Design of an Accumulator Ring for the Diamond-II Upgrade

Ian Martin,
On behalf of the Diamond-II design team

2^nd Topical Workshop on Injection and Injection Systems
Paul Scherrer Institute
2^nd April 2019
Requirements for Diamond-II injector:

Diamond-II upgrade project
proposed storage ring injection scheme
specification for injector

Combined booster / accumulator ring:

proposed lattice design
injection/extraction schemes for new booster
beam parameters during energy ramp
impact of errors
installation strategy

Summary
Diamond-II: Lattice

Proposal for Diamond-II is a ‘Modified Hybrid 6 Bend Achromat’

- Increased photon beam quality (brightness, coherence, spot size, spectrum, ...)
- Increased capacity (additional straights, upgraded/relocated/new beamlines)

Combines two concepts:

- The ESRF-EBS upgrade lattice*
- The Double-Double Bend Achromat cell**

<table>
<thead>
<tr>
<th></th>
<th>Diamond-I</th>
<th>Diamond-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Type</td>
<td>DBA</td>
<td>M-H6BA</td>
</tr>
<tr>
<td>Circumference</td>
<td>561.6 m</td>
<td>560.574 m</td>
</tr>
<tr>
<td>Energy</td>
<td>3 GeV</td>
<td>3.5 GeV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>300 mA</td>
<td>300 mA</td>
</tr>
<tr>
<td>Straight Sections</td>
<td>24</td>
<td>48</td>
</tr>
<tr>
<td>Emittance</td>
<td>2.7 nm.rad</td>
<td>~0.16 nm.rad</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.096 %</td>
<td>0.078 %</td>
</tr>
</tbody>
</table>

**R. Bartolini et al., PRAB 21, 050701 (2018)
Requirements on injected beam:

- 3.5 GeV
- Emittance in range 10-30 nm.rad
- Bunch length in range 20-40 ps
Diamond-II: Injection

Proposal is to use ‘anti-septum’ storage ring injection scheme*

- Off-axis accumulation
- Standard 4-kicker bumps for stored beam
- Kicker 3 contains thin (1 mm) ‘anti-septum’ plate
- Appears like a drift space for injected beam
- Separation of stored / injected beams ~ 3mm

* C. Gough, M. Aiba, IPAC’17, MOPIK104

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Septum</th>
<th>Kicker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Length</td>
<td>1.67 m</td>
<td>0.6 m</td>
</tr>
<tr>
<td>Bend angle</td>
<td>148.4 mrad</td>
<td>9.3 mrad</td>
</tr>
<tr>
<td>Bend radius</td>
<td>11.3 m</td>
<td>64.5 m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>1.04 T</td>
<td>0.18 T</td>
</tr>
<tr>
<td>Pulse shape</td>
<td>Full-sine</td>
<td>Half-sine</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>160 μs</td>
<td>6 μs</td>
</tr>
<tr>
<td>Rep rate</td>
<td>5 Hz</td>
<td>5 Hz</td>
</tr>
</tbody>
</table>

Ian Martin, Accumulator for Diamond-II, PSI, Apr 2019
**Top-up cycle assumptions:**

- Anticipate storage ring lifetime ~3-5 hours (900 bunches, 0.62 nC/bunch)
- Aim to maintain current stability in the storage ring of ~1%
  ⇒ ~2-3 minutes between top-up cycles
- Single bunch injection ~0.1-0.2 nC/shot
  ⇒ ~50 shots per top-up cycle

Potential Issue: Non-closure of orbit bump
  ⇒ well-matched kicker pulsers
  ⇒ uniform coating in kicker vessels
  ⇒ with-beam correction of kicker roll
  ⇒ active suppression of residual kick (TMBF, compensation kicker, ...)
  ⇒ gating signals to beamlines

Could also accumulate in the booster, and only extract beam on the final shot?
(i.e. single-shot top-up into the storage ring, ~5-10 nC/shot, multi-bunch)
New Booster: Specification

**Existing booster:**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Requirement</th>
<th>Existing booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>0.1 - 3.5 GeV</td>
<td>0.1 - 3.0 GeV</td>
</tr>
<tr>
<td>Emittance</td>
<td>&lt;30 nm.rad</td>
<td>134 nm.rad</td>
</tr>
<tr>
<td>Bunch length</td>
<td>&lt;40 ps</td>
<td>100 ps</td>
</tr>
<tr>
<td>Max. extracted current</td>
<td>&gt;10 nC</td>
<td>~2 nC</td>
</tr>
</tbody>
</table>

**Requirements for new booster:**

- must fit in existing tunnel
- high injection efficiency
- long lifetime w.r.t. top-up duration
- long-term reliability
- large dynamic aperture for off-axis accumulation
- low impedance for high-current bunches
**New Booster: Concept**

*Concept for new booster lattice:*

- Construct arcs from ‘TME-style’ unit cells
- ‘Dispersion suppressor’ matching cells
- Straights for injection / extraction / RF
- Average bend radius of arcs ~23 m (to fit around outside of existing booster)

Conducted systematic scan of:

- Number of unit cells
- Magnet / drift lengths
- Quadrupole gradients

Monitored impact on:

- $\varepsilon_x / \alpha_c / \text{max} \beta_{x/y} / \text{chromaticity}$
- $\sigma_E / U_0 / \tau_x / \tau_y / \tau_s$
- Hor. / vert. dynamic aperture
Identification of optimal working point:
- Horizontal tune set for low emittance and moderate phase advance (≈145°/cell)
- Several vertical tune points offer good dynamic aperture

[Graph showing constant ε_x with increasing Q_x and Q_y, and large dynamic aperture]
Identification of optimal working point:
- Vertical tune set to minimise natural chromaticity
- Compromise between lowering quadrupole gradients and lowering $\beta_y$
Main features:

- Zero dispersion long straight section
- Controllable phase advance / beta-functions at injection point
New Booster: Frequency Maps

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## New Booster: Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Existing Booster</th>
<th>Upgraded Booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>GeV</td>
<td>0.1 to 3.0</td>
<td>0.1 to 3.5</td>
</tr>
<tr>
<td>Final Emittance</td>
<td>nm.rad</td>
<td>134.4</td>
<td>13.9</td>
</tr>
<tr>
<td>Circumference</td>
<td>m</td>
<td>158.4</td>
<td>170.5</td>
</tr>
<tr>
<td>Betatron Tunes</td>
<td>-</td>
<td>[7.18, 4.27]</td>
<td>[13.17, 4.37]</td>
</tr>
<tr>
<td>Natural Chromaticity</td>
<td>-</td>
<td>[-9.7, -6.3]</td>
<td>[-25.7, -10.1]</td>
</tr>
<tr>
<td>Final Energy Spread</td>
<td>-</td>
<td>7.3×10^{-4}</td>
<td>10.5×10^{-4}</td>
</tr>
<tr>
<td>Peak Energy Loss per Turn</td>
<td>MeV</td>
<td>0.58</td>
<td>1.64</td>
</tr>
<tr>
<td>Mom. Compact. Factor</td>
<td>-</td>
<td>25.2×10^{-3}</td>
<td>2.77×10^{-3}</td>
</tr>
<tr>
<td>Natural Bunch Length</td>
<td>ps</td>
<td>99.3</td>
<td>41.1</td>
</tr>
<tr>
<td>Peak RF voltage</td>
<td>MV</td>
<td>0.9</td>
<td>2.0</td>
</tr>
<tr>
<td>RF acceptance</td>
<td>%</td>
<td>0.24</td>
<td>0.58</td>
</tr>
<tr>
<td>Damping Times (τ_x, τ_y, τ_z)</td>
<td>ms</td>
<td>[5.46, 5.47, 2.74]</td>
<td>[2.43, 2.43, 1.22]</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

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New Booster: Long Straights

Injection straight

Extraction straight

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New Booster: Injection

Up to 184 bunches

100 ns rise/fall

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New Booster: Injection

On-axis configuration

Up to 184 bunches

100 ns rise/fall

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New Booster: Extraction

200 ns rise time

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New Booster: Energy Ramp

Note: exaction at 3.5 GeV, 0.1 s into the ramp
New Booster: Energy Ramp

Note: excitation at 3.5 GeV, 0.1 s into the ramp
Preliminary assessment made of errors:

- Errors added in Gaussian distribution (3σ)
- One BPM/HCM/VCM per unit cell
- Orbit / tune / chromaticity correction (i.e. no beta-beat or coupling correction)

<table>
<thead>
<tr>
<th>Element</th>
<th>x/y (μm)</th>
<th>Tilt (μrad)</th>
<th>Strength Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>30</td>
<td>200</td>
<td>1×10⁻³</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>30</td>
<td>200</td>
<td>3×10⁻³</td>
</tr>
<tr>
<td>Sextupole</td>
<td>30</td>
<td>200</td>
<td>5×10⁻³</td>
</tr>
</tbody>
</table>

Phase advance per cell:
- ~145° in H
- ~45° in V

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New Booster: Impact of Errors

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New Booster: Impact of Errors

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New Booster: Impact of Errors

6D tracking for dynamic apertures:

**During injection**

**Injection bump off**

Off-axis beam from linac oscillates around closed orbit once injection bump is off
New Booster: Installation Strategy

1.73 m

1.85 m

Existing tunnel > 4.0 m wide
New Booster: Installation Strategy

Strategy:
• Existing booster will remain in use until the long shutdown
• New booster to be partially installed (~80 %) during standard shutdowns over a two-year period preceding this
• Completion of the booster installation and re-configuration of the transfer lines as the storage ring is being removed
• Booster commissioning to be carried out in parallel with storage ring installation

Details:
• Engineering design to be developed in parallel with the storage ring
• Circumference to be consistent with storage ring RF frequency
• Anticipate design and construction will be largely out-sourced, with the new booster based on pre-assembled, pre-aligned and functionally tested girders delivered to site ready to install
• Vacuum vessels pre-installed and under vacuum
• Existing two PETRA-type 5-cell RF cavities to be re-used on new booster
• Additional control and instrumentation areas required to be built
Summary

Injection into Diamond-II storage ring places tight tolerances on injected bunch:

- Increase in beam energy (>3.5 GeV)
- Reduction in emittance (<~30 nm.rad)
- Short bunch length (<40 ps)

Desire to keep off-axis accumulation in the SR whilst minimising disturbance to users during top-up suggest replacing old booster with new combined booster-accumulator ring

Conceptual design of new ring complete

Much work still to do to convert AP design into practical solution

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