High-charge Injector for On-axis Injection into a High-Performance Storage Ring Light Source

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IPAC 2019, Melbourne
May 20-24, 2019
Outline

- Introduction
- Challenges for injector
- Design choices: upgrade of existing injector vs green field
  - APS-U, Argonne National Lab
  - ALS-U, Berkeley Lab
  - HEPS, IHEP, Beijing
- Outlook and summary
MBA storage rings launch a new era for light sources

Multibend achromat (MBA) optics can reduce the horizontal emittance by 1-2 orders of magnitude compared to a third-generation storage ring of the same circumference, thereby increasing the x-ray brightness dramatically.

MAX IV led the development.\(^1\)

Sirius\(^2\) and ESRF-EBS\(^3\) are under construction.

\(^1\)TUYPLM3, \(^2\)TUPGW003, \(^3\)TUPGW005
Many light sources pursuing 4th gen storage ring designs

MBAs and variations: 4th generation synchrotron light sources.

Many innovative ideas as multiple light sources pursue 4th generation source designs, including solutions for injection.

See references in paper (THYYPLM3); also many new reports here at IPAC’19.
MBA designs present new challenges for injection

- MBA storage ring (SR) acceptance and emittance are correlated.
- Highest-performance MBA optics requires swap-out injection.
- Focus on challenges for swap-out injector:
  - High single-bunch charge for timing mode.
  - High single- or bunch-train charge for brightness mode.
  - Emittance
  - Instabilities
  - Beam loading

**swap-out injection:** ALS-U, APS-U, HEPS

**off-momentum injection:** HALS, Soleil
What is swap-out\textsuperscript{1} injection and why choose?

- Swap-out is used to maintain the beam current – analogous to top-up – except that the injectors produce enough single-bunch charge to perform complete bunch replacement, using on-axis injection without accumulation.

- Besides MBA SR dynamic acceptance, other considerations for choosing swap-out include:
  - Enabling small horizontal-gap or helical undulators.
  - Decision to re-use existing injector; upgrade in advance (more options with green field).

<table>
<thead>
<tr>
<th>Upgrade existing</th>
<th>Beam energy</th>
<th>Circumference</th>
<th>SR natural emittance</th>
<th>Injector emittance</th>
<th>Total current</th>
<th>Bunch charge goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS-U\textsuperscript{2}</td>
<td>6 GeV</td>
<td>1104 m</td>
<td>42 pm</td>
<td>60 nm (booster)</td>
<td>200 mA</td>
<td>5-16 nC</td>
</tr>
<tr>
<td>ALS-U\textsuperscript{3,5}</td>
<td>2 GeV</td>
<td>196.5 m</td>
<td>~90 pm</td>
<td>1.9 nm (accum ring)</td>
<td>500 mA</td>
<td>1.2 nC</td>
</tr>
<tr>
<td>HEPS\textsuperscript{4,5}</td>
<td>6 GeV</td>
<td>1360 m</td>
<td>34 pm</td>
<td>32 nm (booster)</td>
<td>200 mA</td>
<td>1.3-14.4 nC</td>
</tr>
</tbody>
</table>

\textsuperscript{1} L. Emery, M. Borland, PAC’03.


\textsuperscript{3} C. Steier, LBL

\textsuperscript{4} MOPRB027, TUZPLS2

\textsuperscript{5} Optimization ongoing.
APS-U injector layout and requirements

<table>
<thead>
<tr>
<th></th>
<th>APS</th>
<th>Achieved</th>
<th>Goal¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR charge</td>
<td>2-4 nC¹</td>
<td>20 nC</td>
<td>20 nC</td>
</tr>
<tr>
<td>Booster charge</td>
<td>2-4 nC¹</td>
<td>12 nC</td>
<td>17 nC</td>
</tr>
<tr>
<td>SR charge (injected)</td>
<td>Accumulated</td>
<td></td>
<td>16 nC</td>
</tr>
<tr>
<td>BTS $\varepsilon_x$ at 6 GeV</td>
<td>&lt; 64 nm</td>
<td>–</td>
<td>&lt; 60 nm</td>
</tr>
</tbody>
</table>

¹ For timing mode. Brightness mode requires 5 nC.

- APS has a low-energy accumulator ring originally designed for damping positrons, up to 6 nC.
- Single-bunch injector enables “guard” bunches in brightness mode.
- With small modifications, achieved 20 nC in PAR.
- Instabilities and beam loading are issues; plan to address before MBA upgrade.
ALS-U From Top-off To Swap-out

- ALS-U optimized for brightness mode, 70x70 pm (no timing mode).
- Planning to build a full-energy accumulator ring (AR) in SR tunnel: off-axis accumulation of booster bunch trains, on-axis injection into SR.
- AR to be installed before MBA upgrade.

Stefano De Santis

**ALS-U**

- linac + booster
  - 1.9 → 2 GeV
  - 327 nC
  - 296 bunches
  - 2 ns spacing
  - 17-30 ps rms length

**SR**

- 327 nC
- 284 bunches
- 2 ns spacing
- 10-40 ps rms length

**AR**

- 30 nC
- 25/26* bunches
- 2 ns spacing
- 16 ps rms length

**ALS**

- ≤1 nC
- 1-4 bunches
- 8 ns spacing
- every ~40 s

- ≤0.4 nC
- 1-4 bunches
- 8 ns spacing
- every ~1 s

**BTS**

- 60 nC
- 26*+26* bunches
- 2 ns spacing
- every 30 s

**BTA**

- Swap-out intrinsically less gradual than top-off.

Potential issue in conjunction of passive HHC use:
Filling an empty SR will have to be done gradually, avoiding inducing large transients in the cavities.
New injection timing system if injector re-used

- Multi-bend SR has smaller circumference; therefore, the rf frequency increases:
  - APS-U: 120 kHz (352 MHz rf)
  - ALS-U: 750 kHz (500 MHz rf)
- Both facilities decided to build a new injection timing system that enables bunch-to-bucket transfer at different rf frequencies.
- Requires fully digital low-level rf; APS-U upgrade in progress, ALS upgraded in 2018.
- Provides an additional booster emittance and injection tuning knob, exploited at APS-U:
  - Presently running booster -0.6% off-momentum, which lowers the transverse emittance due to well-known partition function effect.
  - Plan to run -0.8% off-momentum at extraction, and closer to on-momentum at injection. This enables higher charge.

High single-bunch injector charge for APS-U timing mode

- Injector diagnostics upgrades have been key: e.g., digital rf data acquisition, bunch duration monitors\(^1\), SLM digital cameras, YAG screen in emittance diagnostic in booster extraction line.
- Mature booster impedance and machine model closely reproduces observed charge-dependent injection efficiency\(^2\).
- High-charge plan:
  - Raise linac/PAR energy to >450 MeV to raise PAR instability threshold. Analyze PAR chamber impedance and redesign components where practical.
  - Increase PAR bunch length compression with higher-voltage harmonic rf.
  - Detune booster rf cavities at injection for beam loading compensation. Install high-power rf couplers (HPC) to handle high effective power at extraction. Higher coupling coefficient extends detuning range.

\(^{1}\)J. Dooling et al., IPAC’18.  \(^{2}\)J. Calvey et al., NAPAC’16
As green-field design, HEPS has more injector options

Multi-bunch injection per booster cycle

- Booster used as injector and accumulator.
- SR and booster rf frequency ratio 1:3.
- Booster can ramp energy up/down.
- Multibunch injection for faster fill from zero.
- Future options considering full-energy linac.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>linac repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>booster repetition rate</td>
<td>1 Hz</td>
</tr>
<tr>
<td>flat-bottom/flat-top</td>
<td>200 ms / 200 ms</td>
</tr>
<tr>
<td>kicker/bumper repet. rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>kicker pulse width</td>
<td>&lt; 300 ns (half-sine)</td>
</tr>
</tbody>
</table>

High single-bunch injector charge for HEPS timing mode

Challenge of “swap-out” injection: a full charge injector

“Charge recovery” in the booster at 6 GeV

Two high-energy transport lines

Three 7BA arcs in between
Higher beam losses possible with high-charge swap-out

- Swap-out requires more frequent injection of higher charge per pulse: 10s of seconds compared to minutes for top-up.
- Off-axis accumulation injection efficiency in present rings ~90%.
- On-axis swap-out efficiency inherently less lossy; ≥ 97% achievable.
- Radiation shielding needs to be evaluated, and supplemented as needed.
- APS-U\(^1\) and ALS-U are installing beam loss monitors as a diagnostic to aid in injection tuning.

\(^1\) J. Dooling et al., IPAC'15.
Outlook and Summary

- 4th generation light source designs based on MBA variations are being pursued world-wide to dramatically increase the x-ray brightness, compared to 3rd generation sources.
- High-performance designs and other considerations drive the decision to implement on-axis swap-out injection.
- Injector upgrades or green field designs must meet requirements for timing and/or brightness modes (higher and lower single-bunch charge, respectively).
- Injector upgrade plans (APS-U, ALS-U):
  - New injection timing system needed for asynchronous rf frequencies.
  - Accumulator ring a practical solution for increasing single bunch or bunch train charge.
  - Instability mitigation and/or beam loading compensation are likely needed.
- Green field injector options (HEPS):
  - Choose harmonically-related rf frequencies for injector and SR.
  - Use booster for both injector and accumulator.
- Longer-term approaches may include high-charge full-energy linac or other schemes.
Acknowledgements

Thanks to APS-U Injector Team:

Also thanks to:
R. Hettel, J. Kerby (ANL/APS-U); J. Byrd (ANL)

Special thanks to:
Peter Kuske (HZB); Qing Qin, Ping He, Jiuqing Wang, Gang Xu (IHEP); Stefano De Santis, Daniela Leitner, Fernando Sannibale, Christoph Steier, Changchun Sun (LBL); Patricia Nallin (Sirius).