Injector Requirements for APS Operations

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Outline

- APS injector top-up requirements.
- Present APS injector configuration and operation.
- Injector operating envelope considerations.
- Direct injection.
  - Bunch purity data taken for direct injection using rf gun 2.
  - Simulation of linac macropulse capture using a subharmonic booster rf cavity.
  - Long drive pulse laser assisted rf thermionic guns.
- Interleaving for simultaneous LEUTL and top-up operation.
- Conclusion.
APS Injector Top-up Requirements

- Top-up allows running the SR with low effective emittance and therefore lifetime (~6 hours).
- Single-pulse injection occurs every 2 minutes.
- Injector charge / pulse depends on lifetime and injection efficiency (~80-90 %).
- This mode is the most demanding on the injectors.
- Typically top-up requires 2 - 3.5 nC/cycle to support top-up.
- The single injected pulse must land in one of 23 single buckets (singlets) with good bunch purity for timing experiments.
Standard Storage Ring Operation Modes

- **23 singlets (24 soon) each separated by 150 ns.**
  - Primary operating mode.
  - Lifetime ~ 6 hours, requires top-up for low-emittance lattice.
  - Booster provides 7 GeV and 2.0-3.5 nC/cycle depending on lifetime and injection efficiency.
  - Bunch purity requires the particle accumulator ring (PAR).

- **324 bunch operation.**
  - Allows injector studies during storage ring operations.
  - Long lifetime of ~ 60-70 hours so top-up not required even with low-emittance top-up lattice.
  - Fill every 12 hours.
  - 0.3 to 0.5 nC/cycle for each fill-on-fill.
Injector Configuration and Operation for Storage Ring Operations

Booster Parameters –
•Injection Cycle: 2 Hz
•Extraction Cycle: 2 Hz
•Charge: 0.3 – 5 nC/pulse
•Extraction Energy: 7 GeV

PAR Parameters -
•Injection Rate: 2 – 30 Hz
•Extraction Cycle: 2 Hz
•Injection Pulses: 1-5
•Extracted Charge: 0.3 – 5 nC
•Injection Energy: 325 MeV
•Fundamental rf: h = 1
•Harmonic rf: h = 12

LINAC Parameters -
•Pulse Rate: 2 – 30 Hz
•Injection Pulses: 1-5
•Extracted Charge: 0.3 – 1 nC
•Extraction Energy: 325 MeV
•RG2 Macropulse Length – 11-16 ns
•RG1 Macropulse Length – 30 ns
Injector Safety / Operating Envelope Summary

- Safety envelope based on highest allowable average beam power, highest average repetition rate and highest possible operating energy (Safety Assessment Document Ch. 5).

<table>
<thead>
<tr>
<th>Machine</th>
<th>Safety Envelope</th>
<th>Operating Envelope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac (LEUTL), (700 MeV, 60 pps)</td>
<td>(1kW), 24 nC / Pulse</td>
<td>(825 W), 19.7 nC / Pulse</td>
</tr>
<tr>
<td>PAR, (500 MeV, 2 Hz)</td>
<td>(20 W), 20 nC / Cycle</td>
<td>(10 W), 10 nC / Cycle</td>
</tr>
<tr>
<td>Booster, (7.7 GeV, 2 Hz)</td>
<td>(308 W), 20 nC / Cycle</td>
<td>(154 W), 10 nC / Cycle</td>
</tr>
</tbody>
</table>

- Rep rates are 60 pps for linac/leutl and 2 Hz for par/booster.
- When using PAR and booster there is a factor of 3 margin to support top-up.
- Design booster subharmonic cavity to operating envelope for direct injection.
Injector Configuration and Operation for Direct Injection Using rf Gun2.

Booster Parameters –
- Injection Rate: 2 Hz
- Extraction Rate: 2 Hz
- Charge: 0.3 – 2.2 nC/cycle
- Extraction Energy: 7 GeV

LINAC Parameters -
- Injection Rate: 2 Hz
- Extracted Charge: 0.3 – 2.2 nC/cycle
- Extraction Energy: 325- 450 MeV
- RG2 Macropulse Length – 11-16 ns.
Direct Injection – Storage Ring Bucket Pattern
## Direct Injection Bucket Pattern Summary

<table>
<thead>
<tr>
<th>Gun 2 Kicker Setpoint (kV)</th>
<th>Storage Ring Buckets with more than 10 counts</th>
<th>SR Buckets Containing more than 95 % of the Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.9 (2.2 nC/Cycle)</td>
<td>15</td>
<td>6 (16.7 ns)</td>
</tr>
<tr>
<td>22.5 (1.8 nC/Cycle)</td>
<td>12</td>
<td>5 (13.9 ns)</td>
</tr>
<tr>
<td>20.0 (1.0 nC/Cycle)</td>
<td>11</td>
<td>4 (11.1 ns)</td>
</tr>
<tr>
<td>18.9 (0.5 nC/Cycle)</td>
<td>11</td>
<td>4 (11.1 ns)</td>
</tr>
</tbody>
</table>
Booster Subharmonic Cavity ELEGANT Simulations

- Use the existing booster momentum ramp rate (325 MeV -> 7 GeV in 223 ms).
- Simulate using a single 352 MHz rf cavity system and a low frequency rf system at a subharmonic of 352 MHz.
- Include beam loading in the simulations.
- Tune 352 MHz system on resonance when the bunch is short enough to be completely captured (~2.5 ns).
- Use 110,000 particles to demonstrate at least 1 part in 100,000 bunch purity (1 part in 1,000,000 desired).
- Include radiation damping and quantum excitation.
- May require bunch cleaning at low energy before 352 MHz system is turned on.
Direct Injection Simulation Using Subharmonic Cavity

Full-Width Bunch Length and RF Voltage Ramps vs Time

FW Minimum Bunch Length = 0.508 ns
Direct Injection Simulation Cont.
Direct Injection Using Subharmonic Booster Cavity Parameter Tradeoffs

Subharmonic Cavity Parameters To Achieve ~2.5 ns bunch length at ~3 GeV From Elegant Simulation

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Subharmonic Number</th>
<th>Subharmonic Gap Voltage (kV)</th>
<th>Linac Macropulse Length at 0.325 GeV (ns)</th>
<th>Minimum Bunch Length (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.327</td>
<td>12</td>
<td>650</td>
<td>15.36</td>
<td>2.44</td>
</tr>
<tr>
<td>39.103</td>
<td>9</td>
<td>500</td>
<td>12.94</td>
<td>2.57</td>
</tr>
<tr>
<td>43.991</td>
<td>8</td>
<td>450</td>
<td>11.44</td>
<td>2.57</td>
</tr>
<tr>
<td>58.665</td>
<td>6</td>
<td>400</td>
<td>8.40</td>
<td>2.33</td>
</tr>
</tbody>
</table>

- Idea driven by subharmonic cavity parameter tradeoffs.
- Design to 10 nC / pulse booster operating envelope.
- 5 ns macropulse implies 2 amps off the cathode. What are the limits here?
- Could use 117 MHz subharmonic capture cavity with 5 ns macropulse.
- Bunch cleaning in the booster probably required but easier with subharmonic capture.

- What is the lifetime of cathodes under drive pulse laser conditions?
- What is the drive laser lifetime?
- Emittance measurements.
- Want to use the ITS to demonstrate as many operations issues as possible.
- Eventually test idea using gun 2 after test stand demonstration.
- Repeat storage ring bunch purity measurements.
- Gun 1 needs to be modified to have the same performance as gun 2.
- Gun 1 and PAR in the meantime can still be backup to gun 2.
Interleaving Injector Configuration With PC Gun and PAR for top-up

Booster Parameters –
•Injection Rate: 2 Hz
•Extraction Rate: 2 Hz
•Charge: 0.3 - 3 nC/cycle
•Extraction Energy: 7 GeV

PAR Parameters -
•Injection Rate: 6 Hz
•Extraction Rate: 2 Hz
•Injection Pulses: 1-3
•Extracted Charge: 0.3 – 3 nC/cycle
•Injection Energy: 325 – 450 MeV

LINAC Parameters -
•Pulse Rate: 6 Hz
•Injection Pulses: 1-3
•Extracted Charge: 0.3 – 1 nC
•Extraction Energy: 325 - 450 MeV
Interleaving Injector Configuration With Direct Injection Using the PC Gun

Booster Parameters –
• Injection Rate: 2 Hz
• Extraction Rate: 2 Hz
• Pulses: 1-5
• Charge: 0.3 - 3 nC/cycle
• Extraction Energy: 7 GeV

LINAC Parameters -
• Pulse Rate: 6 Hz
• Injection Pulses: 1-3
• Extracted Charge: 0.3 – 3 nC/cycle
• Extraction Energy: 325 - 500 MeV
PC Gun/LEUTL and Top-up Options

• Interleaving using the PAR.
  - Use the PAR to accumulate the PC gun beam.
  - Can run PC gun at relatively low charge required for FEL experiments.
  - Can use almost the full linac energy (PAR design energy is 450 MeV).
  - Requires a PAR kicker upgrade to go to the full PAR energy.
  - May need pulsed quads for matching the PC gun beam into PAR.

• Direct injection into the booster.
  - No subharmonic cavity required.
  - High charge required (at least 3 nC/cycle every 2 minutes).
  - Can use full energy of the linac.
  - Demonstrated direct booster injection only in studies. Need to resolve timing issue of laser and 352 MHz.
Conclusion

• Top-up represents puts the most severe requirements on the injector in terms of charge/cycle.
• Existing rf guns + PAR meet and exceed top-up requirements and provide the boundary condition for proposed injector modifications.
• Direct injection has been demonstrated using RG2 and can be used to fill the SR in the event the PAR is down.
• Subharmonic capture has been simulated for the booster.
• Can long drive pulse laser be used to shorten the rf gun macropulse?
Conclusion Cont.

• PC gun could in principle be used to support top-up / LEUTL operations.
• Interleaving using the PC gun and PAR is the least severe on PC gun for top-up operations.
• May require pulsed quads to match beam into the PAR.
• Need to run PC gun at least 3 nC / pulse for direct injection top-up.
• Direct injection has been demonstrated using PC gun but timing issue needs to be resolved.