion,ave}$ [m$^{-3}$]</td>
<td>2.7E11</td>
</tr>
<tr>
<td>$\tau_e$ [ms]</td>
<td>2.3</td>
</tr>
<tr>
<td>$\Delta \nu_y$</td>
<td>0.009</td>
</tr>
</tbody>
</table>
Electron cloud effects

• Electron cloud can degrade the beam through
  – Coupled bunch instability => beam losses
  – Single bunch instability => beam size blowup

• Mitigations adopted:
  – Multi-train filling pattern with certain bunch spacing
  – Coating the vacuum chamber with NEG (low SEY)
  – Transverse feedback
Electron cloud build up is simulated with different bunch spacing

- The average electron cloud density in dipole and drift region is around $3.2e10$ m$^{-3}$ with SEY=1.6 & bunch spacing=25ns
- Comparable with the threshold determined by the single bunch instability.
- A lower SEY is expected with NEG coating.
Interaction with beam-beam

• In conventional e+e- storage ring colliders
  – Longitudinal dynamics is not quite sensitive to beam-beam interaction
  – Lengthened bunch is used in beam-beam simulation

• In CEPC
  – The bunch will be lengthened during beam-beam interaction by beamstrahlung
  – More self-consistent to consider impedance in beam-beam simulation

- Only one working point is stable without impedance.
- The beam-beam interaction gets more unstable with longitudinal impedance due to the X-Z coupling.
- Possible mitigations:
  ✓ Beam parameter optimization
  ✓ Impedance reduction
• According to the recent studies by K. Ohmi and D. Shatilov, smaller $\beta_x$ is preferred for X-Z coupling.
  – Larger stable region is obtained by reducing the $\beta_x$ from 0.2m to 0.15m
• By including the longitudinal impedance
  – The stable region is reduced and shifted
  – With only RW, a smaller tune shift and larger stable region are observed
• Beam parameters and impedance should be further optimized.

* D. Shatilov, FCC-ee parameter optimization, ICFA Beam Dynamics Newsletter 72, 30 (2017).
• Preliminary studies with transverse impedance shows no significant influence of the transverse wake field on collision.
  – $\beta_x^* = 0.15\text{m}$
  – With longitudinal and horizontal impedance

• More detailed studies are underway.
Summary

- The collective beam instabilities are potential restrictions in CEPC to achieve high luminosity performance. Different strategies used to mitigate these effects are considered.
- The single bunch instability is dominated by the microwave instability, which can induce longitudinal phase space distortions and couple with the beam-beam interaction. The beam parameters and impedance need to be further optimized to get larger stable region in tune.
- The coupled bunch instabilities need to be damped by efficient feedback systems.
- The two stream instabilities need multi-train filling pattern with certain bunch spacing, along with feedback and vacuum conditioning.