Beam Dynamics Study in the HEPS Storage Ring

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On behalf of the HEPS Accelerator Physics Team

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HEPS Accelerator physics team includes:

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The presented work is part of that done by entire HEPS project team, led by Qing Qin, etc.

Thank worldwide experts for helpful discussions, suggestions, collaborations on HEPS design.
• **Lattice design**
  — hybrid 7BAs, high- and low- beta design

• **Nonlinear optimization**
  — Combination of MOGA and PSO

• **Injection scheme**
  — On-axis injection, accumulation in booster

• **Collective effects**
  — Single- and multi-bunch instabilities

• **Error specification and correction**
  — sextupole movers

• Some issues have been studied, but will not addressed in following slides, such as 
dynamic error measurement, modeling and feedback; beam loss and collimation; 
commissioning simulation; transient injection instabilities; full coupling; etc.
Milestones:
- Dec. 2017, HEPS Project Proposal Report approved
- Dec. 2018, HEPS Feasibility Study Report approved, total budget: 4.76 Billion RMB (manpower excluded), with the following goal parameters

Design goals of the HEPS light source

<table>
<thead>
<tr>
<th>Main parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>6</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>pm·rad</td>
<td>≤ 60</td>
</tr>
<tr>
<td>Brightness</td>
<td>phs/s/mm²/mrad²/0.1%BW</td>
<td>&gt; 10^{22}</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td>200</td>
</tr>
<tr>
<td>Injection</td>
<td>Top-up</td>
<td></td>
</tr>
</tbody>
</table>
Current design satisfies the design goals

<table>
<thead>
<tr>
<th>Parameters</th>
<th>High-brightness mode, 200 mA</th>
<th>High-bunch-charge mode, 200 mA</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>6</td>
<td>6</td>
<td>GeV</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>680</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Bunch Duration (rms)</td>
<td>106</td>
<td>160</td>
<td>ps</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>6</td>
<td>72</td>
<td>ns</td>
</tr>
<tr>
<td>Emittance ratio ((\varepsilon_y/\varepsilon_x)^{[2]})</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>27.5</td>
<td>33</td>
<td>pm•rad</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>2.75</td>
<td>3.3</td>
<td>pm•rad</td>
</tr>
<tr>
<td>Horizontal beam size (rms) (high-/low-β section)</td>
<td>14.3/8.5</td>
<td>15.6/9.3</td>
<td>µm</td>
</tr>
<tr>
<td>Vertical beam size (rms) (high-/low-β section)</td>
<td>4.4/2.3</td>
<td>4.8/2.5</td>
<td>µm</td>
</tr>
<tr>
<td>Lifetime</td>
<td>~4</td>
<td>~0.8</td>
<td>hrs</td>
</tr>
<tr>
<td>Time between two refills</td>
<td>~30</td>
<td>~8</td>
<td>s</td>
</tr>
</tbody>
</table>

[1] In this table, we present beam parameters for the case with high-bunch-charge mode and 200 mA. Operating this mode at a lower current is under study and discussion.

[2] The Full coupling case, with emittance ratio of 1, is under study, but not presented here.
For a high energy photon source, when reducing emittance to a few tens of pm, extremely strong sextupoles will be required.

**HEPS 7BA lattice**, the available minimum emittance is about 90 pm [3].

Hybrid MBA: weaker sextupoles!
Likely a combination of DBA and MBA

By putting all sextupoles within the dispersion bumps, sextupole strength can be well controlled. Hybrid MBA provides a good balance between chromatic correction and emittance minimization.

ESRF-EBS\textsuperscript{[1, 2]}: the first to propose and use this hybrid-7BA lattice, then APS-U\textsuperscript{[3]}....

\textbf{HEPS hybrid-7BA lattice}, the available minimum emittance is about 45 pm\textsuperscript{[4]}.

Use of Anti-bends (ABs): even lower emittance
Allows independent knob of dispersion and beta functions

**SLS-2**: Adopted **BLG (or LGB)** and **AB** in one cell, emittance reduced by a factor of ~4 \(^{[1]}\).

\[
\text{conventional: } \varepsilon = 990 \text{ pm} \ (F = 3.4) \quad \text{LGB/AB: } \varepsilon = 200 \text{ pm} \ (F = 0.69)
\]

- **Cell A** can be more compact.
- **Cell B** promises lower emittance

\[
\begin{align*}
\text{Cell A, } & 2.2 \text{ m} \\
\text{Cell B, } & 2.6 \text{ m}
\end{align*}
\]

**APS-U**: Combining **ABs** into hybrid-7BA, emittance reduced from 67 to 41 pm \(^{[2]}\).

- **Cell B** was adopted in HEPS design

\[\text{[1] A. Streun, talk in KeK, 2016.} \quad \text{[2] M. Borland et al., NAPAC16, WEPOB01.} \quad \text{[3] Y. Jiao et al., IPAC18, TUPMF054.}\]
One family of quads changed to ABs

Replace the middle cell with cell B

Central slice of BLG used for bending magnet beam line

<table>
<thead>
<tr>
<th>Peak field (T)</th>
<th>Critical photon energy (keV)</th>
<th>Peak power density (W/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5T</td>
<td>12.0</td>
<td>702</td>
</tr>
<tr>
<td>0.85T</td>
<td>20.3</td>
<td>1194</td>
</tr>
<tr>
<td>1T</td>
<td>23.9</td>
<td>1405</td>
</tr>
<tr>
<td>1.5T</td>
<td>35.9</td>
<td>2107</td>
</tr>
<tr>
<td>2T</td>
<td>47.9</td>
<td>2810</td>
</tr>
<tr>
<td>3T</td>
<td>71.8</td>
<td>4215</td>
</tr>
<tr>
<td>3PW,(1.6T)</td>
<td>38.3</td>
<td>2349</td>
</tr>
</tbody>
</table>

Courtesy of C. Li
HEPS design optimized for high brightness

low $\varepsilon$, low $\beta$, small ID gap, etc. not always fulfilled at the same time

Highest possible brightness (ID gap $\equiv 5$ mm) 
$\Rightarrow \beta_x \& \beta_y \sim 1$m at the ID section center

Scan based on HEPS parameters, optimized for 20 keV energy [1]

ID gap does depend on $\beta$ (scales roughly as $\beta^{1/2}$)
For a 5-m ID, minimum gap $\Rightarrow \beta_y \sim 2.5$m

HEPS: Alternating high- and low- beta sections, for high-brightness and high-flux, respectively

48 6-m straight sections, 40 available for IDs

• both $\beta_x \& \beta_y \sim 2$m at low-$\beta$ section center
• $\beta_y \sim 7$m at high-$\beta$ section center

Design optimization is still under way.

Nonlinear optimization: combined PSO & MOGA

PSO breeds more diversity, MOGA allows fast convergence

Verified with an optimization problem with known answer (Jiao & Xu, CPC, 027001, 2017)

Simultaneous optimization of brightness and DA

DA depends highly on $\Delta \psi_x$ between sextupole pairs, release $\Delta \psi_y$ for higher brightness (Jiao, IPAC18)

Fix linear parameters, optimizing DA and Touschek lifetime (lifetime increased by a factor of 2)
On-axis injection + high energy accumulation

On-axis swap-out injection \[1\]

Requirements:
- Fast kicker with a pulse width of $\leq\sim 12$ ns
- The injector (a linac + a booster) should be able to provide full-charge bunches
  - 1.33 nC for high-brightness mode, 200 mA
  - 14.4 nC for high-bunch-charge mode, 200 mA

**HEPS**: Return transport line from ring to booster + accumulation in booster at high-energy \[2, 3\]

(a) Used bunch extracted from the ring,
(b) passing through a transport line,
(c) Injected to booster, merged with an existing bunch,
(d) after about 10 thousands’ revolutions in booster, extracted from the booster,
(e) passing through another transport line,
(f) re-injected to the ring

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RF choice: a comprehensive consideration

166.6 MHz fundamental and 500 MHz third harmonic RF cavities

500 MHz RF cavities have been used in IHEP existing facility, the BEPC-II collider.

- Use a lower-frequency 166.6 MHz RF system, to release the requirement on pulsed kicker —12 ns vs. 4 ns (if using 500 + 1500 MHz RF system instead)

- 500 MHz RF cavities as third harmonic cavity for bunch lengthening and weaker collective effects —e.g., smaller emittance growth due to IBS

- The RF choice also allows for POP experiments of longitudinal injection.
  - dynamic damping double-frequency RF system (166.6 + 500 MHz)
  - Static triple-frequency RF system (166.6 + 333.2 + 500 MHz)

Various impedance contributors were considered, impedance optimization is under way.

**Longitudinal impedance** dominated by resistive wall and large number elements, e.g., flanges.

**Transverse impedance** is dominated by the resistive wall impedance and Inj. & Ext. kickers.

Longitudinal and transverse effective impedances are estimated at natural bunch length of 27.6 mm with HC.

<table>
<thead>
<tr>
<th>Objects</th>
<th>$Z_{11}/n$ [mΩ]</th>
<th>$k_I$ [V/pC]</th>
<th>$k_y$ [kV/pC/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive wall</td>
<td>38.2</td>
<td>1.3</td>
<td>11.5</td>
</tr>
<tr>
<td>RF cavities</td>
<td>8.6</td>
<td>1.2</td>
<td>0.11</td>
</tr>
<tr>
<td>Bellows</td>
<td>22.9</td>
<td>0.14</td>
<td>0.89</td>
</tr>
<tr>
<td>Flanges</td>
<td>42.3</td>
<td>5.5E-8</td>
<td>1.3</td>
</tr>
<tr>
<td>ID tapers</td>
<td>1.0</td>
<td>1.6E-6</td>
<td>0.11</td>
</tr>
<tr>
<td>Inj. &amp; Ext. kickers</td>
<td>29.5</td>
<td>0.62</td>
<td>12.8</td>
</tr>
<tr>
<td>In-line absorbers</td>
<td>69.5</td>
<td>7.9E-6</td>
<td>2.7</td>
</tr>
<tr>
<td>BPMs</td>
<td>7.7</td>
<td>0.033</td>
<td>0.25</td>
</tr>
<tr>
<td>Harmonic RF</td>
<td>5.3</td>
<td>0.28</td>
<td>0.038</td>
</tr>
<tr>
<td>LF kicker</td>
<td>0.03</td>
<td>0.13</td>
<td>0.036</td>
</tr>
<tr>
<td>TF kicker</td>
<td>0.5</td>
<td>4.4E-3</td>
<td>0.035</td>
</tr>
<tr>
<td>In-vacuum IDs</td>
<td>0.03</td>
<td>0.032</td>
<td>1.5</td>
</tr>
<tr>
<td>Pumping ports</td>
<td>14.9</td>
<td>0.072</td>
<td>0.56</td>
</tr>
<tr>
<td>Transitions</td>
<td>80.3</td>
<td>3.4E-3</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>326.8</td>
<td>3.8</td>
<td>32.7</td>
</tr>
</tbody>
</table>
Microwave instability threshold $\approx 2.2$ nC. Brightness degradation expected for high-bunch-charge mode (14.4 nC)

Transverse mode coupling instability $I_{th} > 30$ nC. —With a large positive chromaticity (+5)

Multi-bunch instability $I_{th}$ would be above 200 mA —With the aid of positive chromaticity, feed-back, RF HOM damping

Feed-back system, under design

 Courtesy of J. Yue

Courtesy of P. Zhang
The lifetime evaluated based on the ring acceptance in presence of practical errors,
- ID and IBS effect included
- Touschek and vacuum lifetime

**Lifetime (90% chance) at 200 mA:**
- ~3.7 h for high-brightness mode
- ~0.8 h for high-bunch charge mode

**Top-up injection** considered
- At 200 mA, refill every 30 seconds for high-brightness mode, and every 8 seconds for high-bunch-charge mode, to keep a current stability of < 0.3%.
- Small brightness reduction (0.1%, or 2%) in each refill period (~20 ms), but acceptable.
Error requirement and correction

- Requirement on alignment, magnetic field errors, etc. specified.
- Number and locations of BPMs and correctors in the ring optimized and fixed.
- First turn around strategy developed [1].
- Detailed lattice calibration simulation has been done [2,3].

### Table

<table>
<thead>
<tr>
<th></th>
<th>Dipole</th>
<th>Quadrupole</th>
<th>Sextupole</th>
<th>Octupole</th>
<th>Girder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse shift X/Y (µm)</td>
<td>200</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Longitudinal shift Z (µm)</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Tilt about X/Y (mrad)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Tilt about Z (mrad)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Nominal field</td>
<td>3e-4</td>
<td>2e-4</td>
<td>3e-4</td>
<td>5e-4</td>
<td>\</td>
</tr>
</tbody>
</table>

### Graphs

- Offset in sextupoles cause apparent DA reduction
- Sextupole mover
  - Courtesy of C. Li
- DA improved using sext. movers in lattice calibration

### Figures

- Before correct.
- After correct.
- Corrector strengths

### References

More than 80 beam lines are expected for HEPS

In the first construction phase, 14 beam lines will be built
- One bending magnet beam line (middle dipole of 7BA) and 13 ID beam lines
- Different types of IDs, such as CPMU (4), IVU(3), IAU(4), wiggler(1), APPLE-Knot (1), are planned
- ID parameters fixed, but still under optimization for even better performance

4 × 10^{22} \text{phs/}(\text{s}\cdot\text{mm}^2\cdot\text{mrad}^2\cdot0.1\%\text{BW}) @\sim20\text{keV},\text{ for high-brightness mode, } 200 \text{ mA}
- Error effects, collective effects, etc. included.

50% reduction of brightness, for high-bunch-charge mode at 200 mA, due to increasing of the energy spread.

In Closing...

Physics design basically completed for the HEPS light source.

✓ With as many features as possible maximizing the brightness

✓ Solutions to challenges inherent in the ultralow-emittance design

There is no show-stopper for the HEPS construction.

Scheduled to start in mid-2019

Further optimization is still under way and never ends.
Thanks for your attention!