CEPC Linac design

FCCWEEK2018
11 April, 2018

Cai Meng, Guoxi Pei, Jingru Zhang, Xiaoping Li,
Dou Wang, Jie Gao, Shilun Pei, Yunlong Chi

Institute of High Energy Physics, CAS, Beijing
Outline

• Introduction
  • Main parameters
  • Linac layout

• Positron source design

• Linac design
  • Electron linac
  • Positron linac

• Summary
Outline

• Introduction
  • Main parameters
  • Linac layout

• Positron source design

• Linac design
  • Electron linac
  • Positron linac

• Summary
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>$E_{e^-}/E_{e^+}$</td>
<td>GeV</td>
<td>10</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$f_{\text{rep}}$</td>
<td>Hz</td>
<td>100</td>
</tr>
<tr>
<td>e⁻/e⁺ bunch population</td>
<td>$N_{e^-}/N_{e^+}$</td>
<td>nC</td>
<td>&gt;9.4×10⁹</td>
</tr>
<tr>
<td>Energy spread (e⁻/e⁺)</td>
<td>$\sigma_E$</td>
<td></td>
<td>&lt;2×10⁻³</td>
</tr>
<tr>
<td>Emittance (e⁻/e⁺)</td>
<td>$\varepsilon_r$</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
**Positron Linac**

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

**FCC Week 2018, 9-13 April 2018, Amsterdam, Netherlands.**
Introduction

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

- **SAS (the Second Accelerating Section)**
  - Positron beam to 4 GeV && 3 nC

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

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

Layout of Linac

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

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

- **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 1.1GeV/60m
Introduction

**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
- **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 1.1GeV/60m
- **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
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
- **EBTL (Electron Bypass Transport Line)**
  - Electron beam @ 4 GeV & 3 nC
- **TAS (the Third Accelerating Section)**
  - Electron beam to 10 GeV & 3 nC
Introduction

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>

Outline

• Introduction
  • Main parameters
  • Linac layout

• Positron source design

• Linac design
  • Electron linac
  • Positron linac

• Summary
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

FCC Week 2018, 9-13 April 2018, Amsterdam, Netherlands.
• 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
  - \( \text{Ne}^+/\text{Ne}^- > 0.55 \) @ \([-6^\circ , 14^\circ , 235\text{MeV}, 265\text{MeV}]\)

Dynamic results of PSPAS

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

Tungsten radiation length $X_0$ is 0.35 cm.
Outline

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

Electron linac

- 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 $\rightarrow$ 1 triplet + 8 Acc. tubes

- Operation mode:
  - High charge mode (positron production)
    - 4GeV & 10 nC
  - Low charge mode (electron injection)
    - 10 GeV & 3 nC

FCC Week 2018, 9-13 April 2018, Amsterdam, Netherlands.
Linac design

Electron linac $\rightarrow$ Positron production

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

FCC Week 2018, 9-13 April 2018, Amsterdam, Netherlands.
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: 4 GeV → 10 GeV
- Transverse focusing structure
  - FODO, nesting on Acc. tubes
  - Triplet

FCC Week 2018, 9-13 April 2018, Amsterdam, Netherlands.
• Positron linac
  • 3 nC && 10 GeV
  • Energy spread (rms): 0.16%
  • Emittance with DR (rms): 40/24nm
  • Emittance without DR (rms): 120/120nm
CPEC Linac design

Misalignment errors with correction

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

### Error description

<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

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

Field errors

- 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 → 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

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

Short-Range Wakefield

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

\[ W_L(s) = \frac{Z_0 e}{\pi} \exp\left(\frac{s}{4s_0}\right) \left[1 + \frac{s}{\sqrt{s_0}}\right] \]

with

\[ s_0 = \frac{a}{\sqrt{1 - 0.465 \frac{V_p}{\sqrt{1 - 0.078 V_p}}}} \]

For short \( s \) (1) can be rewritten in the following simpler way:

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

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

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

### Injection

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