Can the proton injectors meet the HL-LHC requirements after LS2?

Contents

• What are the HL-LHC requirements for after LS2*?
• Reminder of present proton injector chain performance
• Limitations and mitigations in the injector chain
  – Space charge, electron cloud, beam loading, longitudinal stability, TMCI
• Expected performance after LS2
  – Areas still requiring performance improvement
• Unknowns, risks and remaining issues
• Conclusion

*to date, only ‘final’ HL-LHC requirements after LS3 have been discussed, not LS2: The question of what LHC can accept LS2 – LS3 is not addressed.
Requirements from HL-LHC

Target: 250-300 fb\(^{-1}\) per year

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25ns</th>
<th>50ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1.15E+11</td>
<td>2.0E+11</td>
<td>3.3E+11</td>
</tr>
<tr>
<td>(n_b)</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.58</td>
<td><strong>1.02</strong></td>
<td><strong>0.84</strong></td>
</tr>
<tr>
<td>x-ing angle [(\mu\text{rad})]</td>
<td>300</td>
<td>475</td>
<td>520</td>
</tr>
<tr>
<td>beam separation [(\sigma)]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>(\beta^*) [m]</td>
<td>0.55</td>
<td><strong>0.15</strong></td>
<td><strong>0.15</strong></td>
</tr>
<tr>
<td>(\varepsilon_n) [(\mu\text{m})]</td>
<td>3.75</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>(\varepsilon_L) [eVs]</td>
<td>2.51</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>energy spread</td>
<td>1.00E-04</td>
<td>1.00E-04</td>
<td>1.00E-04</td>
</tr>
<tr>
<td>bunch length [m]</td>
<td>7.50E-02</td>
<td>7.50E-02</td>
<td>7.50E-02</td>
</tr>
<tr>
<td>IBS horizontal [h]</td>
<td>80 \rightarrow 106</td>
<td><strong>25</strong></td>
<td><strong>17</strong></td>
</tr>
<tr>
<td>IBS longitudinal [h]</td>
<td>61 \rightarrow 60</td>
<td><strong>21</strong></td>
<td><strong>16</strong></td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>0.68</td>
<td><strong>2.5</strong></td>
<td><strong>2.5</strong></td>
</tr>
<tr>
<td>geom. reduction</td>
<td>0.83</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>beam-beam / IP</td>
<td>3.10E-03</td>
<td><strong>3.9E-03</strong></td>
<td><strong>5.0E-03</strong></td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>(7.4 \times 10^{34})</td>
<td>(8.4 \times 10^{34})</td>
<td></td>
</tr>
<tr>
<td>Events / crossing</td>
<td>19</td>
<td><strong>141</strong></td>
<td><strong>257</strong></td>
</tr>
</tbody>
</table>

O. Brüning, HI-LUMI event 16-18 November 2011
Required parameters through injector chain

• With these LHC numbers what are required main parameters for (L4) PSB, PS and SPS, for 25 and 50 ns?

• Depend on emittance blowup and beam loss. Assumptions made:
  – PSB inj-extr: 5% emittance blowup, 5% beamloss
  – PS inj-extr: 5% emittance blowup, 5% beamloss
  – SPS inj-extr: 10% emittance blowup, 10% beamloss (including scraping)
  – LHC inj-flat top: 10% emittance blowup, 10% beamloss

• Total assumed beamloss 27% (PS injection to LHC flat-top), and total emittance growth 33% (or $\Delta \varepsilon \approx 0.7$ um with 2.5 um in LHC)
  – For comparison, 2011 operation saw 13% beamloss (PS injection to LHC flat-top), with $\Delta \varepsilon$ 0.4 – 0.5 um (to SPS extraction), and $\Delta \varepsilon$ 0.5 – 0.6 um LHC
Required parameters through injector chain

<table>
<thead>
<tr>
<th></th>
<th>PSB inj</th>
<th>PSB extr</th>
<th>PS inj</th>
<th>PS extr</th>
<th>SPS inj</th>
<th>SPS extr</th>
<th>LHC inj</th>
<th>LHC coll</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy GeV</td>
<td>0.16</td>
<td>2</td>
<td>2</td>
<td>26</td>
<td>26</td>
<td>450</td>
<td>450</td>
<td>7000</td>
</tr>
<tr>
<td>Nb</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>72</td>
<td>72</td>
<td>288</td>
<td>288</td>
<td>2808</td>
</tr>
<tr>
<td>Ib [e11 p+]</td>
<td>32.0</td>
<td>30.5</td>
<td>30.5</td>
<td>2.4</td>
<td>2.4</td>
<td>2.2</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Ib in LHC [e11 p+]</td>
<td>2.7</td>
<td>2.5</td>
<td>2.5</td>
<td>2.4</td>
<td>2.4</td>
<td>2.2</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Exyn [m m .m rad]</td>
<td>1.9</td>
<td>2.0</td>
<td>2.0</td>
<td>2.1</td>
<td>2.1</td>
<td>2.3</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy GeV</td>
<td>0.16</td>
<td>2</td>
<td>2</td>
<td>26</td>
<td>26</td>
<td>450</td>
<td>450</td>
<td>7000</td>
</tr>
<tr>
<td>Nb</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>36</td>
<td>36</td>
<td>144</td>
<td>144</td>
<td>1404</td>
</tr>
<tr>
<td>Ib [e11 p+]</td>
<td>26.4</td>
<td>25.2</td>
<td>25.2</td>
<td>4.0</td>
<td>4.0</td>
<td>3.6</td>
<td>3.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Ib in LHC [e11 p+]</td>
<td>4.4</td>
<td>4.2</td>
<td>4.2</td>
<td>4.0</td>
<td>4.0</td>
<td>3.6</td>
<td>3.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Exyn [m m .m rad]</td>
<td>2.2</td>
<td>2.4</td>
<td>2.4</td>
<td>2.5</td>
<td>2.5</td>
<td>2.7</td>
<td>2.7</td>
<td>3.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>loss %</th>
<th>PSB</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>blowup %</th>
<th>PSB</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
• 2011 was excellent: $1.5 \times 10^{11}$ with 2.5 um for 50 ns (at LHC flat-top)
  – Around $1.1 \times 10^{11}$ with 2.8 um for 25 ns, extracted from SPS
• Large improvement is required for either 25 or 50 ns beam!
Limits: space charge/brightness

- **PSB:** $\varepsilon_{xy} \text{ [um]} \approx -0.42 \, N_b \text{ [e12]} / \Delta Q_y$, with 160 MeV injection
  - **Confident** to run with $\Delta Q_y \approx -0.3$ (and maybe even higher...-0.5??)
  - Brightness $14e11 \, p+/\text{urad}$, or 1.7 um for $2.4e12 \, p+$
- **PS:** $\varepsilon_{xy} \text{ [um]} \approx -0.26 \, N_b \text{ [e12]} / \Delta Q_y - 0.38$, with 2 GeV injection
  - **Confident** to run with $\Delta Q_y \approx -0.26$
  - Brightness $\sim 12e11p+/\text{urad}$ (2.0 um /$2.4e12 \, p+$)
  - Cannot digest fully what PSB can provide
- **SPS:** $\varepsilon_{xy} \text{ [um]} \approx -1.22 \, N_b \text{ [e12]} / \Delta Q_y$, with Q20 optics at 26 GeV
  - **Can hope** to run with $\Delta Q_y \approx -0.15$ (single bunch brightness)
  - Gives $1.2e11 \, p+/\text{urad}$ or 1.6 um for $2.0e11 \, p+$

- For 25 ns: suggests **limit will be PS**, as PSB delivers more than PS can digest (although $\Delta Q$ above -0.26 maybe possible, depending on time at injection)
- For 50 ns: PS could deliver 1.0 um for $2.0e11$, **so limit in SPS**
PSB brightness/SC limit

Expected PSB brightness limit at injection energy of 160 MeV

Tune spreads calculated from Laslett formula give -0.3 as a conservative limit, and then extrapolate observed brightness behaviour to 160 MeV

PSB not expected to be a limit for 50 ns beam, and prospect to run with ΔQ above -0.3 for 25 ns
PS brightness/SC limit

Expected PS brightness limit at injection energy of 2 GeV (h=7, no compression, bunch length 160 ns, dp/p = 0.0013)

\[
\Delta Q_y = \frac{r_p N_b}{(2\pi)^{3/2} \gamma^3 \beta^2 \sigma_z} \frac{1}{\sqrt{\varepsilon_y}} \int \frac{\sqrt{\beta_y(s)}}{\sqrt{\beta_y(s)\varepsilon_y} + \sqrt{\beta_x(s)\varepsilon_x + \sigma_{\Delta p/p}^2 D_x^2(s)}} \, ds
\]

PS at limit for 50 ns beam, while for 25 ns HL-LHC requirement is 41% above its brightness limit...
SPS brightness/SC limit

Expected SPS brightness limit at injection energy of 26 GeV (Q20)

SPS at limit for 25 ns beam, while for 50 ns HL-LHC requirement is 28% above brightness “limit”

Single bunch…reached $\Delta Q_y$ -0.19 in MD with Q20 from Laslett formula
Other limitations

• **SPS TMCI**: single bunch
  – With Q20 looks like being above \( \sim 3.6 \times 10^{11} \) per bunch \( (Q' = 0) \)

• **PS longitudinal coupled bunch instability**
  – One turn delay feedback should increase limits from present \( \sim 1.7 \times 10^{11} \) to about \( 3 \times 10^{11} \) per bunch
  – Much more of an issue for performance reach with 50 ns

• **PS beam loading in 10, 20, 40 MHz RF systems**
  – Limited by transient phase for splitting – will suffer in splitting quality – more critical for 50 ns beam
  – Limit expected to be \( \sim 3 \times 10^{11} \) per bunch, for 25 and 50 ns spacing

• **PS-SPS transfer parameters** – studies ongoing
SPS longitudinal instabilities

• Longitudinal stability: 25 ns beam unstable at $2-3 \times 10^{10}$ p+/b
  – Presently mitigated with long. emittance blowup (0.6 eVs) and 800 MHz
• Need $\geq 0.9$ eVs for 25 ns stability with x2 nominal $I_b$ (Q26)
  – Maybe gain from lower impedance (200 MHz and kickers), x2 800 MHz V
  – Would be very beneficial to transfer longer (e.g. 1.8 ns) bunches to LHC (but need to mitigate capture losses in LHC) -> MD
  – Q20: instability thresholds higher, but need smaller $\varepsilon_l$ to get same bunch length for given $V_{RF}$
• After upgrade, expect x2 intensity possible wrt 2011
  – $2.3 \times 10^{11}$ p+/b for 25 ns, and $>3.4 \times 10^{11}$ p+/b for 50 ns
  – Main unknown is beam stability with high intensity (combination of single- and coupled-bunch effects)
SPS beam loading

- SPS 200 MHz: x2 power, 4→6 (shorter) cavities, -20% impedance
  - Will allow 10 MV at extraction for 3 A RF current (now 1.5 A)
  - Need to operate existing power plants in pulsed mode (0.75→1.05 MW)
- After upgrade: same voltage available as now (if pulsed) for 2.3e11 p+/b (25 ns) and 4.6e11 p+/b (50 ns).
  - With larger emittance more $V_{RF}$ needed for same bunch length
  - Will anyway have 10% longer bunches for 2x nominal I, with 10 MV
‘Operational’ limitations

• Mainly in SPS (to date)
  – Heating of extraction kickers: should be ‘solved’ with final shielded MKE in LS1. Expect limit to be at least twice present beam power
  – ZS sparking: interference with slow extracted FT beams. Difficult to solve – ‘ppm’ main voltage modulation being studied. Last resort is ZS off and retracted during LHC beam, which strongly impacts beam to North Area
  – Outgassing of dump and impact on injection kickers MKP vacuum: extra differential pumping and sectorisation planned. Effect is mainly a limitation for scrubbing and setting up, rather than LHC filling
• PS: observed but not yet a limitation.
  – Studies are ongoing to investigate HL-LHC regime
  – Mitigations being investigated (coating, double bunch rotation, ...)
• SPS: presently major performance limit (beamloss, vacuum, ecloud instability and incoherent emittance growth):
  – More serious for 25 ns beam
  – Expected to be removed when machine is aC coated (LIU baseline)
  – Scrubbing for 25 ns will be tough...StSt chambers, OP limitations...
  – HBW feedback could cure vertical single bunch ECI

<table>
<thead>
<tr>
<th>Beampipe profile</th>
<th>SEY threshold @ $1.1 \times 10^{11}$ p/bunch</th>
<th>SEY threshold @ $2.5 \times 10^{11}$ p/bunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID 156 (LSS)</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>ID 130 (LSS)</td>
<td>1.45</td>
<td>1.05</td>
</tr>
<tr>
<td>MBA (Dipole)</td>
<td>1.4</td>
<td>1.45</td>
</tr>
<tr>
<td>MBB (Dipole)</td>
<td>1.15</td>
<td>1.25</td>
</tr>
</tbody>
</table>
25 ns after LIU upgrade

- Limit is $2.3 \times 10^{11}$ p+/b in 3.6 um at SPS extraction ($1.6 \times 10^{11}$ in 2.3 um)

- Fundamental limit: space charge in PS
50 ns after LIU upgrade

- Limit is $2.7 \times 10^{11}$ p+/b in 2.7 um at SPS extraction (closer to HL-LHC requirement)

- Limited by longitudinal instabilities in PS and SPS, and by brightness in SPS
‘Conceivable’ improvements?

- Reduce losses (and SPS blowup) even further?

- Will be **real challenge** to achieve with x2 beam intensities

- Consider as “stretch” goal - also for HL-LHC...!

<table>
<thead>
<tr>
<th>Stretch</th>
<th>PSB</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>loss %</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>blowup %</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>
Hope for 25 ns?

- Increasing PS space charge limit from -0.26 to -0.32?
  - Maybe sufficient *if losses + blowup at “stretch” levels*
  - Would give potential for 2.1e11 in 2.3 um from SPS
  - 180 ns bunches in h=7 to lower space charge by 12%?
Otherwise for 25 ns...

- If losses + blowup remain as now estimated:
  - Need to increase PS $\Delta Q$ limit from -0.26 to -0.37 (!) and PSB $\Delta Q$ limit from -0.30 to -0.36
  - PSB could be OK, PS seems out of reach
Hope for 50 ns?

- Longitudinal stability in PS: would need $3.7 \times 10^{11}$ p+/b
  - If losses + blowup can be brought to “stretch” levels, could then dream of $3.4 \times 10^{11}$, 3.2 um extracted from SPS

  ![Graph showing emittance vs bunch intensity]

  - But requires 20% improvement in PS long. stability reach (on top of the factor $\sim 2$ assumed possible wrt today!!).
Otherwise for 50 ns....

- If PS longitudinal stability limit is ~3e11 p+/b
  - Could reach 2.8e11, 2.3 um extracted from SPS, if SPS $\Delta Q$ reaches -0.17, and losses + blowup at “stretch” levels
  - Means SPS multibunch at single bunch brightness limit...
## Table of dreams?

<table>
<thead>
<tr>
<th></th>
<th>25 ns</th>
<th>50 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I [e11]</td>
<td>Exy [um]</td>
</tr>
<tr>
<td>HL-LHC target (LHC flat-top)</td>
<td>2.0 2.5</td>
<td>3.3 3.0</td>
</tr>
<tr>
<td>LIU scenario (SPS extraction)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIU baseline (&gt;LS2)</td>
<td>2.3 3.6</td>
<td>2.7 2.7</td>
</tr>
<tr>
<td>+ &quot;stretch&quot; blowup/losses (&gt;LS3)</td>
<td>2.3 3.3</td>
<td>2.8 2.5</td>
</tr>
<tr>
<td>+ PS ΔQ to -0.32, PSB DQ to -0.31 (&gt;LS3)</td>
<td>2.1 2.3</td>
<td>3.4 3.2</td>
</tr>
<tr>
<td>+ PS longitudinal stability 3.7e11 (&gt;LS3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ SPS ΔQ to -0.17 (&gt;LS3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Length of LS2: **minimum 12 months**
  – Required by SPS 200 MHz
  – 18 m if new 850 kW cooling not ready 2016

• 2019 commissioning: **several months**
Re-commissioning after LS2

• Will not be “plug n play” to recover pre-LS2 performance

• Three ‘new’ injectors to startup, together
  – PSB: new ramp to 2 GeV, (maybe) new H- injection at 160 MeV, new RF, new instrumentation, new beam transfer
  – PS: new 2 GeV injection, new longitudinal FB, new instrumentation
  – SPS: (probably) rebuilt after ecloud coating (744 MBs, 216 MQs), ‘new’ RF 200 MHz, new high bandwidth FB, new orbit and BLM system, new scraper and TL collimators

• Normal startup: 1-2 weeks per machine

• Must count months per machine to recover pre-LS2 performance
  – A concrete LS2 plus commissioning plan to work on (in 2012)

• Will certainly take period LS2-LS3 to reach baseline LIU goals
Unresolved questions/issues

• Electron cloud
  – aC coating or scrubbing (+HBW damper) in SPS?
  – Potential issue with aC of unexplained high vacuum pressure
  – Is ecloud going to be an issue in PS?

• Can Q20 be deployed operationally in SPS after LS1?
  – Need to still solve some issues
  – Need to get experience if we have any hope to push to required levels

• Prospects for increasing (already ambitious) target for PS longitudinal stability?

• Prospect for PS exceeding -0.26 in space charge tune shift?
  – Resonance compensation studies, longer bunches from PSB?
Conclusions (I)

• For HL-LHC era, requirements are challenging
  • 25 ns: need x2 present intensity, x2 present brightness
  • 50 ns: need x2.3 present intensity, 50% above present brightness
• Baseline LIU does not reach HL-LHC ‘point-like’ requirements.
• To even get close:
  • Need all planned upgrades to be fully effective, and to approach single bunch limits with multi-bunch operation
  • Need “stretch” loss/blowup levels in injectors, with HL-LHC ≤10% blowup, and losses of around 3%...
• Limits are different for 25 and 50 ns production
  • PSB performance sufficient with 160 MeV injection for both
  • 25 ns: PS space charge tune shift (2 GeV injection fixed by PSB).
  • 50 ns: brightness in SPS, PS longitudinal stability, PS beamloading
Conclusions (II)

• Not *totally* impossible to approach HL-LHC request, providing
  1. Losses and blowup can eventually be reduced to “stretch” levels
  2. PS can run with higher space charge tune shift, nearer $\Delta Q \approx -0.32$
  3. PS longitudinal stability can improve significantly above present expectation (today at 1.7e11, LIU baseline 3e11, need 3.7e11)
  4. SPS can increase brightness limit, to $\Delta Q \approx -0.17$

• Realistic time for re-commissioning after LS2 to be foreseen
Question: can the proton injectors meet the HL-LHC requirements after LS2?

• Answer: “No. Not after LS2, but maybe after LS3”
• Interaction between HL-LHC and LIU teams is mandatory: 2nd joint meeting on March 30 at CERN