Lessons from SPS studies in 2010

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session 09: LHC injectors upgrade
Outline

- Review of the SPS MD studies in 2010
- Expectations for possible SPS upgrades

Acknowledgments:


**LIU/TF:** R. Garoby, B. Goddard, V. Mertens

**TE/ABT:** M. Barnes, B. Balhan, R. Barlow, J. Borburgh, **BE/BI**

**PS&PSB teams and OP shifts** for help in MDs

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Questions

1. Source of limitations/bottlenecks (up to ultimate intensity)

2. Possible cures and mitigation measures

3. p/b and emittance as a function of the distance between bunches today and after upgrade

4. What should be done for delivering smaller transverse emittances at ultimate beam current?
Known intensity limitations and 2010 studies

- **Single bunch**
  - TMCI (transverse mode coupling instability)
  - loss of Landau damping
  - space charge
  - longitudinal instability

- **Studies with high (twice ultimate) intensities, nominal and small transverse emittances;** $\gamma_t=22.8$ (nominal) and $\gamma_t=18$ ("low") optics

- **Multi-bunch**
  - e-cloud → talk of J.M. Jimenez
  - beam loss (many reasons)
  - longitudinal coupled bunch instabilities
  - beam loading in the 200 MHz and 800 MHz RF systems
  - heating and outgassing of machine elements, septum (ZS) sparking

- **Studies with nominal 25, 50, 75, (150) ns spaced LHC beam, ultimate (injected) 25&50 ns spaced beam**
Very high intensity single bunch

- Many parallel MD sessions (B. Salvant et al.) → TMCI
- Injected bunch:
  - intensity up to $3.5 \times 10^{11}$
  - $\varepsilon_{H/V} \sim 1.3 \, \mu m$, then 2.5 $\mu m$
    (to reduce losses and emittance blow-up in SPS)
  - $\varepsilon_L = 0.35 \, eVs$, $\tau = 3.8 \, ns$
    (nominal LHC)
- Long. instability $N > 1.4 \times 10^{11}$
- Issue with MOPOS before BI upgrade at the end of run
Transverse Mode Coupling Instability (TMCI)

- TMCI threshold  \( \sim \varepsilon_L |\eta| \),
  \( \eta = 1/\gamma^2 - 1/\gamma_t^2 \)
- Cures:
  - higher chromaticity \( \xi_v \)
  - higher \( \eta \) (lower \( \gamma_t \))
  - larger \( \varepsilon_L \) (capture losses)
  - impedance reduction (if known)
  - wide-band FB (W. Hofle & LARP)

- End FB intensity \((2.25-3.3) \times 10^{11}\)
  for \( \xi_v = (0.05-0.3), \xi_H = 0.25 \)
- Emittance blow-up?

B. Salvant et al.

Threshold  \( \sim 1.6 \times 10^{11} \) for \( \xi_v \sim 0 \)
(close to prediction from the SPS transverse impedance model)

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Transverse emittance measurements in the SPS

• Measurements during the cycle and along batch(es) are essential to study origin of emittance blow-up (if any)

• Measurements with Wire Scanners (WS) in 2010:
  – Average for all bunches (no bunch-by bunch)
  – One measurement per cycle (difference between “in” & “out”)
  – First measurement at 10 ms after injection

• BI improvements for 2011 (L. Jensen):
  – new electronics for 2nd WS (linear, now broken) with possibility to gate acquisition (over 50-100 ns, as in the past)
  – cross-calibrations (WS 1&2, “in”&“out”, PS&LHC)
  – expert involvement (settings are critical) plus fellow(?)
  – BGI (rest gas) monitor – continuous beam profile measurements during cycle, average for all bunches over 20 ms
Transverse emittance vs bunch intensity for a single bunch

- Data from single bunch MDs in 2010 (C. Bhat, B. Salvant et al.,) + 50 ns beam (PS Double Batch, E. Metral et al., 2008)
- Settings optimised up to $2 \times 10^{11}$
- $\xi_V$ in range 0.0-0.3, $\xi_H$=0.25

nominal int. $\epsilon_{H/V} \sim 1.2 \mu m$
ultimate int. $\epsilon_{H/V} \sim 3.0 \mu m$

Linear fit:

$H: \epsilon = -1.14 + 2.22 \left( N/10^{11} \right)$
$V: \epsilon = -1.03 + 2.17 \left( N/10^{11} \right)$

→ Emittance blow-up above space charge limit ($N/\epsilon$=const)
# SPS MDs with LHC beams in 2010 – v1.9

<table>
<thead>
<tr>
<th>Week</th>
<th>Date</th>
<th>Spacing</th>
<th>Max. inj. intensity</th>
<th>Comments/Results</th>
</tr>
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<tbody>
<tr>
<td>17</td>
<td>27-29.04</td>
<td>25 ns</td>
<td>nominal</td>
<td>“scrubbing”, dedicated SC, 1-4 batches, low beam loss (5%)</td>
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<tr>
<td>22</td>
<td>02-03.06</td>
<td>25 ns</td>
<td>ultimate</td>
<td>36 h, part. dedic. SC, 1-3 batches</td>
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<tr>
<td>29</td>
<td>20-21.07</td>
<td>25 ns</td>
<td>nominal</td>
<td>practically lost</td>
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<tr>
<td>35</td>
<td>03-04.09</td>
<td>50 ns</td>
<td>ultimate</td>
<td>8 h, 4 batches</td>
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<tr>
<td></td>
<td></td>
<td>25 ns</td>
<td>nominal</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>19-20.10</td>
<td>25 ns</td>
<td>nominal</td>
<td>36-72 bunches; dedicated SC → 1-2 batches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 ns</td>
<td>nominal</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>09.11</td>
<td>50 ns</td>
<td>nominal</td>
<td>floating MD</td>
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<tr>
<td>46</td>
<td>17-18.11</td>
<td>75 ns</td>
<td>nominal</td>
<td></td>
</tr>
</tbody>
</table>
Ultimate 25 ns beam

- Large efforts in whole inject. chain
- Up to $1.9 \times 10^{11}$/bunch injected, $\varepsilon_L \sim 0.4$ eVs, $\varepsilon_{H/V} \sim 4.5/5 \, \mu$m
- Emittance blow-up $5 \rightarrow 10 \, \mu$m (larger in H-plane and for more batches) with $\xi_{H/V} = 0.2/0.3$
- Voltage increased during cycle $0.65 \rightarrow 0.75$ eVs to reduce losses & reduced on flat top: $7.2 \rightarrow 5.5$ MV to reduce outgassing and heating in kickers
- Beam unstable longitudinally on flat bottom with 12 bunches
- 36 hours MD – stopped due to MKE heating to 70 deg

Bunch intensity on flat top decreases with number of batches:
- $1.62 \times 10^{11}$ - 1 batch, $1.51 \times 10^{11}$ - 3

Beam losses: 30% → 20%
Ultimate 50 ns beam

- Only 8 h MD at the end of block - in || to LHC set-up (150 ns beam)
- $1.8 \times 10^{11}$/bunch injected $\rightarrow$ maximum $1.52 \times 10^{11}$/bunch on FT, 15% losses for ultimate intensity
- Nominal: $\varepsilon_{H/V} = 2.7/2.8 \, \mu m$ on FT
  ultimate: injected $\varepsilon_{H/V} = 3.2/3.9 \, \mu m$
- Voltage programme as for 25 ns nominal beam
- Increase in $\xi_{H/V}$ from (0.05/0.18) had no effect on losses
  $\rightarrow$ More time for optimisation in 2011

Bunch intensity on flat top vs injected bunch intensity

Losses increase with bunch intensity

J. Muller

28/01/2011

SPS lessons
Nominal LHC beams in 2010

Transverse emittance vs bunch intensity

- Nominal 50&75 ns beam: extracted emittances determined by injected with no/small blow-up

- Nominal 25 ns beam: blow-up PS ext. $\varepsilon_{H/V} = 2.0/1.5 \, \mu m \rightarrow SPS (t=0.55 \, s) \varepsilon_{H/V} = 3.2/3.3 \, \mu m$
  flat top: $\varepsilon_{H/V} = 3.2/3.6 \, \mu m$

- Larger emittances in V-plane

→ 50 ns and 75 ns beams: one can hope to get single-bunch emittances ($\sim 3 \, \mu m$ for ultimate intensity)

25 ns beam - can hope for same after e-cloud mitigation
Transverse emittances vs bunch spacing for the same total and bunch intensities

50 ns spacing

No emittance increase with n batches, small (<10%) blow-up during the cycle

25 ns spacing

Vertical emittance increase with n batches, measurement at 0.55 s (26 GeV)
e-cloud vs bunch intensity for 25&50 ns spacing (MD w35)

- A factor 3-5 difference between 25 ns and 50 ns beams
- Some increase of e-cloud current with intensity for 50 ns beam
Nominal LHC beams: beam quality issues

- **25 ns beam**
  - low (5%) losses (with low $\xi=0.1$)
  - heating and outgassing of kickers: MKDH3, MKP and MKE - limitation for dedicated MD cycle (or dedicated LHC filling)
  - no limitations from ZS after change of settings by ABT group

- **50 ns beam**
  - beam stability issue: need of controlled emittance blow-up in addition to the 800 MHz RF
Bunch length variation on flat top: effect of beam loading in the 200 MHz RF on emittance blow-up by band-limited noise

\[
V = V_t^{200} \sin \phi + V_t^{800} \sin(4\phi + \Phi_2 + \Delta \phi_2),
\]

\[
\Delta \phi_2 = 4\Delta \phi_s \text{meas} \left(1 + \frac{4V_t^{800}}{V_t^{200}(-\cos \phi_s)}\right)
\]

T. Argyropoulos et al., HB2010
Longitudinal multi-bunch instability: 50 ns beam, 2 RF, no controlled blow-up

Short PS bunches are unstable in SPS (450 GeV/c)

Long PS bunches
Multi-bunch instability due to loss of Landau damping?

- Narrow window for the injected parameters: losses increase for longer bunches and beam is unstable for lower emittance (blow-up required for 50&75 ns beams)

\[ \varepsilon = 0.46 \text{ eVs} \]

\[ \text{SPS transmission decreases for larger injected } \varepsilon \]

→ loss of Landau damping due to inductive impedance (MKE)
### Intensity limitations for 25 ns beam - 2010

<table>
<thead>
<tr>
<th>Intensity /bunch</th>
<th>Origin</th>
<th>Leads to</th>
<th>Present/future cures/measures</th>
</tr>
</thead>
</table>
| $0.2 \times 10^{11}$ | longitudinal multi bunch instability due to loss of Landau damping (longitudinal impedance) | - beam loss during ramp  
  - bunch variation on FT | (FB, FF, long. damper)  
  - 800 MHz RF system  
  - emit. blow-up $\to$ RF  
  - low $\gamma_t$ optics |
| $0.7 \times 10^{11}$ | e-cloud due to the StSt vacuum chamber ($\delta_{SEY}=2.5$, 1.3 is critical for SPS) | - dynamic pressure rise  
  - transv. (V) emit. blow-up  
  - instabilities  
  - losses (via high chrom.) | - scrapping run ($\delta\to1.6$)  
  - high chrom. (0.2/0.4)  
  - transv. damper (H)  
  - (50/75 ns spacing)  
  - coating ($\delta\to1.0$) |
| $1.3 \times 10^{11}$ | not known exactly e-cloud, impedance, space charge, beam loading | - flat bottom/capture beam loss (>5%) | - (lower chromaticity)  
  - WP, RF gymnastics  
  - collimation |
| $1.5 \times 10^{11}$ | beam loading in 200 MHz RF system | - voltage reduction on FT  
  - phase modulation | - feedback & FF  
  - RF cavities shortening |
| $1.6 \times 10^{11}$ | TMCI (transverse mode coupling instability) due to transverse impedance | - beam losses  
  - emittance blow-up | - higher chromaticity  
  - low $\gamma_t$ optics  
  - transverse high bw FB |

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SPS lessons
Low $\gamma_t$ - solution for everything?

• Successful MDs with a single bunch (H. Bartosik, Y. Papaphilippou et al.): $\gamma_t = 22.8 \rightarrow 18$, increase in $\eta$: 2.86 @26 GeV/c and 1.6 @450 GeV/c

• Expected increase in beam stability for the same bunch parameters $N_{th} \sim \eta$ for TMCI (observed!) and longitudinal instabilities (to be seen in 2011)

• For the same parameters: $V \sim \eta$. Already maximum voltage (7.5 MV) is used now for extraction to LHC $\rightarrow$ longer bunches for the same emittance and voltage $\rightarrow$ 200 MHz RF upgrade should help

• But probably emittance blow-up for the same intensity can also be reduced: loss of Landau damping $N_{th} \sim \varepsilon^2 \eta \tau$. Since $\tau \sim (\varepsilon^2 \eta/V)^{1/4} \rightarrow \varepsilon \sim \eta^{-1/2}$ and $\tau = \text{const}$ for $V=\text{const}$

Issues:
• If LHC itself needs higher longitudinal emittances at injection
• Fast cycles in SPS

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Some MD results for low $\gamma_t$

No TMCI up to $3.2 \times 10^{11}$

Small transverse emittances

- **FB**: no transverse blow-up for
  - $\varepsilon_{H/V} = 2.0/2.3, \ 2.6 \times 10^{11}$
  - $\varepsilon_{H/V} = 2.5/2.6, \ 3.3 \times 10^{11}$
  but too low voltage (1.8 MV) $\rightarrow$ losses (10-15%) and longer bunch ($\sim 30\%$?)
- **Acceleration** of $2.5 \times 10^{11}$
  - 5% capture losses
  - $\varepsilon_{H/V} = 2.4/2.9$
  - $\tau = 1.5$ ns on FT
  $\rightarrow$ Studies with nominal and ultimate LHC beams (long. beam stability)

H. Bartosik et al.

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What is the SPS space charge limit at 26 GeV/c?

Single bunch data with nominal ($\gamma_t = 22.8$) and “low $\gamma_t$” optics ($\gamma_t = 18$)

“Low $\gamma_t$” data scaled by 30% in intensity (for low $V$ and losses) - linear fit: $\varepsilon = 1.4 \left( N/10^{11} \right)$

→ space charge limit $\Delta Q_{sc} > \sim 0.13$
(nominal LHC beam $\Delta Q = 0.05$)

→ preliminary results, accurate measurements in 2011

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## LHC beams in SPS

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>SPS @ 450 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nom.</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>ns</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>max bunch intensity</td>
<td>(10^{11})</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>number of bunches</td>
<td>4x72</td>
</tr>
<tr>
<td>total intensity on FT</td>
<td>(10^{13})</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>long. emittance</td>
<td>eVs</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>norm. h/v emittance</td>
<td>μm</td>
</tr>
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</tbody>
</table>

* double batch injection in PS: 1.1/1.4

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SPS lessons
Main lessons/results from 2010

- **Nominal 25 ns** beam in good shape: low beam losses (5%) with low $\xi_v = 0.1$
- **Ultimate** (injected) beam - needs studies
  - 25 ns: large losses and emittances, instabilities
  - 50 ns: 15% losses, $1.5 \times 10^{11}$/bunch at 450 GeV/c in 4 batches
- **TMCI threshold** is at ultimate intensity (low $\xi$). Ultimate single bunch accelerated to 450 GeV/c with low loss and $\xi_v$, but with some emittance blow-up. More problems for small injected emittances.
- **New low $\gamma_t$ optics**: promising results for beam stability and brightness
- **Loss of Landau damping** for small inj. long. emittances, bunch length variation on flat top after controlled emittance blow-up in 2 RF

Limitations for dedicated LHC filling/MD: MKE, MKP, MKDH3 heating/outgassing

MDs issues: transverse emittance measurements, time allocation, data analysis

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SPS lessons
Conclusions - Q&A

• \( p/b \) and emittance as a function of the distance between bunches today and after upgrade
  - now one can hope to get single-bunch emittances for 50&75 ns beams with 3 µm for ultimate intensity; probably less (2.5 µm) with low \( \gamma_t \) (RF voltage limit to be seen); > 4 µm for 25 ns ultimate beam
  - after upgrades (e-cloud and impedance reduction) one can hope to be at the space charge limit (≈2.5 µm for ultimate intensity) for 50&25 ns beams
• what should be done for delivering smaller transverse emittances at ultimate current?
  - studies, smaller PS beam, improvement of trans. emittance measurement
  - e-cloud mitigation, transverse impedance reduction, strong transverse FB
  - low \( \gamma_t \) optics with 200 MHz RF upgrade
Spare slides
Some data for space charge

- ppbar time - $\Delta Q = 0.07$
- Protons at 14 GeV/c (H. Burkhardt et al., PAC 2003) $\Delta Q = 0.14/0.18$ with 10% losses ($N = 1.2 \times 10^{11}$, 3 ns, $\varepsilon_{H/V} = 3.43/3.75 \, \mu m$)
- Nominal LHC bunch $\Delta Q = 0.05$, ultimate $\Delta Q = 0.07$
- 50 ns nominal intensity beam with single batch injection in PS (2008): $\varepsilon_{H/V} = 1.1/1.4 \, \mu m$ at 450 GeV/c (E. Metral) $\rightarrow \Delta Q = 0.15$
- Recent studies with high intensity single bunch (B. Salvant et al., 2010) $2.5 \times 10^{11} \rightarrow \Delta Q = 0.1$ for $\varepsilon = 3.5 \, \mu m$
- LHC ions in the SPS: $\gamma = 7.31$, $N_e = 1.5 \times 10^{10}$, (50% more than nominal), $\varepsilon = 0.5 \, \mu m$ (1/2 nominal). In DR $\Delta Q = 0.08 \rightarrow \Delta Q = 0.24...$ but with 25% losses
  $\rightarrow$ Space charge limit alone seems to be more close to $\Delta Q = 0.15$

Interplay with other effects (multi-bunch) is probably also important
e-cloud build-up for low emittances

C. Octavio Domínguez, Giovanni Rumolo, Frank Zimmermann

Simulations with $B=0.117$ T, 50 ns beam, $SEY=1.6$, $R=0.7$
e-cloud build-up for low emittances
C. Octavio Domínguez, Giovanni Rumolo, Frank Zimmermann

Simulations with $B=2.025$ T, 50 ns beam,
SEY=1.7, R=0.7
SPS scrubbing run in 2002

First measurement in SPS 10 ms after injection - G. Arduini
Possible issues with controlled longitudinal emittance blow-up

50 ns beam

Non-uniform emittance blow-up due to beam loading in a double RF system

75 ns beam

Non-uniform emittance blow-up and beam instability (?) for short injected bunches

T. Argyropoulos et al.

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SPS lessons
Nominal and low $\gamma_t$ optics
(H. Bartosik, Y. Papaphilippou)

- Nominal working point for LHC beams (Q26):
  $Q_x = 26.13$, $Q_y = 26.18$, $y_t = 22.8$,
  $\eta(\text{@26GeV}) = 0.63E-3$,
  maximal horizontal dispersion $\sim 4.8m$

- New working point for LHC beams (Q20):
  $Q_x = 20.13$, $Q_y = 20.18$, $y_t = 18$,
  $\eta(\text{@26GeV}) = 1.8E-3$,
  maximal horizontal dispersion $\sim 8m$