Beam Dynamics Studies in the BEPCII Storage Rings

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Contents

- Introduction
- Determination of beam parameters
- Single beam dynamics
- Beam instabilities
- Summary
1. Introduction

- BEPCII — An upgrade project of the BEPC
- A two-ring factory like machine
- Provide beam to HEP & SR
Goals of the BEPCII

Collision Mode

- Beam energy range: 1-2.1 GeV
- Optimized beam energy: 1.89 GeV
- Luminosity: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ @1.89 GeV
- Full energy injection: 1-1.89 GeV

SR Mode

- Beam energy: 2.5 GeV
- Beam current: 250 mA
- Keep the present beam lines useable
### Design Parameters of Ring (Col. Mode)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>1.89</td>
</tr>
<tr>
<td>Circumference</td>
<td>m</td>
<td>237.53</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>0.91</td>
</tr>
<tr>
<td>Bunch number</td>
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<tr>
<td>Bunch current</td>
<td>mA</td>
<td>9.8</td>
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<td>Bunch spacing</td>
<td>m</td>
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<tr>
<td>Bunch length</td>
<td>cm</td>
<td>1.5</td>
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<tr>
<td>RF frequency</td>
<td>MHz</td>
<td>499.80</td>
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<tr>
<td>Harmonic number</td>
<td></td>
<td>396</td>
</tr>
<tr>
<td>Emittance (x/y)</td>
<td>nm·rad</td>
<td>144/2.2</td>
</tr>
<tr>
<td>$\beta$ function at IP (x/y)</td>
<td>m</td>
<td>1.0/0.015</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>mrad</td>
<td>±11</td>
</tr>
<tr>
<td>Design luminosity</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>$1 \times 10^{33}$</td>
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### Design Parameters of Ring (SR Mode)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>2.5</td>
</tr>
<tr>
<td>Circumference</td>
<td>m</td>
<td>241.13</td>
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<tr>
<td>Beam Current</td>
<td>mA</td>
<td>250</td>
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<tr>
<td>Natural emittance</td>
<td>nm·rad</td>
<td>120</td>
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<tr>
<td>RF frequency</td>
<td>MHz</td>
<td>499.80</td>
</tr>
<tr>
<td>Harmonic number</td>
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<tr>
<td>RF Voltage</td>
<td>MV</td>
<td>3.0</td>
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<tr>
<td>Energy loss per turn</td>
<td>keV</td>
<td>335</td>
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<tr>
<td>SR Power</td>
<td>kW</td>
<td>84</td>
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<tr>
<td>Natural bunch length</td>
<td>cm</td>
<td>1.2</td>
</tr>
<tr>
<td>Momentum compact factor</td>
<td></td>
<td>0.016</td>
</tr>
<tr>
<td>Tune (x/y/z)</td>
<td></td>
<td>7.28/5.18/0.036</td>
</tr>
<tr>
<td>SR Damping time (x/y/z)</td>
<td>ms</td>
<td>12/12/6</td>
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</table>
### Parameters of on-line lattice

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>237.53</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>1.89</td>
</tr>
<tr>
<td>RF voltage (MV)</td>
<td>1.5</td>
</tr>
<tr>
<td>Tune (x/y/s)</td>
<td>6.54/5.59/0.035</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>0.0237</td>
</tr>
<tr>
<td>Nature chromaticity (x/y)</td>
<td>−10.8/−20.8</td>
</tr>
<tr>
<td>Nature horizontal emittance (nm·rad)</td>
<td>132</td>
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<tr>
<td>Nature energy spread</td>
<td>$5.16 \times 10^{-4}$</td>
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<tr>
<td>Nature bunch length (cm)</td>
<td>1.36</td>
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<tr>
<td>$\beta_{x,y} @ IP$ (m) (x/y)</td>
<td>1/0.015</td>
</tr>
<tr>
<td>$\beta_{x,y, \text{max}} @ IR$ (m) (x/y)</td>
<td>70.2/91.4</td>
</tr>
<tr>
<td>$\beta_{x,y, \text{max}} @ \text{arc}$ (m) (x/y)</td>
<td>24.2/23.5</td>
</tr>
<tr>
<td>$D_{x,\text{max}}$ (m)</td>
<td>2.28</td>
</tr>
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</table>
2. Determination of beam parameters

• $\beta$ functions and transverse tunes
  — Optics correction with LOCO, based on the measured response matrix.
  — COD correction with response matrix.
  — Measured with the method of tune modulation. $(\beta$ in arcs and $\beta^*$ at the IP)
β functions at the IP

- Thick lens model
- Tune modulation method
- Horizontal bending effect of the SCQ near the IP included
• Formulae

\[
\bar{\beta}_y = \pm \frac{2}{\Delta kl} \left[ \cot(2\pi Q_y)(1 - \cos(2\pi \Delta Q_y)) + \sin(2\pi \Delta Q_y) \right]
\]

\[
\bar{\beta}_x = \pm \frac{2}{\left( \Delta kl + \frac{\theta}{\rho} \right)} \left[ \cot(2\pi Q_x)(1 - \cos(2\pi \Delta Q_x)) + \sin(2\pi \Delta Q_x) \right]
\]

\[
\bar{\beta}_y = \left\{ L_0 \sin^2(k_0 l) + \frac{k_0 l - \sin(k_0 l)\cos(k_0 l)}{2k_0^2 l} + \frac{L_1^2 [k_0 l + \sin(k_0 l)\cos(k_0 l)]}{2k_0 l} \right\} \cdot \frac{1}{\beta_y^*}
+ \frac{k_0 l + \sin(k_0 l)\cos(k_0 l)}{2k_0 l} \cdot \beta_y^*
= C_1 \cdot \frac{1}{\beta_y^*} + C_2 \cdot \beta_y^*
\]

\[
\bar{\beta}_x = \left\{ L_0 \sinh^2(k_0 l) - \frac{k_0 l - \sinh(k_0 l)\cosh(k_0 l)}{2k_0^2 l} + \frac{L_1^2 [k_0 l + \sinh(k_0 l)\cosh(k_0 l)]}{2k_0 l} \right\} \cdot \frac{1}{\beta_x^*}
+ \frac{k_0 l + \sinh(k_0 l)\cosh(k_0 l)}{2k_0 l} \cdot \beta_x^*
= D_1 \cdot \frac{1}{\beta_x^*} + D_2 \cdot \beta_x^*
\]

\[
\beta_y^* = \frac{\bar{\beta}_y - \sqrt{\bar{\beta}_y^2 - 4C_1 C_2}}{2C_2}
\]

\[
\beta_x^* = \frac{\bar{\beta}_x - \sqrt{\bar{\beta}_x^2 - 4D_1 D_2}}{2D_2}
\]
### Results

<table>
<thead>
<tr>
<th></th>
<th>$\beta_x$ (m)</th>
<th>$\beta_y$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCQW-1*</td>
<td>1.293</td>
<td>60.87</td>
</tr>
<tr>
<td>SCQE-1</td>
<td>3.661</td>
<td>60.60</td>
</tr>
<tr>
<td>IP-1</td>
<td>0.983</td>
<td>0.0171</td>
</tr>
<tr>
<td>SCQW-2</td>
<td>2.202</td>
<td>62.45</td>
</tr>
<tr>
<td>SCQE-2</td>
<td>3.658</td>
<td>62.12</td>
</tr>
<tr>
<td>IP-2</td>
<td>0.986</td>
<td>0.0167</td>
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</table>

*1 and 2 mean the measurements at different time*
• Transverse tunes

• After the optics corrections with response matrix, measured tunes are close to the nominal values.

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>Measured (BER)</th>
<th>Measured (BPR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_x$</td>
<td>6.54</td>
<td>6.544</td>
<td>6.540</td>
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<tr>
<td>$\nu_y$</td>
<td>5.59</td>
<td>5.559</td>
<td>5.596</td>
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</table>
• Dispersion function
  — Measured with the method of RF frequency shift.
  — Small difference between measured and theoretical dispersions at most BPMs.
• Chromaticity

\( y = 1.5955x + 0.5456 \)

\( \xi_x \sim 1.6, \quad \xi_{x0} = 1.0 \)
Chromaticity measured at the 1st stage of commissioning

<table>
<thead>
<tr>
<th>Nominal $\xi_x/\xi_y$</th>
<th>Meas. $\xi_x/\xi_y$</th>
<th>Nominal $\xi_x/\xi_y$</th>
<th>Meas. $\xi_x/\xi_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5.0/-5.0</td>
<td>-5.33/-5.02</td>
<td>-1.0/-1.0</td>
<td>-1.28/-0.82</td>
</tr>
<tr>
<td>-3.0/-3.0</td>
<td>-3.19/-2.46</td>
<td>+1.0/+1.0</td>
<td>+1.05/+0.95</td>
</tr>
<tr>
<td>-2.0/-2.0</td>
<td>-2.33/-0.89</td>
<td>+5.0/+5.0</td>
<td>+4.50/+3.28</td>
</tr>
<tr>
<td>Natural $\xi_{x0}/\xi_{y0}$</td>
<td>-11.7/-10.4</td>
<td>Meas. $\xi_{x0}/\xi_{y0}$</td>
<td>-10.33/-10.07</td>
</tr>
</tbody>
</table>
• Optimized RF frequency
- Transverse coupling
- Adjusted with the vertical bump in sextupoles
- Measured with tune split method
- Method using response matrix is under way
3. Single Beam Dynamics

- Bunch lengthening
- Tune variation vs. bunch current
- Impedance
- Beam lifetime
• **Bunch lengthening**

  - Bunch length in BER/BPR measured with streak camera.
  - Single bunch stored in BER/BPR, respectively, in bunch length measurement.
  - Keep $V_{\text{rf}}$ fixed, measure the bunch length vs. bunch current.
• Bunch length fitting

\[ \rho(z) = \rho_0 + \rho_1 \exp \left( -\frac{1}{2} \frac{(z - \bar{z})^2}{1 + \text{sgn}(z - \bar{z}) A^2 \sigma_z^2} \right) \]
Static image measured and reduced by

\[ \sigma_l = \sqrt{\sigma_m^2 - \sigma_{\text{static}}^2} \]
• Results of bunch lengthening

\[ y = 1.2065x^{0.0802} \]
\[ L_{ave} = 118 \text{nH} \Rightarrow |Z/n|_0 = 0.94 \ \Omega \]
• According to

\[ \frac{\sigma_l}{\sigma_{l0}} \approx 1 + \frac{e\alpha_p I_b \omega_0 L}{8\sqrt{\pi} \nu_s^2 E} \left( \frac{R}{\sigma_{l0}} \right)^3 \]

we get

\[ \frac{\sigma_l}{\sigma_{l0}} \approx 1 + 0.0185 I_b \quad \Rightarrow \quad y = 1 + 0.0173 x \]
$y = 0.8951 x^{0.145}$
\[ L_{\text{ave}} = 32.1 \text{nH} \Rightarrow |Z/n|_0 = 0.25 \Omega \]

\[
\frac{\sigma_l}{\sigma_{l_0}} = 1 + 0.0053 I_b \quad \Rightarrow \quad y = 1 + 0.007x
\]
• Design estimation on impedance

\[ n = \frac{\omega}{\omega_0} \]

\[ L = 29 \text{ nH}, \quad |Z/n|_0 = 0.2 \Omega \]
• Tune variation vs bunch current

• Betatron tunes vary with single bunch current

• Effective impedance can be got from the tune variation

\[
\frac{dv_\perp}{dI} = \frac{R}{4\sqrt{\pi} (E/e) \sigma_\perp} \bar{\beta}_\perp Z_{\perp,\text{eff}}
\]

\[
Z_{\perp,0} = \frac{b^2}{2R} Z_{\perp,\text{eff}}
\]
BPR:

Hori. tune vs. bunch current
\[ |Z/n|_0 \sim 1.38 \pm 0.021 \ \Omega \]

Vert. tune vs. bunch current
\[ |Z/n|_0 \sim 0.81 \pm 0.004 \ \Omega \]
BER:

Hori. tune vs. bunch current
$|Z/n|_0 \sim 1.43 \pm 0.032 \Omega$

Vert. tune vs. bunch current
$|Z/n|_0 \sim 1.15 \pm 0.014 \Omega$
• **Estimated impedance**

- Bunch lengthening $\Rightarrow$
  - BPR: $|Z/n|_0 = 0.94\Omega$, BER: $|Z/n|_0 = 0.25\Omega$

- Tune variation $\Rightarrow$
  - BPR & BER: $|Z/n|_0 \sim 1.0\,\Omega$
• **Beam Lifetime**

• Single bunch beam lifetime in both rings measured for several times under different machine conditions

• Multi-bunch beam lifetime observed with different beam current, together with vacuum pressure

• Some calculations done on beam lifetime
• Observations

• BER: $I_b = 4.5 \sim 30 \text{ mA}, \ V_{rf} = 1.69 \text{ MV}$

\[ \nu_s = 0.0344 \]
• BPR: $I_b = 1.5 \sim 16.5 \text{ mA}$, $V_{rf} = 1.61 \text{ MV}$, $\nu_s = 0.0334$
Single bunch lifetime

![Graph showing the relationship between single bunch current and lifetime for positrons and electrons.](image-url)
• Beam lifetime:

\[
\frac{1}{\tau} = - \frac{1}{N} \frac{dN}{dt}
\]

Long enough

Without beam collision:

\[
\frac{1}{\tau} = \frac{1}{\tau_g} + \frac{1}{\tau_q} + \frac{1}{\tau_t}
\]
• **Touschek lifetime**

• Got from single bunch lifetime, say, the lifetime of 1mA ~ Touschek lifetime

• Similar in BER & BPR, we get

  \[ \tau_t = 10 \text{ hrs } @ 1\text{mA} \]

• In the BEPCII design book, the calculated

  \[ \tau_t = 7.1 \text{ hrs } @ 9.8\text{mA} \]
• **Beam-gas lifetime**

• In the BPR, \( <p> = 0.178 \text{ nTorr @1mA} \)

• The residual gas consists of 70% CO and 30% \( \text{H}_2 \) in the BPR.

• BER: 70% \( \text{H}_2 \) + 30% CO

• The calculated beam-gas lifetime is 146 hrs @1mA in BPR

• The calculated total lifetime @1mA is 43 hrs, >> 10 hrs!
• Multi-bunch beam lifetime

• Beam current: 100mA, 200mA, 300mA, 400mA and 500mA for both BER & BPR
• BPR beam lifetime @ 500mA

- 500mA*500mA collision observation
- Bunch current ~5mA
- Average vacuum pressure = 3.58 nTorr
- 70%CO + 30%H₂ in residual gas
- Beam-gas lifetime calculated ~7.3 hrs
- Touschek lifetime ~2.0 hrs@5mA
- Beam-beam lifetime ~6.0 hrs
- Calculated beam lifetime ~1.24 hrs
- Observed beam lifetime ~1.12 hrs when collision
• BER beam lifetime @ 500mA

• $<p> = 1.79$ nTorr

• Calculated beam-gas lifetime $\sim 33\text{hrs}@500\text{mA}$, 30\%CO+70\%H$_2$

• Touschek lifetime $\sim 2.0\text{hrs}@5\text{mA}$

• Calculated beam lifetime $\sim 1.44\text{hrs}$

• Observed beam lifetime $\sim 3\text{hrs}@500\text{ mA}$ when collision

◆ Observed lifetime of e+ beam agrees well as the expected value, but e- beam doesn’t

◆ Vacuum needs to improve further.
Beam collision at 500mA in both rings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>e⁺</th>
<th>e⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>1.8899</td>
<td>1.8899</td>
</tr>
<tr>
<td>Current [mA]</td>
<td>503.339</td>
<td>503.337</td>
</tr>
<tr>
<td>Lifetime [hr]</td>
<td>1.12</td>
<td>2.94</td>
</tr>
<tr>
<td>Inj. Rate [mA/min]</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
4. Beam Instabilities

- Single bunch — Bunch lengthening
- Electron cloud — Observed clearly in the positron ring
  — beam blow-up, bunch oscillation, etc.
  — preliminary analyses
Observation on coupled bunch instability

Spectrum distribution

- **e− beam**: 99-bunch, uniform filling
  - 4 RF buckets spacing
  - $\Sigma I_b = 40\,\text{mA}$

- **e+ beam**: 99-bunch, uniform filling
  - 4 RF buckets spacing
  - $\Sigma I_b = 40\,\text{mA}$
Sidebands of positron beam

99-bunch uniform filling
4 RF buckets spacing
$\Sigma I_b = 35\text{mA}$, $I_{th} \sim 35\text{mA}$

99-bunch uniform filling
4 RF buckets spacing
$\Sigma I_b = 100\text{mA}$
Sidebands of positron beam

198-bunch uniform filling
2 RF buckets spacing
\( \Sigma I_b = 31 \text{mA}, I_{th} = 29\sim31 \text{mA} \)

198-bunch uniform filling
2 RF buckets spacing
\( \Sigma I_b = 28.9 \text{mA} \)
Positron beam:
48 bunches
uniform filling
bunch spacing: 8 RF buckets

ΣI = 50mA

ΣI = 56mA

ΣI = 60mA
Threshold current of ECI in e+ ring

<table>
<thead>
<tr>
<th>Bunch No.</th>
<th>Bunch spacing (RF bucket)</th>
<th>( I_b ) (mA)</th>
<th>( I_{th} ) (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>8</td>
<td>~1.0</td>
<td>~50</td>
</tr>
<tr>
<td>99</td>
<td>4</td>
<td>~0.35</td>
<td>~35</td>
</tr>
<tr>
<td>198</td>
<td>2</td>
<td>~0.15</td>
<td>~30</td>
</tr>
</tbody>
</table>
Mode distribution comparison

Same filling pattern:
99 bunches with 4 RF buckets spacing

\[ e^- \text{ beam, } \sum I_b = 70\text{mA} \]

\[ e^+ \text{ beam, } \sum I_b = 55\text{mA} \]

\[ e^+ \text{ beam, } \sum I_b = 60\text{mA} \]
Filling pattern: 198 bunches with 2 RF buckets spacing

- e⁻ beam, $\sum I_b = 46\text{mA}$
- e⁺ beam, $\sum I_b = 38\text{mA}$

Filling pattern: 50 bunches with 4 RF buckets spacing

- e⁻ beam, $\sum I_b = 60\text{mA}$
- e⁺ beam, $\sum I_b = 70\text{mA}$
Observations on the vertical bunch size with streak camera

- $I_b = 3.27\,\text{mA}$
- $I_b = 4.46\,\text{mA}$
- $I_b = 5.0\,\text{mA}$
- $I_b = 6.3\,\text{mA}$
- $I_b = 7.1\,\text{mA}$
- $I_b = 8.0\,\text{mA}$
- $I_b = 9.0\,\text{mA}$

No blow-up in single bunch case when $I_b$ increases
Positron bunch train (8 bunches, $S_b = 8\text{ns}$) case with different $I_b$

- $I_b = 5.0\text{mA}$
  - Feedback off

- $I_b = 5.0\text{mA}$
  - Feedback on

- $I_b = 7.0\text{mA}$
  - Feedback off

- $I_b = 7.0\text{mA}$
  - Feedback on

- $I_b = 9.0\text{mA}$
  - Feedback on

Vertical blow-up is not clearly Feedback has no effect to the blow-up.
$N_b = 93$, bunch spacing = 4 RF buckets

$N_b = 63$, bunch spacing = 6 RF buckets

No clear blow-up in vertical between the head and tail bunches
• ECI Simulation results
5. Summary

• The two rings of the BEPCII reached their design parameters after optics corrections.
• Single and multi-bunch beam phenomena are understood by experimental studies.
• Collective effects, such as ECI, are observed and analyses are under way.
• Understanding the machine with more experiments is necessary.
Thanks for your attentions!