Protons: Baseline and Alternatives, Studies Plan

Outline

• Introduction: Goals and means of the LIU project

• Impact of the foreseen LIU improvements on performance of LHC injector synchrotrons and studies required in Run 2
  – PSB
  – PS
  – SPS

• Parameter reach at LHC injection for LIU beams
  – New beams after LS1: pure batch compression (PBC), 8b+4e, doublet
  – LHC beams after the full upgrade (LS2)

• Conclusions
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Goals and means of the LIU project

**Boost performance of the injectors to match HL-LHC requirements**

- Increase brightness and intensity

⇒ Inject H⁻ into the PSB at 160 MeV (replace Linac2 with Linac4, re-design injection into PSB)
⇒ Raise injection energy in the PS to 2 GeV (increase field in the PSB magnets, replace main power supply, change transfer equipment, re-design PS injection)
⇒ Upgrade PSB, PS and SPS to make them capable to accelerate and manipulate higher intensity beams (RF upgrade, impedance reduction, electron cloud mitigation, feedbacks, etc.)

**Increase injectors’ reliability and lifetime to cover HL-LHC run (until ~2035!) (closely related to consolidation)**

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF...)
⇒ Improve radioprotection measures (shielding, ventilation...)

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*HL-LHC: High-Luminosity LHC*
Linac4 beam parameters determine beam parameters at PSB injection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>$H^-$</td>
</tr>
<tr>
<td>Output Energy</td>
<td>160 MeV</td>
</tr>
<tr>
<td>Bunch Frequency</td>
<td>352.2 MHz</td>
</tr>
<tr>
<td>Max. Rep. Frequency</td>
<td>2 Hz</td>
</tr>
<tr>
<td>Max. Beam Pulse Length</td>
<td>0.4 ms</td>
</tr>
<tr>
<td>Max. Beam Duty Cycle</td>
<td>0.08 %</td>
</tr>
<tr>
<td>Chopper Beam-on Factor</td>
<td>65 %</td>
</tr>
<tr>
<td>Chopping scheme:</td>
<td>222 transmitted /133 empty buckets</td>
</tr>
<tr>
<td>Source current</td>
<td>80 mA</td>
</tr>
<tr>
<td>RFQ output current</td>
<td>70 mA</td>
</tr>
<tr>
<td>Linac pulse current</td>
<td>40 mA</td>
</tr>
<tr>
<td>Transverse emittance</td>
<td>0.4 $\pi$ $\mu$m</td>
</tr>
</tbody>
</table>

Maximum repetition frequency of accelerating structures 50 Hz

**Details in A. Lombardi’s talk**

- HL-LHC goal:
  - $\sim$28 turns $\rightarrow$ $3.4 \times 10^{12}$ p/Ring in 1.7 $\mu$m
- High intensity ISOLDE
  - $\sim$100 turns $\rightarrow$ $14 \times 10^{12}$ p/Ring
PSB performance
(LHC beam parameters @PSB extraction)

\[ y = 0.0059x \]

- Injection at 160 MeV (relaxed space charge)
- \( H^- \)-injection (more efficient phase space painting)

⇒ Linac4 will allow PSB to produce double brightness LHC beams
⇒ Deliver beam to PS at 2GeV

Slope mainly determined by:
- Multi-turn injection process
- Space charge during 50 MeV injection

\[ y = 0.0118x \] present performance
# Key dates for LIU-PSB before LS2

<table>
<thead>
<tr>
<th>Subject</th>
<th>Action</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upgrade of main RF systems</td>
<td>New Finemet-based systems or upgrade of existing C02+C04 systems</td>
<td>Decision by end 2015</td>
</tr>
<tr>
<td>New H+ injection at 160 MeV from Linac 4</td>
<td>Mechanical mock-up. Half-sector test + stripping foil test</td>
<td>Scheduled mid 2016</td>
</tr>
</tbody>
</table>

**In terms of machine studies:**
- 5 Finemet modules system successfully tested with beam in Ring 4 during Run 1
- 5 additional modules installed in PSB during LS1. Will be used for beam test throughout Run 2
- First review (with external reviewers) on 09/09/2014

**In terms of modelling:**
- Simulations of injection into PSB from Linac4 to produce new brightness curve for LHC beams as well as study injection losses for high intensity beams
- Improve the optics model of the machine (linear and nonlinear)
- Improve the impedance model of the machine to study stability of future beams
PS brightness limitations overview

Acceleration/Bunch splittings
Longitudinal CBI → New damper
Transient beam loading → 1 turn delay FB
Transition crossing → No limitation expected

Injection flat bottom:
Space charge → Injection @2GeV
Headtail instability → Transverse FB
PS brightness limitations overview

**Injection flat bottom:**
- Space charge \(\rightarrow\) Injection @2GeV
- Headtail instability \(\rightarrow\) Transverse FB

**Acceleration/Bunch splittings**
- Longitudinal CBI \(\rightarrow\) New damper
- Transient beam loading
- Transition crossing \(\rightarrow\) No limitation expected

**Maximum SC tune spread @injection**
\[\Delta Q_y = 0.31 \rightarrow 2 \text{ GeV will allow for more brightness}\]

**Maximum intensity per bunch @extraction due to CBI**
\[N_b = 2 \times 10^{11} \text{ ppb} \rightarrow 3 \times 10^{11} \text{ ppb} \text{ with new feedback}\]
Pending decisions for LIU-PS

<table>
<thead>
<tr>
<th>Subject</th>
<th>Action</th>
<th>Decision date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance compensation</td>
<td>New skew sextupoles and octupoles</td>
<td>Q4-2014</td>
</tr>
<tr>
<td>Increase of 40/80 MHz voltage for better capture in SPS</td>
<td>New C40 (C80) system</td>
<td>Q4-2014</td>
</tr>
<tr>
<td>Upgrade of main RF systems (beam loading performance)</td>
<td>New power amplifiers for C10 systems</td>
<td>Q1-2015</td>
</tr>
</tbody>
</table>

In terms of machine studies (and from LHC beam operation):
- Systematic study with re-installed octupoles will be done in 2014 (simulations predict that 4th order resonance is structure resonance)
- C40 (C80): Test to increase the power and voltage capability of existing cavities by installing new power supplies and changing the coupling
- C10: Studies to optimize feedbacks and beam loading behaviour of the existing systems (+ new one-turn delay feedback)
- Finemmet cavity as wide-band kicker for longitudinal feedback already installed in the PS → Decisive tests on its potential will be conducted during Run 2
More PS machines studies in Run 2

In terms of machine studies and LHC beam operation:

• Operational development
  → New production scheme for LHC beams (longer bunches, larger longitudinal emittances from PSB) → covered in Y. Papaphilippou’s talk
  → New RF manipulation schemes, i.e. pure batch compression (PBC) and 8b+4e
  → 80+ bunch scheme (production/extraction schemes)

• Nonlinear optics model of the machine

• Space charge
  → Special high dispersion optics
  → Fully coupled optics
  → Hollow bunches (together with PSB)

• TMCI at transition

• Electron cloud:
  → Parameter studies with new electron cloud monitors (direct observation)
  → Beam instability for larger bunch currents
  → Effect of uniformly filled machine (80+ bunch transfer scheme)

• Impedance model via dedicated beam measurements
Pure batch compression (PBC) scheme

Alternative production scheme for 25 ns beams
→ Pure batch compression at 2.5 GeV (from h=9 to h=21)
→ Twice double splitting at FT
→ Trains of 32 bunches to the SPS (11% lower # of bunches in LHC)
→ Trains of 16 bunches of 50 ns beams can also be produced

Potential production of ultra-bright 25 ns (and 50 ns) beams
→ Relaxed electron cloud in downstream machines (due to short trains)
→ Interesting for space charge studies in SPS
→ Studies on transport of sub-µm emittances through injection chain
8b+4e scheme

- Creates trains with 4 missing bunches every 8 bunches (H. Damerau, RLIUP)
  - Allows accelerating higher intensity bunches in the SPS
  - Is expected to reduce e-cloud effects

- Standard scheme ➔ Double split from $h=7$ to $h=21$, leaving empty bucket – bunch pattern $6x(8b+4e) + 8b$. This beam has been produced at the PS (H. Damerau, 2014)
- BCMS ➔ merging and triple splitting suppressed – bunch pattern $3x(8b+4e) + 8b$
SPS limitations overview

**Injection flat bottom:**
- Capture losses
- Incoherent losses
- Space charge
- TMCI

**Ramp and flat top:**
- Longitudinal instability
- Beam loading
- RF power

**Along the whole cycle:**
- Electron cloud for 25 ns
SPS limitations overview

**Injection flat bottom:**
- Capture losses, incoherent losses
- Space charge
- TMCI

**Ramp and flat top:**
- Longitudinal instability
- Beam loading
- RF power

**Along the whole cycle:**
- Electron cloud for 25 ns

Maximum SC tune spread @injection
\[ \Delta Q_y = 0.21 \rightarrow \text{still margin for 25 ns beams} \]

Maximum intensity per bunch @extraction due to RF power and longitudinal instabilities
\[ N_b = 1.3 \times 10^{11} \text{ ppb} \rightarrow 2 \times 10^{11} \text{ ppb} \text{ with RF upgrade and a-C coating} \]
## Key dates for LIU-SPS before LS2

<table>
<thead>
<tr>
<th>Subject</th>
<th>Action</th>
<th>Decision date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron cloud mitigation</td>
<td>a-C coating of vacuum chambers</td>
<td>Mid 2015 (with external reviewers)</td>
</tr>
<tr>
<td>Damping of intra-bunch instabilities</td>
<td>New Wide-band (GHz) transverse damper</td>
<td>End 2016 (CERN/LARP review with external experts)</td>
</tr>
<tr>
<td>Machine impedance reduction</td>
<td>Improved shielding of ZS, pumping modules, etc.</td>
<td>End 2015</td>
</tr>
<tr>
<td></td>
<td>Shielding/mode damping/redesigning vacuum flanges.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kicker design.</td>
<td></td>
</tr>
<tr>
<td>Improvement of operation/reduction of irradiation</td>
<td>New external (high energy) beam dump</td>
<td>Q4-2014 to start civil engineering for LS2</td>
</tr>
</tbody>
</table>
E-cloud mitigation (a-C coating)

- Thin film of a-C provides intrinsically low Secondary Electron Yield
  - Suppression of e-cloud in prototype chambers demonstrated with beam in SPS
  - 4 SPS half cells (including quadrupoles) with a-C coating ready for the startup in 2014 → further tests with beam
E-cloud mitigation (scrubbing)

- Thin film of a-C provides intrinsically low Secondary Electron Yield
  - Suppression of e-cloud in prototype chambers demonstrated with beam in SPS
  - 4 SPS half cells (including quadrupoles) with a-C coating ready for the startup in 2014 → further tests with beam

- Scrubbing lowers SEY with accumulated dose (machine time)
  - Dedicated runs (1 to 2 weeks) performed at 26 GeV in cycling mode (~40 s cycle length) – about 40 days integrated time from 2002 (see talk on SPS scrubbing run)
  - Additional scrubbing accumulated during 25 ns MDs
  - 25 ns beam preserved “within budgets” in the SPS from 2011 onwards

2012: 4x72 bunches (1.15x10^{11} p/b @inj.)
Doublet beam: a possible boost to scrubbing

- Injection of long bunches into SPS (with 25 ns spacing)
- Capturing each bunch in 2 neighboring 200 MHz buckets
- **Successfully tested in MDs** at the end of 2012/13 run with $1.6 \times 10^{11}$ p/doublet
- Clear enhancement on **e-cloud detectors** compared to standard 25 ns beam measured
Doublet beam: a possible boost to scrubbing

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- Clear enhancement on **e-cloud detectors** compared to standard 25 ns beam measured
- Enhanced **pressure rise** compared to standard 25 ns beam measured in the arcs
Scrubbing or coating? A possible strategy ...

- **SCRUBBING RUN I (1 week + 2 days)**
  - Beams: nominal intensity
  - Goal: recover the 2012 performance and test doublet beam

- **SCRUBBING RUN II (2 weeks)**
  - Gradually increase intensity up to 2e11 p/b
  - Scrubbing successful for high intensity?

**LIU-SPS Review: coating? (after data analysis!)**

- **Scrubbing qualification**: No degradation for 2e11 p/b with 4x72 bunches and 5x48 bunches
- Results from the 4 coated half cells
- Simulations for higher brightness beams (from Linac4)
High bandwidth transverse feedback (CERN/LARP)

- High bandwidth (intra-bunch) feedback
  - It can suppress electron cloud induced coherent motion
    - Make scrubbing more efficient \(\rightarrow\) Improve beam quality and stabilize pi-mode in doublets
    - Avoid running with high chromaticity settings \(\rightarrow\) better beam lifetime and emittances
  - Was shown to work for dipole mode in 2012/2013 machine studies

- LARP support to be defined for the future
  - 2014 – 2015: Hardware upgrade for demo system, operation of wideband stripline kicker with two R&K amplifiers and support for machine studies during Run 2 (people, MD analysis tools)
  - Resources for electromagnetic design of slotline kicker are being clarified

See also LIU SPS High Bandwidth Feedback review
Impedance reduction

- Longitudinal plane
  - After full RF upgrade: 4 cavities with 1.05 MW & 2 cavities with 1.6 MW → $2.0 \times 10^{11}$ p/b (scaling to preserve bunch length at extraction based on present understanding)
  - Identifying and reducing longitudinal impedance would allow for larger accelerated intensity → Big effort in machine studies + impedance modeling – ongoing

- Transverse plane
  - Reduction of transverse impedance entails an increase of TMCI threshold @inj  
    Makes possible use with larger $\gamma_t$ optics loosening constraint on RF power
  (see talks by H. Bartosik and T. Argyropoulos)

\[ V \text{ for } \tau = \text{const} \quad \text{(LD & PWD) } \]
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• Conclusions
Pure batch compression (PBC) scheme

- PSB brightness: 1.16e-12 um/(p/b)
- PS bunch splitting factor: 4
- PS bunch length: 150 ns
- PS momentum spread: 9.0e-04
- PS injection energy: 1.4 GeV
- LHC number of bunches: 2450

<table>
<thead>
<tr>
<th>PBC</th>
<th>Intensity (p/b)</th>
<th>Emittance (μm)</th>
<th>Bunch pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns</td>
<td>1.3 x 10^{11}</td>
<td>0.95</td>
<td>32b</td>
</tr>
</tbody>
</table>
**8b+4e**

- Limited to $1.8 \times 10^{11}$ p/b in the SPS because of longitudinal instabilities
- Brightness limited by
  - PSB brightness for standard scheme
  - No outstanding bottleneck for BCMS
8b+4e

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- Brightness limited by
  - PSB brightness for standard scheme
  - No outstanding bottleneck for BCMS

<table>
<thead>
<tr>
<th>Bunch pattern</th>
<th>Intensity (p/b)</th>
<th>Emittance ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>$1.8 \times 10^{11}$</td>
<td>2.3</td>
</tr>
<tr>
<td>BCMS</td>
<td>$1.8 \times 10^{11}$</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Doublet beam

- We need to accelerate $1.6 \times 10^{11}$ p/doublet in the SPS
  - $\varepsilon_{x,y} \sim 3$ μm at best at injection
  - RF power and longitudinal instability limitation in the SPS $\rightarrow$ intensity perhaps achievable with a 3x slower ramp rate, tentatively on Q20
  - Longitudinal emittance about 0.4 eVs at injection from simulations (J. Esteban-Müller)
  - Beam quality possibly degraded due to e-cloud and longitudinal limitations

- Need to gain experience in the SPS with dedicated MDs in 2014 for complete parameter list at flat top
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  – SPS

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• Conclusions
Standard scheme (72b trains) after LS2

Post-LS1 – Standard scheme – 1.4GeV – 25ns

PSB brightness: 1.16e−12um/(p/b)
PS bunch splitting factor: 12
PS bunch length: 220ns
PS momentum spread: 1.8e−03
PS injection energy: 1.4GeV
LHC number of bunches: 2760
Standard scheme (72b trains) after LS2

- With Linac 4
- LIU upgrades
  - SPS 200 MHz upgrade
  - SPS e-cloud mitigation
  - PSB-PS transfer at 2 GeV

- Limitations standard scheme
  - SPS: longitudinal instabilities + beam loading
  - PSB: brightness

- Performance reach
  - $2.0 \times 10^{11}$ p/b in $1.88 \mu$m (@ 450GeV)
  - $1.9 \times 10^{11}$ p/b in $2.26 \mu$m (in collision)
BCMS scheme (48b trains) after LS2

• With Linac 4
  • LIU upgrades
    – SPS 200 MHz upgrade
    – SPS e-cloud mitigation
  – PSB - PS transfer at 2 GeV

• Limitations BCMS scheme
  – SPS: longitudinal instabilities + beam loading
  – PS: space charge
  – SPS: space charge

• Performance reach
  – $2.0 \times 10^{11}$ pb in $1.37 \mu m$ (@ 450 GeV)
  – $1.9 \times 10^{11}$ pb in $1.65 \mu m$ (in collision)

Operational limits of beam intercepting devices in SPS, transfer lines and LHC will determine the operational use of BCMS beams (see V. Kain's talk)
### Overview on post LS2 LIU parameters

<table>
<thead>
<tr>
<th></th>
<th>PSB</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N$ ($10^{11}$ p)</td>
<td>$\epsilon_{x,y}$ ($\mu$m)</td>
<td>$E$ (GeV)</td>
<td>$\epsilon_z$ (eVs)</td>
<td>$B_t$ (ns)</td>
<td>$\delta p/p_0$</td>
<td>$\Delta Q_{x,y}$</td>
</tr>
<tr>
<td>LIU</td>
<td>29.55</td>
<td>1.55</td>
<td>0.16</td>
<td>1.4</td>
<td>650</td>
<td>1.8 $\cdot$ 10$^{-3}$</td>
<td>(0.55, 0.66)</td>
</tr>
<tr>
<td>BCMS</td>
<td>14.77</td>
<td>1.13</td>
<td>0.16</td>
<td>1.4</td>
<td>650</td>
<td>1.8 $\cdot$ 10$^{-3}$</td>
<td>(0.35, 0.44)</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>34.21</td>
<td>1.72</td>
<td>0.16</td>
<td>1.4</td>
<td>650</td>
<td>1.8 $\cdot$ 10$^{-3}$</td>
<td>(0.58, 0.69)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>PS (double injection)</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LIU</td>
<td>$N$ ($10^{11}$ p/b)</td>
<td>$\epsilon_{x,y}$ ($\mu$m)</td>
<td>$E$ (GeV)</td>
<td>$\epsilon_z$ (eVs/b)</td>
<td>$B_t$ (ns)</td>
<td>$\delta p/p_0$</td>
<td>$\Delta Q_{x,y}$</td>
</tr>
<tr>
<td>Standard</td>
<td>28.07</td>
<td>1.63</td>
<td>2.0</td>
<td>3.00</td>
<td>205</td>
<td>1.5 $\cdot$ 10$^{-3}$</td>
<td>(0.16, 0.28)</td>
</tr>
<tr>
<td>BCMS</td>
<td>14.04</td>
<td>1.19</td>
<td>2.0</td>
<td>1.48</td>
<td>135</td>
<td>1.1 $\cdot$ 10$^{-3}$</td>
<td>(0.19, 0.31)</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>32.50</td>
<td>1.80</td>
<td>2.0</td>
<td>3.00</td>
<td>205</td>
<td>1.5 $\cdot$ 10$^{-3}$</td>
<td>(0.18, 0.30)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SPS (several injections)</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>LIU</td>
<td>$N$ ($10^{11}$ p/b)</td>
<td>$\epsilon_{x,y}$ ($\mu$m)</td>
<td>$p$ (GeV/c)</td>
<td>$\epsilon_z$ (eVs/b)</td>
<td>$B_t$ (ns)</td>
<td>$\delta p/p_0$</td>
<td>$\Delta Q_{x,y}$</td>
</tr>
<tr>
<td>Standard</td>
<td>2.22</td>
<td>1.71</td>
<td>26</td>
<td>0.37</td>
<td>3.0</td>
<td>1.5 $\cdot$ 10$^{-3}$</td>
<td>(0.09, 0.16)</td>
</tr>
<tr>
<td>BCMS</td>
<td>2.22</td>
<td>1.25</td>
<td>26</td>
<td>0.37</td>
<td>3.0</td>
<td>1.5 $\cdot$ 10$^{-3}$</td>
<td>(0.12, 0.21)</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>2.57</td>
<td>1.89</td>
<td>26</td>
<td>0.37</td>
<td>3.0</td>
<td>1.5 $\cdot$ 10$^{-3}$</td>
<td>(0.10, 0.17)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th></th>
<th></th>
<th></th>
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<th>bunches/train</th>
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<tbody>
<tr>
<td>LIU</td>
<td>$N$ ($10^{11}$ p/b)</td>
<td>$\epsilon_{x,y}$ ($\mu$m)</td>
<td>$p$ (GeV/c)</td>
<td>$\epsilon_z$ (eVs/b)</td>
<td>$B_t$ (ns)</td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2.00</td>
<td>1.88</td>
<td>450</td>
<td>0.60</td>
<td>1.65</td>
<td>72</td>
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<tr>
<td>BCMS</td>
<td>2.00</td>
<td>1.37</td>
<td>450</td>
<td>0.60</td>
<td>1.65</td>
<td>48</td>
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<tr>
<td>HL-LHC</td>
<td>2.32</td>
<td>2.08</td>
<td>450</td>
<td>0.65</td>
<td>1.65</td>
<td>72</td>
</tr>
</tbody>
</table>
### Parameter overview and main conclusions

- **LIU beams for studies identified and target parameters set**
- **Studies during Run 2 will be crucial to update parameter tables and steer some LIU related decisions** ➔ lots of MD time and resources needed!

<table>
<thead>
<tr>
<th>LIU beams (during Run 2)</th>
<th>Intensity @SPS extraction</th>
<th>Normalized transverse emittance @SPS extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBC (32 bunches/PS batch)</td>
<td>$1.3 \times 10^{11}$ p/b</td>
<td>$0.95 \ \mu$m</td>
</tr>
<tr>
<td>Standard 8b+4e (56 bunches/PS batch)</td>
<td>$1.8 \times 10^{11}$ p/b</td>
<td>$2.3 \ \mu$m</td>
</tr>
<tr>
<td>Doublet (72 doublets/PS batch)</td>
<td>$1.6 \times 10^{11}$ p/b</td>
<td>$&gt;3 \ \mu$m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIU beams (after LS2)</th>
<th>Intensity @SPS extraction</th>
<th>Normalized transverse emittance @SPS extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIU - standard scheme (72 bunches/PS batch)</td>
<td>$2 \times 10^{11}$ p/b</td>
<td>$1.88 \ \mu$m</td>
</tr>
<tr>
<td>LIU - BCMS scheme (48 bunches/PS batch)</td>
<td>$2 \times 10^{11}$ p/b</td>
<td>$1.37 \ \mu$m</td>
</tr>
</tbody>
</table>
THANK YOU FOR YOUR ATTENTION!
Standard scheme (72b trains) after LS2

- **LIU upgrades**
  - SPS 200 MHz upgrade
  - SPS e-cloud mitigation
  - PSB-PS transfer at 2 GeV

- **Limitations standard scheme**
  - SPS: longitudinal instabilities + beam loading
  - PSB: brightness

- **Performance reach**
  - $2.0 \times 10^{11}$ p/b in $1.88 \mu m$ (@ 450GeV)
  - $1.9 \times 10^{11}$ p/b in $2.26 \mu m$ (in collision)
Summary

1. Present performance and post-LS1
   → 25 ns beams from both standard and BCMS production schemes
     ✓ Perform about within budgets throughout the LHC injector chain
     ✓ Were used in 2012 for the LHC scrubbing and pilot physics runs
   → After LS1, an important margin for improvement comes from the relaxation of the longitudinal constraints at the PSB-PS transfer.
   ➜ The pure BC scheme holds great promise to produce ultra-bright 25 ns beams for the post-LS1 era with short trains (favorable against electron cloud)

2. Only Linac4
   → Standard 25 ns beams: 50% higher brightness is in reach (limited by PS space charge)
   → BCMS beams: no improvement with Linac4 because they are presently already at the limit for space charge in PS
   → Possible additional gains by creating hollow bunches or using alternative optics in the PS at injection
   → Single batch PSB-PS transfer could be used to reduce LHC filling time by 17%
# Post-LS1 scenarios: summary

## Post-LS1 25 ns beam options – October 1, 2013

<table>
<thead>
<tr>
<th></th>
<th>PSB</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>δp/p₀</th>
<th>ΔQₓ,ᵧ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (10^{11} p)</td>
<td>εₓ,ᵧ (µm)</td>
<td>E (GeV)</td>
<td>εₓ (eVs)</td>
<td>B₁ (ns)</td>
<td></td>
<td></td>
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<tr>
<td>Post-LS1</td>
<td>Standard</td>
<td>19.21</td>
<td>2.02</td>
<td>0.05</td>
<td>1.0</td>
<td>1100</td>
<td>2.4·10⁻³</td>
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<tr>
<td></td>
<td>BCMS</td>
<td>9.60</td>
<td>1.06</td>
<td>0.05</td>
<td>1.0</td>
<td>1100</td>
<td>2.4·10⁻³</td>
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<tr>
<td></td>
<td>Pure BC</td>
<td>6.40</td>
<td>0.78</td>
<td>0.05</td>
<td>1.0</td>
<td>1100</td>
<td>2.4·10⁻³</td>
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<table>
<thead>
<tr>
<th></th>
<th>PS (double injection)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>δp/p₀</th>
<th>ΔQₓ,ᵧ</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>N (10^{11} p/b)</td>
<td>εₓ,ᵧ (µm)</td>
<td>E (GeV)</td>
<td>εₓ (eVs/b)</td>
<td>B₁ (ns)</td>
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<tr>
<td>Post LS1</td>
<td>Standard</td>
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<td>220</td>
<td>1.8·10⁻³</td>
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<tr>
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<td>BCMS</td>
<td>9.12</td>
<td>1.11</td>
<td>1.4</td>
<td>1.48</td>
<td>150</td>
<td>1.4·10⁻³</td>
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<tr>
<td></td>
<td>Pure BC</td>
<td>6.08</td>
<td>0.72</td>
<td>1.4</td>
<td>1.0</td>
<td>150</td>
<td>0.9·10⁻³</td>
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<table>
<thead>
<tr>
<th></th>
<th>SPS (several injections)</th>
<th>after filamentation (εₓ=0.35 eVs, B₁=4 ns @inj)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>ΔQₓ,ᵧ</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>N (10^{11} p/b)</td>
<td>εₓ,ᵧ (µm)</td>
<td>p (GeV/c)</td>
<td>εₓ (eVs/b)</td>
<td>B₁ (ns)</td>
<td>δp/p₀</td>
<td></td>
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<tr>
<td>Post-LS1</td>
<td>Standard</td>
<td>1.44</td>
<td>2.22</td>
<td>26</td>
<td>0.42</td>
<td>3.0</td>
<td>1.5·10⁻³</td>
</tr>
<tr>
<td></td>
<td>BCMS</td>
<td>1.44</td>
<td>1.16</td>
<td>26</td>
<td>0.42</td>
<td>3.0</td>
<td>1.5·10⁻³</td>
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<td>Pure BC</td>
<td>1.44</td>
<td>0.86</td>
<td>26</td>
<td>0.42</td>
<td>3.0</td>
<td>1.5·10⁻³</td>
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<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>bunches/train</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (10^{11} p/b)</td>
<td>εₓ,ᵧ (µm)</td>
<td>p (GeV/c)</td>
<td>εₓ (eVs/b)</td>
<td>B₁ (ns)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-LS1</td>
<td>Standard</td>
<td>1.30</td>
<td>2.44</td>
<td>450</td>
<td>0.47</td>
<td>1.63</td>
<td>72</td>
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<tr>
<td></td>
<td>BCMS</td>
<td>1.30</td>
<td>1.28</td>
<td>450</td>
<td>0.47</td>
<td>1.63</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Pure BC</td>
<td>1.30</td>
<td>0.95</td>
<td>450</td>
<td>0.47</td>
<td>1.63</td>
<td>32</td>
</tr>
</tbody>
</table>
### 2012 performance with standard production scheme: summary table

Standard Production Scheme – September 30, 2013

#### PSB (1 b after capture, c=285 ms)

<table>
<thead>
<tr>
<th>Achieved</th>
<th>( N ) ((10^{11}) p)</th>
<th>( \epsilon_{x,y} ) ((\mu)m)</th>
<th>( E ) (GeV)</th>
<th>( \epsilon_{z} ) (eVs)</th>
<th>( B_t ) (ns)</th>
<th>( \delta p/p_0 )</th>
<th>( \Delta Q_{x,y} )</th>
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</thead>
<tbody>
<tr>
<td>50 ns</td>
<td>12.56</td>
<td>1.41</td>
<td>0.05</td>
<td>1.0</td>
<td>1100</td>
<td>2.4 (\cdot) 10(-3)</td>
<td>(0.51, 0.61)</td>
</tr>
<tr>
<td>25 ns</td>
<td>17.73</td>
<td>2.14</td>
<td>0.05</td>
<td>1.0</td>
<td>1100</td>
<td>2.4 (\cdot) 10(-3)</td>
<td>(0.51, 0.59)</td>
</tr>
</tbody>
</table>

#### PS (4+2 b/inj)

<table>
<thead>
<tr>
<th>Achieved</th>
<th>( N ) ((10^{11}) p/b)</th>
<th>( \epsilon_{x,y} ) ((\mu)m)</th>
<th>( E ) (GeV)</th>
<th>( \epsilon_{z} ) (eVs/b)</th>
<th>( B_t ) (ns)</th>
<th>( \delta p/p_0 )</th>
<th>( \Delta Q_{x,y} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ns</td>
<td>11.93</td>
<td>1.48</td>
<td>1.4</td>
<td>1.2</td>
<td>180</td>
<td>0.9 (\cdot) 10(-3)</td>
<td>(0.24, 0.31)</td>
</tr>
<tr>
<td>25 ns</td>
<td>16.84</td>
<td>2.25</td>
<td>1.4</td>
<td>1.2</td>
<td>180</td>
<td>0.9 (\cdot) 10(-3)</td>
<td>(0.25, 0.30)</td>
</tr>
</tbody>
</table>

#### SPS (4 \(\times\) 36-72 b/inj)

<table>
<thead>
<tr>
<th>Achieved</th>
<th>( N ) ((10^{11}) p/b)</th>
<th>( \epsilon_{x,y} ) ((\mu)m)</th>
<th>( p ) (GeV/c)</th>
<th>( \epsilon_{z} ) (eVs/b)</th>
<th>( B_t ) (ns)</th>
<th>( \delta p/p_0 )</th>
<th>( \Delta Q_{x,y} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ns</td>
<td>1.89</td>
<td>1.55</td>
<td>26</td>
<td>0.42</td>
<td>3.0</td>
<td>1.5 (\cdot) 10(-3)</td>
<td>(0.09, 0.15)</td>
</tr>
<tr>
<td>25 ns</td>
<td>1.33</td>
<td>2.36</td>
<td>26</td>
<td>0.42</td>
<td>3.0</td>
<td>1.5 (\cdot) 10(-3)</td>
<td>(0.05, 0.07)</td>
</tr>
</tbody>
</table>

#### LHC (n \(\times\)144-288 b/inj)

<table>
<thead>
<tr>
<th>Achieved</th>
<th>( N ) ((10^{11}) p/b)</th>
<th>( \epsilon_{x,y} ) ((\mu)m)</th>
<th>( p ) (GeV/c)</th>
<th>( \epsilon_{z} ) (eVs/b)</th>
<th>( B_t ) (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ns</td>
<td>1.70</td>
<td>1.71</td>
<td>450</td>
<td>0.46</td>
<td>1.60</td>
</tr>
<tr>
<td>25 ns</td>
<td>1.20</td>
<td>2.60</td>
<td>450</td>
<td>0.42</td>
<td>1.47</td>
</tr>
</tbody>
</table>
## 2012 performance with BCMS scheme: summary table

BCMS scheme – October 1, 2013

<table>
<thead>
<tr>
<th>PSB (1 b after capture, c=285 ms)</th>
<th>$N$ (10^{11} p)</th>
<th>$\epsilon_{x,y}$ (µm)</th>
<th>$E$ (GeV)</th>
<th>$\epsilon_z$ (eVs)</th>
<th>$B_t$ (ns)</th>
<th>$\delta p/p_0$</th>
<th>$\Delta Q_{x,y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>50 ns</td>
<td>6.28</td>
<td>0.89</td>
<td>0.05</td>
<td>1000</td>
<td>2.2 \cdot 10^{-3}</td>
<td>(0.41, 0.52)</td>
</tr>
<tr>
<td></td>
<td>25 ns</td>
<td>8.48</td>
<td>1.15</td>
<td>0.05</td>
<td>1000</td>
<td>2.2 \cdot 10^{-3}</td>
<td>(0.46, 0.56)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PS (4+4 b/inj)</th>
<th>$N$ (10^{11} p/b)</th>
<th>$\epsilon_{x,y}$ (µm)</th>
<th>$E$ (GeV)</th>
<th>$\epsilon_z$ (eVs/b)</th>
<th>$B_t$ (ns)</th>
<th>$\delta p/p_0$</th>
<th>$\Delta Q_{x,y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>50 ns</td>
<td>5.96</td>
<td>0.94</td>
<td>1.4</td>
<td>150</td>
<td>0.8 \cdot 10^{-3}</td>
<td>(0.21, 0.28)</td>
</tr>
<tr>
<td></td>
<td>25 ns</td>
<td>8.05</td>
<td>1.20</td>
<td>1.4</td>
<td>150</td>
<td>0.8 \cdot 10^{-3}</td>
<td>(0.24, 0.31)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SPS (max 3 × 24-48 b/inj)</th>
<th>$N$ (10^{11} p/b)</th>
<th>$\epsilon_{x,y}$ (µm)</th>
<th>$p$ (GeV/c)</th>
<th>$\epsilon_z$ (eVs/b)</th>
<th>$B_t$ (ns)</th>
<th>$\delta p/p_0$</th>
<th>$\Delta Q_{x,y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>50 ns</td>
<td>1.89</td>
<td>0.98</td>
<td>26</td>
<td>0.42</td>
<td>3.0</td>
<td>1.5 \cdot 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>25 ns</td>
<td>1.27</td>
<td>1.27</td>
<td>26</td>
<td>0.42</td>
<td>3.0</td>
<td>1.5 \cdot 10^{-3}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LHC (max 8 × 96 b/inj)</th>
<th>$N$ (10^{11} p/b)</th>
<th>$\epsilon_{x,y}$ (µm)</th>
<th>$p$ (GeV/c)</th>
<th>$\epsilon_z$ (eVs/b)</th>
<th>$B_t$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>50 ns</td>
<td>1.70</td>
<td>1.08</td>
<td>450</td>
<td>0.46</td>
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<td></td>
<td>25 ns</td>
<td>1.15</td>
<td>1.39</td>
<td>450</td>
<td>0.42</td>
</tr>
</tbody>
</table>

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