SPS collective effects and limitations

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http://cern.ch/spsu/
LHC beams in the SPS: acceleration from 26 to 450 GeV/c

Maximum intensity achieved (1-4 batches) at 450 GeV/c:

- single bunch – 3.0x10^{11}
- 50 ns beam (2011) - 1.8x10^{11} p/b (not stabilized), beam losses ~ 10%
- 25 ns beam (2010): injected 1.9x10^{11} p/b, losses ~ 20-30% (more for more batches)
### SPS beams in 2011

#### Beam parameters

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

* Q20 optics
Intensity and beam quality (BQM!) limitations

• Single bunch effects
  – space charge → working point optimisation (H. Bartosik et al. + study of G. Franchetti, GSI)
  – TMCI (Transverse Mode Coupling Instability)
  – loss of Landau damping
  – longitudinal/microwave instability

• Multi-bunch effects (total intensity or local density)
  – e-cloud
  – beam loss (many possible reasons) → PS-SPS beam transfer studies
  – longitudinal coupled bunch instabilities
  – beam loading in the 200 MHz and 800 MHz RF systems
  – heating of machine elements (MKE, MKDV kickers, ...)
  – vacuum (beam dump and MKDV outgassing), ZS septum sparking
## Intensity limitations for 25 ns beam - 2011

<table>
<thead>
<tr>
<th>Intensity /bunch</th>
<th>Origin</th>
<th>Leads to</th>
<th>Present/future cures/measures</th>
</tr>
</thead>
</table>
| 0.2x10^{11}      | loss of Landau damping / longitudinal multi bunch instability due to longitudinal impedance | - beam loss during ramp  
- bunch variation @450GeV/c | FB, FF, longitud. damper  
- 800 MHz RF system  
- emit. blow-up → RF |
| 0.5x10^{11}      | e-cloud due to the StSt vacuum chamber (δ_{SEY}=2.5, 1.3 is critical for SPS) | - dynamic pressure rise  
- transv. (V) emit. blow-up  
- instabilities  
- beam losses | - scrubbing run (δ→1.6)  
- high chrom. (0.2/0.4)  
- transv. damper (H)  
- (50/75 ns spacing)  
- a-C coating (δ→1.0) |
| >1.2x10^{11}     | beam loading / ecloud / impedance / space charge (?) | - flat bottom/capture beam loss (>5%) | - (lower chromaticity)  
- WP, RF gymnastics  
- collimation |
| 1.5x10^{11}      | beam loading in 200 MHz RF system | - voltage reduction on FT  
- b-by-b phase modulation | - Feedback & FF  
- RF cavities shortening |
| 1.6x10^{11}      | TMCI (transverse mode coupling instability) due to transverse impedance | - beam losses  
- emittance blow-up | - higher chromaticity  
- high voltage  
- transverse high bw FB |
Cures

- Understanding the limitations: MD studies, simulations, calculations
- Impedance identification and reduction (MKE kickers, MKDV, 200 MHz RF)
- Low $\gamma_t$ (Q20 optics) → talk of H. Bartosik
- e-cloud mitigation → talk of M. Taborelli
- Upgrade of the 200 MHz RF system → talk of E. Montesinos
- Landau cavities (800 MHz RF system)
- Controlled longitudinal emittance blow-up
- High bandwidth transverse feedback (e-cloud, TMCI)
• injected emittance is increasing with intensity (~ 30%)
• emittance blow-up in SPS above 2x10^{11}, more in H-plane
Transverse Mode Coupling Instability

- **Measurements** (B. Salvant et al.): threshold @26 GeV/c - $1.6 \times 10^{11}$ for $\xi_V = 0$ ($\varepsilon_L = 0.35$ eVs, $\tau = 3.8$ ns); $(2.25-3.3) \times 10^{11}$ for $\xi_V$ in range 0-0.3, $\xi_H = 0.25$

- Threshold scales (matched $V$) $\sim \varepsilon_L \eta$, where $\eta = 1/\gamma^2 - 1/\gamma_t^2$

- **Cures:**
  - high $\xi_V$, $\varepsilon_L$ and $\eta \rightarrow$ lower $\gamma_t$ (Q20 optics!)
  - impedance reduction... but $\sim 30\%$ of transverse SPS impedance is still unknown $\rightarrow$ ongoing work (B. Salvant et al.)
  - transverse wide-band FB (W. Hofle et al. with LARP)
SPS impedance

• Reduce known high impedance → loss of Landau damping, heating
  ▪ MKE: serigraphy – the last after LS1 (M. Barnes et al.)
    Transverse impedance issue. New design (B. Goddard)?
  ▪ MKDV, MKDH: complete transition pieces between magnet and tank
    (heating, outgassing)
  ▪ 800 MHz TW cavities: active damping → new FB and FF (2014?)
  ▪ 200 MHz TW cavities: reduction by 20% due to modifications

• Search for unknown impedances:
  ▪ transverse (broad-band and narrow-band)
  ▪ longitudinal (narrow-band?)
Longitudinal impedance: reactive part

- Kickers - main contribution to $\text{Im} Z \to$ loss of Landau damping
- Not much room for extra impedance,
- Similar for resistive impedance (stable phase shift measurements)

Quadrupole synchrotron frequency shift

- Simulations
- Measurements

slope $b$
Longitudinal multi-bunch instability and its cures

• Threshold: reduces with energy ~1/E, single batch (25 ns spacing) with $2 \times 10^{10} \text{p/b}$ is unstable at the end of the ramp, beam is lost at nominal intensity

Possible source: fundamental /HOMs of 200 MHz or 800 MHz RF systems

Cures:
- FB, FF, longitudinal damper for 200 MHz
- 800 MHz RF system in bunch shortening mode through the cycle, $V_{800} \sim 0.1 \times V_{200}$, $V_{800} \sim 0.15 \times V_{200}$ in the last MD
- controlled longitudinal emittance blow-up ($0.35 \rightarrow 0.42 \text{ eVs} \rightarrow 0.65 \text{ eVs}$)

T. Bohl et al.
Emittance blow-up by band-limited noise: intensity effects

Synchrotron frequency distribution is modified by potential well distortion and beam loading (depending on bunch position in the batch) effects.

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

T. Argyropoulos et al., HB2010
Longitudinal multi-bunch instability due to loss of Landau damping

Short PS bunches

Long PS bunches

T. Argyropoulous et al.
PS-SPS transfer: capture loss - measurements

(a) Transmission PS \rightarrow SPS

(b) Bunch length in PS

Experimental results: MD measurements from July 2011

H. Damerau et al.
PS-SPS transfer: capture loss - simulations

• PS RF gymnastics simulated with measured particle distribution (H. Timko)
  → Measured SPS transmission is reproduced with 20% emittance blow-up!
• different bunch lengths but similar emittances; SPS: V = 2 MV
• no intensity effects, beam loading or injection phase errors
Low $\gamma_t$ (Q20) optics

For the same longitudinal parameters required $V \sim \eta$
- limit at 450 GeV/c to 7.5 MV
  $\rightarrow$ 200 MHz RF upgrade
  $\rightarrow$ more 800 MHz voltage also

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 $V=\text{const}$. 
800 MHz needed for both cycles
In Q20 instability starts later but controlled emittance blow-up (smaller) is still required
Losses ~ (8 – 9)%

T. Argyropoulos et al.
MD Nov. 2011
Q26 – 1.49 ns
Q20 – 1.53 ns
200 MHz TW RF system upgrade

Voltage/cavity on Flat Top

- Now: 2x4+2x5 sections
- Power/cavity (E. Montesinos):
  - 1.05 MW pulsed
- 5-section cavities are useless for ultimate intensities and 1 MW limit
- 7.5 MV used @450 GeV for beam transfer to LHC → more V needed for higher intensities (larger emittance)

→ Rearrange 4 cavities (+ 2 spares) into 6 shorter cavities of 2x4+4x3 sections with 2 extra power plants to
  - reduce beam loading/cavity and beam coupling impedance (∼L^2)
  - restore voltage for ultimate beam
  - more voltage for Q20 optics

Total voltage on Flat Top

- Voltage/cavity on Flat Top
- Total voltage on Flat Top
- τ = const

25/11/2011

LIU Day
Summary

• High bunch intensities were achieved in 2011 for 50 ns beam
• Beam loss is important limitation for high intensity beams
• More MD time needed for optimisation of high intensity and high brightness beams
• Cures for longitudinal instability (800 MHz and emittance blow-up) are limited – need additional improvements (e.g. Q20, impedance reduction)
• MKE kickers give dominant contribution to longitudinal broadband impedance, improvement is expected after LS1
• Q20 optics is a very promising solution for beam stability, need more optimisation, transfer to LHC should be studied
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