CEPC Linac design
Outline

• Introduction
  • Main parameters
  • Linac layout
• Positron source design
• Linac design
  • Electron linac
  • Positron linac
• Summary
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Introduction

• Linac design goal and principles
  • Simplicity
    • Layout
    • S-band accelerating structure (2856.75MHz)
      • 2856.75MHz =3.25MHz × 879, Linac
      • 650 MHz =3.25MHz × 200, Booster
      • 1300 MHz =3.25MHz × 400, Collider
  • High Availability and Reliability
    • ~ 15% backups for Klystrons and accelerating structure
    • Always providing beams that can meet requirements of Booster

Main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻ / e⁺ beam energy</td>
<td></td>
<td>GeV</td>
<td>10</td>
</tr>
<tr>
<td>Repetition rate</td>
<td></td>
<td>Hz</td>
<td>100</td>
</tr>
<tr>
<td>e⁻ / e⁺ bunch population</td>
<td></td>
<td>nC</td>
<td>&gt;1.5</td>
</tr>
<tr>
<td>Energy spread (e⁻ / e⁺)</td>
<td>σₑ</td>
<td></td>
<td>&lt;2 × 10⁻³</td>
</tr>
<tr>
<td>Emittance (e⁻ / e⁺)</td>
<td>εₑ</td>
<td>nm</td>
<td>&lt;120</td>
</tr>
<tr>
<td>e⁻ beam energy on Target</td>
<td></td>
<td>GeV</td>
<td>4</td>
</tr>
<tr>
<td>e⁻ bunch charge on Target</td>
<td></td>
<td>nC</td>
<td>10</td>
</tr>
</tbody>
</table>
Introduction

Main parameters

• Layout
  • Smaller emittance requirement **possibility** and high **potential**
    • **Damping Ring** for positron beam
      • Larger errors tolerance
      • Higher injection efficiency, easier injection design
      • Shorter damping time to damp the extraction beam of booster to collider

• Bunch charge: **3nC**
  • Enough redundancy and high bunch charge requirement possibility or potential
    • High electron beam energy ~4 GeV for positron production

• One-bunch-per-pulse
  • Only **short-range Wakefield** need to be considered
  ✔ Two-bunch-per-pulse
Position Linac

• ESBS (Electron Source and Bunching System)
  • 50 MeV & 11nC for positron production
Positron Linac

• ESBS (Electron Source and Bunching System)
  • 50 MeV & 11nC for positron production

• FAS (the First Accelerating Section)
  • Electron beam to 4 GeV & 10nC for positron production
Introduction

Positron Linac

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- PSPAS (Positron Source and Pre-Accelerating Section)
  - Positron beam larger than 200 MeV & larger than 3 nC
Introduction

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- **PSPAS (Positron Source and Pre-Accelerating Section)**
  - Positron beam larger than 200 MeV & larger than 3 nC

- **SAS (the Second Accelerating Section)**
  - Positron beam to 4 GeV & 3 nC
- **DR (Damping Ring)**
  - Positron beam 1.1 GeV/60 m
Introduction

Layout of Linac

Positron Linac

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- **DR (Damping Ring)**
  - Positron beam 1.1 GeV/60 m

- **TAS (the Third Accelerating Section)**
  - Positron beam to 10 GeV & 3 nC
Electron Linac

- ESBS (Electron Source and Bunching System)
  - 50 MeV & 3.3 nC
Electron Linac

- ESBS (Electron Source and Bunching System)
  - 50 MeV & 3.3 nC
- FAS (the First Accelerating Section)
  - Electron beam to 4 GeV & 3 nC

**Introduction**

**Layout of Linac**
Electron Linac

- **ESBS (Electron Source and Bunching System)**
  - 50 MeV && 3.3 nC
- **FAS (the First Accelerating Section)**
  - Electron beam to 4 GeV && 3 nC
- **EBTL (Electron Bypass Transport Line)**
  - Electron beam @ 4 GeV && 3 nC
**Electron Linac**

- **ESBS (Electron Source and Bunching System)**
  - 50 MeV && 3.3 nC

- **FAS (the First Accelerating Section)**
  - Electron beam to 4 GeV && 3 nC

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  - Electron beam @ 4 GeV && 3 nC

- **TAS (the Third Accelerating Section)**
  - Electron beam to 10 GeV && 3 nC
CPEC Linac design

Introduction

Layout of Linac

**Accelerating structure**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>~3 m</td>
</tr>
<tr>
<td>Frequency</td>
<td>S-band/2856.75 MHz</td>
</tr>
<tr>
<td>Aperture</td>
<td>&gt;19 mm</td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>21 MV/m</td>
</tr>
<tr>
<td>SLED</td>
<td>Yes</td>
</tr>
<tr>
<td>Mode</td>
<td>1 (Kly.)-&gt;4 (Acc. tube)</td>
</tr>
</tbody>
</table>

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Positron source

- Layout of positron source
  - Target (Conventional)
    - W@15mm
    - Rms electron beam size: 0.5mm
  - AMD (Adiabatic Matching Device)
    - Length: 100mm
    - Aperture: 8mm → 26mm
  - Capture & Pre-accelerating structure
    - Length: 2 m
    - Aperture: 25 mm
    - Gradient: 22 MV/m
  - Chicane
    - Wasted electron separation

Layout of PSPAS

- 4 GeV Electron
- Flux Concentrator
- 22 MV/m
- Solenoid
- Chicane
- > 200 MeV

FCC Week 2018, 9-13 April 2018, Amsterdam, Netherlands.
Positron source

- SuperKEKB positron linac commissioning (3.3 GeV)
  - 2014, N(e+)/N(e-)~20%
  - 2015, N(e+)/N(e-)~30% [designed 50%]

- CEPC positron source
  - Positron bunch charge > 3 nC
  - Electron beam:
    - 4GeV
    - 10nC/bunch (maybe lower)
  - Electron beam: 4 kW

- Energy deposition
  - 0.784 GeV/e- @ FLUKA
  - 784 W → water cooling

- Target
  - tungsten
  - 15 mm
  - Beam size: 0.5 mm
Positron source

- Norm. RMS. Emittance
  - 2500 mm-mrad
- Energy: >200 MeV
- Positron yield
  - Ne+/Ne- > 0.55 @ [-6°, 14°, 235MeV, 265MeV]
### Positron source Parameters

| Incident e- beam energy | SLC 33 GeV | LEP (LIL) 200 MeV | KEKB/SUPER KEKB 3.3/3.3 GeV | FCC-ee (conv.) 4.46 GeV | CEPC 4 GeV |
| e-/bunch \([10^{10}]\) | 3-5 0.5 - 30 (20 ns pulse) | 6.25/6.25 | 5.53 | 6.25 |
| Bunch/pulse | 1 1 | 2/2 | 2 | 1 |
| Rep. rate | 120 Hz 100 Hz | 50 Hz/50 Hz | 200 Hz | 100 Hz |
| Incident Beam power | ~20 kW 1 kW (max) | 3.3 kW 15 kW | 4 kW | 4 kW |
| Beam size @ target | 0.6 - 0.8 mm < 2 mm | />0.7 mm | 0.5 mm | 0.5 mm |
| Target thickness | 6X0 2X0 /4X0 | 4.5X0 | 4.3X0 |
| Target size | 70 mm 5 mm | 14 mm 0.5 mm | 10 mm |
| Target | Moving Fixed | Fixed/Fixed | Fixed |
| Deposited power | 4.4 kW /0.6 kW | 2.7 kW 0.78kW |
| Capture system | AMD \(\frac{1}{4}\) transformer/AMD | AMD | AMD |
| Magnetic field | 6.8T->0.5T 1 T->0.3T | /4.5T->0.4T 7.5T->0.5T | 6T->0.5T |
| Aperture of 1st cavity | 18 mm 25mm/18 mm | /30 mm 20 mm | 25 mm |
| Gradient of 1st cavity | 30-40 MV/m ~10 MV/m | /10 MV/m 30 MV/m | 22 MV/m |
| length of 1st cavity | 1m 3m | 2m | 3m |
| Linac frequency | 2855.98 MHz 2998.55 MHz | 2855.98 MHz 2855.98 MHz | 2856.75 MHz |
| e+ yield @ CS exit | ~1.6 e+/e- ~0.003 e+/e- (linac exit) | /~0.5 e+/e- | ~0.7 e+/e- | ~0.55 e+/e- |

Tungsten radiation length \(X_0\) is 0.35 cm.
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• Summary
• Focusing structure: **Triplet**
  • Long drift length for accelerating tubes
  • Beam size in Acc. tubes is small and easy control
  • Same beam envelopes at X/Y planes
  • 1 triplet+4 Acc. tubes → 1 triplet+8 Acc. tubes
• Operation mode:
  • High charge mode (positron production)
    • 4GeV & 10 nC
  • Low charge mode (electron injection)
    • 10 GeV & 3 nC
Linac design

Electron linac $\rightarrow$ Positron production

- High charge mode
- 10 nC @ 4 GeV
- Energy spread (rms): 0.5%
- Emittance growth with errors
Linac design

Electron linac ➔ Electron injection

• High charge mode
  • 10 nC @ 4 GeV
  • Energy spread (rms): 0.5%
  • Emittance growth with errors

• Low charge mode
  • 3 nC @ 10 GeV
  • Energy spread (rms): 0.15%
  • Emittance (rms): 5 nm
Linac design

• PSPAS→SAS (DR) +TAS
  • SAS: 200 MeV→4 GeV
  • Damping Ring @ 1.1 GeV
  • TAS: 4GeV→10 GeV

• Transverse focusing structure
  • FODO, nesting on Acc. tubes
  • Triplet
linac design

- Positron linac
  - 3 nC & 10 GeV
  - Energy spread (rms): 0.16%
  - Emittance with DR (rms): 40/24nm
  - Emittance without DR (rms): 120/120nm
Linac design

Misalignment errors with correction

- Positron linac
  - One-to-one correction scheme
  - Errors: Gaussian distribution, 3σ truncated
- Beam orbit
  - RMS value < 0.3 mm
  - Rms value < 0.1 mm (high energy part)

<table>
<thead>
<tr>
<th>Error description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translational error</td>
<td>mm</td>
<td>0.1</td>
</tr>
<tr>
<td>Rotation error</td>
<td>mrad</td>
<td>0.2</td>
</tr>
<tr>
<td>Magnetic element field error</td>
<td>%</td>
<td>0.1</td>
</tr>
<tr>
<td>BPM uncertainty</td>
<td>mm</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Linac design

Field errors

• Simulation condition
  • 5000 seeds
  • Accelerating tubes
    • phase errors and amp errors
    • 4 in 1 KLY, 4 accelerating tubes in one group
    • $3\sigma$--Gaussian

• Energy spread < 0.2%
  • Phase errors: 0.5 degree (rms)
  • Grad. errors: 0.5% (rms)

• Energy jitter: 0.2%
### Linac design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>1.1</td>
</tr>
<tr>
<td>Circumference</td>
<td>M</td>
<td>58.5</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>Hz</td>
<td>100</td>
</tr>
<tr>
<td>Bending radius</td>
<td>M</td>
<td>3.62</td>
</tr>
<tr>
<td>Dipole strength $B_0$</td>
<td>T</td>
<td>1.01</td>
</tr>
<tr>
<td>$U_0$</td>
<td>keV</td>
<td>35.8</td>
</tr>
<tr>
<td>Damping time x/y/z</td>
<td>ms</td>
<td>12/12/6</td>
</tr>
<tr>
<td>$\delta_0$</td>
<td>%</td>
<td>0.05</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>mm.mrad</td>
<td>287.4</td>
</tr>
<tr>
<td>Nature $\sigma_z$</td>
<td>mm</td>
<td>7 (23ps)</td>
</tr>
<tr>
<td>$\varepsilon_{inj}$</td>
<td>mm.mrad</td>
<td>2500</td>
</tr>
<tr>
<td>$\varepsilon_{ext x/y}$</td>
<td>mm.mrad</td>
<td>704/471</td>
</tr>
<tr>
<td>$\delta_{inj}/\delta_{ext}$</td>
<td>%</td>
<td>0.3/0.06</td>
</tr>
<tr>
<td>Energy acceptance by RF</td>
<td>%</td>
<td>1.0</td>
</tr>
<tr>
<td>$f_{RF}$</td>
<td>MHz</td>
<td>650</td>
</tr>
<tr>
<td>$V_{RF}$</td>
<td>MV</td>
<td>1.8</td>
</tr>
</tbody>
</table>

---

### Damping Ring

- Emittance not critical
- One bunch in DR(200ns)
  - 10 ms $\rightarrow$ 20ms
- Two bunch: yes
- IBS
  - Emittance growth
- CSR (Coherent synchrotron radiation)
  - CSR Instability
Summary

• The CEPC linac works with 100 Hz repetition, 10 GeV and one-bunch-per-pulse;
• The linac can provide positron beam and electron beam with 3nC bunch charge, which is larger than the requirements;
• One preliminary damping ring is proposed;
• By now seems it’s no problem in linac design and further works are on the way.
Linac design

Short-Range Wakefield

• k. Yokoya and K. bane’s Wakefield model

![Graph showing the short-range wakefield](image)

\[
W_L(s) = \frac{Z_0 e}{\pi} \exp\left(\frac{\sqrt{s}}{4s_0}\right) \text{erfc}\left(\frac{\sqrt{s}}{4s_0}\right)
\]

with

\[
s_0 = \frac{a}{8 \left(1 - 0.464 \sqrt{\frac{e_p}{p}} - 0.077 \sqrt{\frac{e_p}{p}}\right)}
\]

For short \(s\) (l) can be rewritten in the following simpler way:

\[
W_L(s) \approx \frac{Z_0 e \alpha}{\pi a^2} \exp\left(\frac{-s}{\sqrt{s_0}}\right)
\]

The short-range wake is obtained by Inverse Fourier transforming:

\[
W_L(s) = \frac{Z_0 e}{\pi} \exp\left(\frac{\sqrt{s}}{4s_0}\right) \text{erfc}\left(\frac{\sqrt{s}}{4s_0}\right)
\]

where

\[
W_L(s) = 0 \quad \text{for} \quad s > 0 \quad \text{and} \quad W_L(s) = 0 \quad \text{for} \quad s < 0.
\]

For short \(s\) (l) can be rewritten in the following simpler way:

\[
W_L(s) = \frac{Z_0 e \alpha}{\pi a^2} \exp\left(\frac{-s}{\sqrt{s_0}}\right)
\]

where

\[
S_0 = 0.169 \frac{a^{1.79} \sqrt{G}}{L^{1.17}}
\]

\[\zeta = \frac{L}{a}\]

\[r = \frac{a}{\lambda} \]

For short \(s\) (l) can be rewritten in the following simpler way:

\[
W_L(s) = \frac{Z_0 e}{\pi a^2} \left[1 + W_{L1} \sqrt{s} + W_{L2} \zeta + W_{L3} \sqrt{\zeta} \right]
\]

\[
W_T(s) = \frac{Z_0 e}{\pi a^4} \left[2 + W_{T1} \sqrt{s} + W_{T2} \zeta + W_{T3} \sqrt{\zeta} \right]
\]

\[
W_{L1} = -1.614 \alpha^{0.2}\]

\[
W_{L2} = +1.012 \alpha^{0.199}\]

\[
W_{L3} = -0.231 \alpha^{0.211}\]

\[
W_{T1} = -2.781 \alpha^{0.217}\]

\[
W_{T2} = +1.637 \alpha^{0.511}\]

\[
W_{T3} = -0.364 \alpha^{0.763}\]

## Injection

<table>
<thead>
<tr>
<th>Mode</th>
<th>Higgs</th>
<th>W</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Mode</td>
<td>Top-up</td>
<td>Full</td>
<td>Top-up</td>
</tr>
<tr>
<td>Bunch number</td>
<td>242</td>
<td>1524</td>
<td>6000</td>
</tr>
<tr>
<td>Bunch Charge (nC)</td>
<td>0.72</td>
<td>1</td>
<td>0.576</td>
</tr>
<tr>
<td>Beam Current (mA)</td>
<td>0.5227</td>
<td>0.726</td>
<td>2.63</td>
</tr>
<tr>
<td>Current threshold</td>
<td>1 mA</td>
<td>4 mA</td>
<td>10 mA</td>
</tr>
<tr>
<td>Number of Cycles</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Current decay</td>
<td>3%</td>
<td>4.17%</td>
<td>3%</td>
</tr>
<tr>
<td>Ramping Cycle (sec) (Up + Down)</td>
<td>10</td>
<td>6.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Filling time (sec) (e+, e-)</td>
<td>25.84</td>
<td>45.68</td>
<td>275.2</td>
</tr>
<tr>
<td>Injection period (sec)</td>
<td>73.1</td>
<td>131</td>
<td>438</td>
</tr>
<tr>
<td>Full Injection time</td>
<td>600 s</td>
<td>900 s</td>
<td>2.2 Hour (从230mA）对撞</td>
</tr>
</tbody>
</table>
Error study

• Electron linac
  • First orbit correction + multi-particles simulation
  • Low charge
    • Beam orbit can be controlled well
  • High charge
    • Misalignments of Acc. Tubes
    • BPM noisy
    • Wakefield
• In operation, the orbit and emittance growth can be controlled better; Correction is based on multi-particles orbit
• Meet the requirements for positron production