Studies of collective instabilities in HEPS booster and the possible mitigation

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Outlines

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3. Studies of RF Modulation in HEPS Booster
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1. Introduction
Introduction

• High Energy Photon Source (HEPS) is a 6-GeV synchrotron light source under construction in Beijing, China.

<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>Circumference</td>
<td>m</td>
<td>1360.4</td>
</tr>
<tr>
<td>Emittance</td>
<td>pm·rad</td>
<td>&lt; 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>
</tbody>
</table>
Introduction --- Swap-out injection with high energy accumulation

Introduction

• The proposed ramping process is based on the idea of multi-bunch (10 bunches) operation in the HEPS booster.
  - 499.8 MHz RF cavity
    - $V_{\text{peak}} = 2 \text{ MV} @ 500 \text{ MeV}$
    - $V_{\text{peak}} = 8 \text{ MV} @ 6 \text{ GeV}$
  - Ramping curve:
    - 200 ms @ 500 MeV for injecting the LINAC beam to the booster
    - 400 ms for energy ramping up to 6 GeV
    - 200 ms @ 6 GeV for beam re-injection and extraction
    - 200 ms for energy ramping down to 500 MeV
Introduction

• HEPS storage ring:
  – “high-bunch-charge mode"
    ➢ 14.4 nC/bunch in HEPS storage ring
  – on-axis swap-out injection scheme
    ➢ “full-charge bunch” injection --- mismatched bunch with 14.4 nC!
    ➢ injection imperfection induced initial transverse offset;

• HEPS booster:
  – need to provide high charge bunch (>14.4 nC) to the storage ring
2. (Single-Bunch) Instabilities in HEPS Booster
Study of Collective Instabilities in HEPS Booster

- **Single-bunch effects** (effects during injection not included)
  - microwave instability
  - transverse single-bunch instability
    - TMCI
    - head-tail

- **Coupled-bunch effects**
  - transverse coupled-bunch instability
  - longitudinal coupled-bunch instability

- **Longitudinal effects**
  - longitudinal broad-band impedance

- **Transverse effects**
  - transverse broad-band impedance
  - transverse resistive-wall impedance

- **HOM effects**
  - HOM impedance (on-going)
    - 6 PETRA-type 5-cell copper cavities
Impedance Modeling

- Detailed engineering designs of components are used in the impedance calculations.

### Key Contributions

<table>
<thead>
<tr>
<th>Component</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellows</td>
<td>159</td>
</tr>
<tr>
<td>BPM</td>
<td>80</td>
</tr>
<tr>
<td>High Energy Inj.&amp;Ext kickers</td>
<td>3</td>
</tr>
<tr>
<td>Low Energy Injection kickers</td>
<td>1</td>
</tr>
<tr>
<td>Flange</td>
<td>691</td>
</tr>
<tr>
<td>Feedback kicker</td>
<td>1</td>
</tr>
<tr>
<td>Tune Kicker</td>
<td>1</td>
</tr>
<tr>
<td>Transition</td>
<td>-</td>
</tr>
<tr>
<td>5-Cell Cavity</td>
<td>6</td>
</tr>
<tr>
<td>Vacuum pumping ports</td>
<td>157</td>
</tr>
<tr>
<td>Resistive Wall</td>
<td>-</td>
</tr>
</tbody>
</table>
MWI in HEPS Booster --- not a problem for the project

- full energy ramping curve was included;
- longitudinal broad-band impedance only;
- significant bunch lengthening and energy spread growth at the low energy (500 MeV) of the HEPS booster;

very weak bunch lengthening and no energy spread growth at the extraction
Coupled-bunch instability in the HEPS booster

- transverse resistive-wall impedance induced transverse coupled-bunch instability
  - small finite chromaticity and bunch-by-bunch feedback should be able to cure it.

\[ \tau_{\text{growth}} \approx 11 \text{ms} \]
\[ \tau_{\text{growth}} \approx 100 \text{ms} \]

- 500 MeV \( \xi = 0 \)
- 6 GeV \( \xi = 0 \)
Coupled-bunch instability in the HEPS booster

- transverse resistive-wall impedance induced transverse coupled-bunch instability
  - small finite chromaticity and bunch-by-bunch feedback should be able to cure it.

\[ \tau_{\text{growth}} \approx 11 \text{ ms} \]

\[ 500 \text{ MeV} \]

\[ \xi = 0 \]
Transverse single-bunch instability in HEPS booster

- There were big discussions on how to achieve 14.4 nC/bunch in the HEPS storage ring.
Transverse single-bunch instability @ 6 GeV --- not a problem for the project
Transverse single-bunch instability @ 500 MeV

The 8th Low Emittance Rings Workshop, 26 – 30 October 2020, INFN-LNF, Frascati, Italy
Transverse single-bunch instability with energy ramping
500 MeV \rightarrow 6 \text{ GeV}
Transverse single-bunch instability with energy ramping:
500 MeV → 6 GeV

High amplitude oscillation!
Significant emittance growth!
Transverse single-bunch instability with energy ramping: 500 MeV → 6 GeV

The 8th Low Emittance Rings Workshop, 26 – 30 October 2020, INFN-LNF, Frascati, Italy
Nonlinearity of the lattice plays key role especially at 500 MeV

**Tracking using nonlinear one-turn map**

**Tracking using linear one-turn map**
Nonlinearity of the lattice plays key role especially at 500 MeV

\[ \xi_y = +1 \]
linear map

\[ \xi_y = +3 \]
linear map

\[ \xi_y = +1 \]
nonlinear map

\[ \xi_y = +3 \]
nonlinear map
Nonlinearity of the lattice plays key role especially at 500 MeV.
Short summary --- 1

• Comprehensive studies on the influences of different parameters (initial bunch parameters, nonlinearity, momentum compaction, etc.) on the TMCI threshold in the HEPS booster;

• Suggestions on the booster lattice design (TMCI dominated at low energy)
  − Reduce the beta function in vertical direction
  − Increase momentum compaction factor
  − Keep the chromaticity small

• Strongly affecting the booster lattice design and the work flow of the whole machine.
3. Studies of RF Modulation in HEPS Booster
Preliminary study on the implementation of RF modulation in HEPS booster

There is evidence showing that **lengthening the injection bunch** does help ease the injection transient instability and increase the injection efficiency.

Bunch lengthening by RF modulation in the booster

**RF Voltage Modulation***

\[
\phi_{n+1} = \phi_n - 2\pi \nu_s \frac{\eta}{|\eta|} P_n \\
P_{n+1} = P_n - \frac{4\pi \alpha}{\omega_0} P_n \\
-2\pi \nu_s \left[1 + b \sin(\nu_m \theta_{n+1} + \chi)\right] \sin \phi_{n+1}
\]

**RF Phase Modulation**

\[
\phi_{n+1} = \phi_n + 2\pi \nu_s \eta \delta_n + \Delta \varphi(\theta) \\
\delta_{n+1} = \delta_n + \frac{eV}{\beta^2 E} (\sin \phi_{n+1} - \sin \phi_s)
\]

[*][**]: S. Y. Lee, Accelerator Physics (fourth edition)
Preliminary test

- Voltage modulation, $A_m = 15\% V_{RF}$, $\nu_m \approx 2\nu_s$

\[
\phi_{n+1} = \phi_n - 2\pi\nu_s \frac{\eta}{|\eta|} P_n
\]

\[
P_{n+1} = P_n - \frac{4\pi\alpha}{\omega_0} P_n - 2\pi\nu_s [1 + b \sin(\nu_m \theta_{n+1} + \chi)] \sin \phi_{n+1}
\]

- Phase modulation, $A_m = 0.1 \text{ rad}$, $\nu_m \approx 2\nu_s$

\[
\phi_{n+1} = \phi_n + 2\pi h \eta \delta_n + \Delta \varphi(\theta)
\]

\[
\delta_{n+1} = \delta_n + \frac{eV}{\beta^2 E} (\sin \phi_{n+1} - \sin \phi_s)
\]
Scanning the **modulation frequency** and **modulation amplitude**
More details in the selected case

More details in the selected case

\[\text{injection efficiency w/o RF modulation} \approx 86\%\]
Short summary --- 2

• The idea of using RF modulation in the booster to suppress the injection transient instability was proved in principle in simulation.

• Increase of the injection efficiency was observed in simulations.
4. Summary
Summary

• The requirement of 14.4 nC/bunch in HEPS storage ring leads to quite some difficulties in the study of collective instabilities in HEPS storage ring.

• Comprehensive studies on the influences of different parameters (initial bunch parameters, nonlinearity, momentum compaction, etc.) on the TMCI threshold in the HEPS booster.

• The idea of using RF modulation in the booster to raise the injection efficiency was proved in principle in simulations.
Thank you for your attention!