
E-cloud team:
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Before 2012

- Dedicated scrubbing runs from 2002 to 2009
  - At 26 GeV/c (~40 s cycle length)
  - Observed beam instabilities, emittance growth, pressure rise all around the SPS
  - Efficiency typically limited by heating/outgassing of specific element

<table>
<thead>
<tr>
<th>Year</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>14 days</td>
</tr>
<tr>
<td>2003</td>
<td>8 days</td>
</tr>
<tr>
<td>2004</td>
<td>10 days</td>
</tr>
<tr>
<td>2006</td>
<td>5 days</td>
</tr>
<tr>
<td>2007</td>
<td>7 days</td>
</tr>
<tr>
<td>2008</td>
<td>2.5 days</td>
</tr>
<tr>
<td>2009</td>
<td>1.5 days</td>
</tr>
<tr>
<td>2012</td>
<td>5 days</td>
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</table>

~1 month before 2005 long shutdown
16 days in 2006 – 2009

- MDs with LHC beams in 2010-11 showed for the first time that 4 batches of 25 ns beam with $1.2 \times 10^{11}$ p/b could be accelerated in the SPS with $\varepsilon_{x,y} < 3 \, \mu$m
Scrubbing 2012

- One week dedicated scrubbing (studies) in the SPS
- Scrubbing ‘status’ of the SPS was confirmed for nominal intensity
  - No measurable emittance growth over 4 batches and long flat bottom
Scrubbing 2012

- One week dedicated scrubbing (studies) in the SPS
- High intensity tests up to ‘ultimate’ (1.8e11 p/b)
  - Disclaimer: Quality probably not optimal from PS, bunches longer than 4 ns at injection
  - Sharp increase of pressure rise (arcs, LSS5) when making intensity steps – however, signs of conditioning over few hours
Scrubbing 2012

- One week dedicated scrubbing (studies) in the SPS
- High intensity tests up to ‘ultimate’ (1.8e11 p/b)
  - Electron cloud distribution measured in the strip monitors
  - Stripes moving outwards and occupying larger regions, however depleting the center

MBA

MBB
Scrubbing 2012

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already known from simulations
Scrubbing 2012

- One week dedicated scrubbing (studies) in the SPS
- High intensity tests up to ‘ultimate’ (1.8e11 p/b)
- A stronger flux is observed in the outer regions of the liners which were not reached by the scrubbing performed with the nominal bunch intensity.
- The bunch intensity used for the scrubbing run defines the maximum intensity for which an "EC free" operation can be guaranteed afterwards.
- Radial steering can be employed to condition a wider region, but this comes at the expense of the overall scrubbing time and the effectiveness is modulated around the machine according to the dispersion function.
Scrubbing 2014

- One week (October) + 3 days (December) dedicated scrubbing in the SPS
- First week in 2014 was used to recover SPS performance post-LS1
  - One week found indeed to be sufficient to recover a ‘scrubbing status’ of the SPS to allow for LHC beam production within target parameters

<table>
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<th>Beam type</th>
<th>Bunch intensity (injected)</th>
<th>Number of bunches</th>
<th>Transverse emittances (at 26 GeV)</th>
<th>Beam lifetime after each injection</th>
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<td>25 ns Standard</td>
<td>~1.25 x 10^{11} p/b</td>
<td>288 (4 x 72)</td>
<td>$\epsilon_{H,V} \approx 2.6 \mu m$</td>
<td>~200 s, ~210 s, ~180 s</td>
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Scrubbing 2014

- One week (October) + 3 days (December) dedicated scrubbing in the SPS
- High intensity test ($2 \times 10^{11}$ p/b)

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<tr>
<td>25 ns – High intensity</td>
<td>$~2.0 \times 10^{11}$ p/b</td>
<td>288 (4 x 72)</td>
<td>$\varepsilon_{H,V} &gt; 5.0 \mu$m</td>
<td>$~40$ s, $~30$ s, $~20$ s</td>
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Scrubbing 2014

- One week (October) + 3 days (December) dedicated scrubbing in the SPS
- High intensity test ($2 \times 10^{11}$ p/b)
  - Horizontal instabilities
Scrubbing 2014

- One week (October) + 3 days (December) dedicated scrubbing in the SPS
- High intensity test ($2 \times 10^{11}$ p/b)
  - Horizontal instabilities
  - Emittance growth
Scrubbing 2014

- One week (October) + 3 days (December) dedicated scrubbing in the SPS
- High intensity test (2e11 p/b)

Accumulated during Scrubbing Run 1 (October)

Signals measured with ~2.0 x 10^{11} p/b
Scrubbing 2015

- Two full weeks dedicated scrubbing in the SPS split in four blocks of 3.5 days

arc gauge 40660
Scrubbing 2015

- Two full weeks dedicated scrubbing in the SPS split in four blocks of 3.5 days
- Significant improvement of flat bottom transmission when injecting about $1.9 \times 10^{11}$ p/b – a combination of improved machine settings and scrubbing
- Remaining losses hopefully from beam loading

![Graph showing data](image)
High intensity studies in 2017

- Horizontal tune shift along the batch observed for intensities >6e10 p/b
  - Most likely due to electron cloud (to be confirmed in simulations)
High intensity studies in 2018

- 48 bunches of BCMS with $1.9 \times 10^{11}$ p/b injected show blow-up from e-cloud
High intensity studies in 2018

- Continuous emittance growth with 2e11 p/b measured with BGI
emittance blow-up of first batch over ~ 20 s reduced to about 15% after a few days of high intensity scrubbing
SPS machine configuration for scrubbing

- Fast vacuum valves blocked open (by vacuum piquet)
- Concentrate losses on the momentum scraper by horizontal bump
- Extraction elements off, ZSs at -30 kV
  - ZS sparking is expected to be less severe after LS2 due to ZS upgrade
- MKPL interlock levels to 6e-7 mbar (SW) and 7e-7 mbar (HW)
  - Heating (and related outgassing) will be a limitation after LS2 (see next slides)
Operational limitations from MKPL in 2015

Reached close to 55° after 2 days of high intensity scrubbing in 2015
Operational limitations from MKPL in 2018

- Reached high temperatures even without dedicated scrubbing, just from nominal operation and high intensity studies on Thursdays
Power loss in kickers as function of bunch length

![Graph showing power loss in kickers as a function of bunch length.](image)

- MKPL
- MKPS
- MKE (200 mm serigraphy)
- MKE (180 mm serigraphy)

N=2.6e11 ppb
Power loss in kickers along cycle

- MKPL [W/m]
- MKPS [W/m]
- MKE (180 mm serigraphy) [W/m]
- MKE (200 mm serigraphy) [W/m]
- Total number of protons [1e10]
- Bunch length [m/1e4]

Strong heating of MKPL expected at high beam energy (short bunches)

N=2.6e11 ppb
... confirms expected behavior (MKE on flat bottom more critical than MKPS while opposite on the ramp)
Conclusions

- Beam degradation from e-cloud as well as improvement due to scrubbing clearly observed in SPS
  - After LS1 it took 1 week to recover acceptable performance of nominal 25 ns beam
- When ramping up intensity, the stripes in dipole magnets move outside
  - Recrudescence of instabilities (both horizontal and vertical) and pressure rise
  - Scrubbing needed to condition these regions of the dipole chambers and therefore scrubbing time needs to be allocated for every “intensity step”
  - Scrubbing could be combined with beam setup and performance optimization of the high intensity LHC beams
- Dedicated scrubbing runs are affected by operational limitations
  - Kicker heating (in particular for MKPL) becoming much more severe for LIU intensities will prohibit scrubbing in long blocks and potentially makes scrubbing very inefficient
  - Scrubbing in parallel to North Area physics should become feasible thanks to ZS upgrade
THANK YOU FOR YOUR ATTENTION