Long-term beam losses in the CERN injector chain

S. Gilardoni – CERN –BE/ABP

In collaboration with:
LHC injectors (today vs tomorrow)

- Present
  - LHC injectors
  - Linac 2
  - Linac 4
  - PSB
  - PS
  - SPS
  - LHC / HL-LHC

- LIU (2019)
  - Proton flux / Beam power
    - 50 MeV
    - 160 MeV
    - 1.4 GeV
    - 2.0 GeV
    - 26 GeV
    - 450 GeV
    - 7 TeV

Linac2
PSB
PS
SPS
LHC / HL-LHC
To LHC

LHC injectors (today vs tomorrow)

LHC-type beams: maximum intensity with minimum emittance compatible with the collider needs.

Proton flux / Beam power

Present LIU (2019)

50 MeV Linac2 Linac4
160 MeV
1.4 GeV PSB PSB
2.0 GeV
26 GeV PS PS
450 GeV SPS
7 TeV LHC / HL-LHC

Output energy
High intensity beams: maximize protons on target, minimizing losses (emittance compatible with machine apertures)
LHC and Injectors – 50 ns

1 SPS batch (144 bunches)

1 PS batch (36 bunches)

2012-2013 LHC - 26.7 km - 1380 bunches – 50 ns

- Field in main magnets
- Proton beam intensity (current)
- Beam transfer

SPS

PS

PSB

1.2 seconds

450 GeV

26 GeV

1.4 GeV

To LHC

Abort gap

Tim
LHC25(50)ns Production Scheme

Production scheme:
a) Double batch injection from PSB (4 + 2 bunches, 6 bunches for PS at h=7)
b) Up to 4 batches of 72 bunches each transferred to the SPS (288 bunches)

Transverse emittance produced in the PSB, longitudinal in the PS

- Multi-turn proton injection in PSB
- RF gymnastics in PS:
  - Triple splitting
  - Acceleration
  - 2 x Double splittings
    - (1 Double splitting for 50 ns)
  - Bunch rotation

- 3 RF systems in PSB
- 5 RF systems in PS
- 2 RF systems in SPS

→ Each bunch from the Booster divided by $12 \rightarrow 6 \times 3 \times 2 \times 2 = 72$
LHC 25(50)ns BCMS

Production scheme:
- a) Double batch injection from PSB (4 + 4 bunches, 8 bunches for PS at \( h = 9 \))
- b) Up to 5 batches of 48 bunches each transferred to the SPS (240 bunches)

**Transverse emittance produced in the PSB, longitudinal in the PS**
- Multiturn proton injection in PSB with **shaving**
- RF gymnastics in PS:
  - Batch compression
  - Bunch merging
  - Triple splitting
- Acceleration
- 2 x Double splittings
  (1 Double splitting for 50 ns)
- Bunch rotation
<table>
<thead>
<tr>
<th>Schemes 25 ns</th>
<th>PSB – PS bunches</th>
<th>RF gym. in PS</th>
<th>RF gym. at injection</th>
<th>RF gym. at extraction</th>
<th>b/Train to SPS</th>
<th>SPS injections</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-spitting (standard scheme)</td>
<td>4 + 2</td>
<td>/3 ↗ /2 /2</td>
<td></td>
<td></td>
<td>72</td>
<td>4</td>
</tr>
<tr>
<td>BCMS</td>
<td>4 + 4</td>
<td>+2C/3 ↗ /2 /2</td>
<td></td>
<td></td>
<td>48</td>
<td>5</td>
</tr>
<tr>
<td>BCS</td>
<td>4 + 4</td>
<td>C ↗ /2 /2</td>
<td></td>
<td></td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>8b+4e</td>
<td>4 + 2</td>
<td>/2 ↗ /2 /2</td>
<td></td>
<td></td>
<td>48</td>
<td>5</td>
</tr>
</tbody>
</table>

/ Splitting | C Batch Compression | + Merging | ➤ Acceleration to 26 GeV/c
The SPS was delivering 450 kW peak power on target, 350 kW on average.

The number of protons taken by LHC during 2012 is less than the number of protons lost in the injectors for CNGS.

In the PS, about 8-12% of the total CNGS intensity is lost.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Protons delivered</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNGS</td>
<td>3.9x10^{19}</td>
<td>79.6%</td>
</tr>
<tr>
<td>LHC type</td>
<td>1.1x10^{18}</td>
<td>2.3%</td>
</tr>
<tr>
<td>rest</td>
<td>8.9x10^{18}</td>
<td>18.1%</td>
</tr>
<tr>
<td>Total</td>
<td>4.9x10^{19}</td>
<td></td>
</tr>
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</table>

* RP survey 2012
The complex in few numbers

<table>
<thead>
<tr>
<th></th>
<th>Operation</th>
<th>Record</th>
<th>After LIU (2020)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LHC</td>
<td>CNGS</td>
<td>LHC</td>
</tr>
<tr>
<td>SPS beam energy [GeV]</td>
<td>450</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>50</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Bunch intensity ([10^{11}])</td>
<td>1.6</td>
<td>0.105</td>
<td>1.3</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>144</td>
<td>4200</td>
<td>288</td>
</tr>
<tr>
<td>SPS beam intensity ([10^{13}])</td>
<td>2.3</td>
<td>4.4</td>
<td>3.75</td>
</tr>
<tr>
<td>PS beam intensity ([10^{13}])</td>
<td>0.6</td>
<td>2.3</td>
<td>1.0</td>
</tr>
<tr>
<td>PS cycle length [s]</td>
<td>3.6</td>
<td>1.2</td>
<td>3.6</td>
</tr>
<tr>
<td>SPS cycle length [s]</td>
<td>22.8</td>
<td>6.0</td>
<td>21.6</td>
</tr>
<tr>
<td>PS momentum [GeV/c]</td>
<td>26</td>
<td>14</td>
<td>26</td>
</tr>
</tbody>
</table>
PSB intensity limitations

- Losses during injection process:
  - Conventional multi-turn injection (40-50% losses)
  - Losses at injection septum and longitudinal capture
- Space charge (losses, emittance blow up)
PSB intensity limitations

- Losses during injection process:
  - Conventional multi-turn injection (40-50% losses)
  - Losses at injection septum and longitudinal capture
- Space charge (losses, emittance blow up)
- Instabilities along the cycle (efficiency of the transverse feedback)
- Brightness from PSB limited for LHC beams but no issue with intensity
PSB: choice of working point (I/II)

Before 2005

- Injection
- Ejection

Graph showing:
- Design intensity
- Np 4 rings / 10^13
- Various Q values
- Various years (1972 to 2012)
- Milestones:
  - Tune 4.2-5.3
  - New linac
  - 2nd harmonic cavities
  - Beam-loading feedback
  - h = 1+2 Ring 2 the champion
  - Tune 4.2-4.3 all rings > 10^13

11/25/2014

Document reference 14
Choice of working point (II/II)

Low WP 4,17 4,23

- $2Q_v=9$
- $2(Q_h-Q_v)=0$
- All 3rd order resonances, No syst.

High WP 4,17 5,23

- $2Q_v=11$
- Systematic $3Q_v=16$
- $Q_h-Q_v=-1$
H.W.P. versus L.W.P.

- HWP: R2 good performances; two bad: R1 and R4
- LWP: quasi all rings equal. 5% more intensity.
- LWP: orbit correction needed and done, change vertical shaving dipole and Transfer line matching.
- Strength and effects of resonances are much smaller especially for outer rings
- Limitation: Montague resonance
- Vertical emittance of the LHC beam is a bit larger.
PSB R2 resonance compensation and tr. feedback regulation effects at 160 MeV

• The PSB presents visible resonances up to the sextupolar order in the working area.
• Multipoles are present to compensate them...

**Bare machine**

- \[Q_x + 2Q_y = 13\]
- \[2Q_x + Q_y = 13\]
- \[2Q_y = 9\]
- \[Q_x - Q_y = 0\]
- \[Q_x = 4\]
- \[Q_y = 4\]

\[3Q_y = 13\]
PSB R2 resonance compensation and tr. feedback regulation effects at 160 MeV

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Bare machine… …after few iterations…

Beam instability
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Bare machine…

…after few iterations…

Beam instability
PSB R2 resonance compensation and tr. feedback regulation effects at 160 MeV

- The PSB presents visible resonances up to the sextupolar order in the **working area**.
- Multipoles are present to compensate them...

Bare machine...

...after few iterations...

...the final result.

Beam instability

...cured adjusting the tr. feedback...

End September 2014 tests

See E. Benedetto talk
PSB R2 long term losses by space charge

- Big effort to evaluate losses due to space charge (main bottleneck in the machine) and resonance lines interactions (like the $2Q_y=9$ half-integer).
- Optimization of the optics model through beam-based measurements.

Reference:
V. Forte et al., “CERN PS Booster Space Charge Simulations with a Realistic Model for Alignment and Field Errors”, IPAC’14, Dresden, Germany, TUPRI029
PS brightness limitations overview

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

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

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**Flat top:**
- Longitudinal CBI → New damper
- Electron cloud → Transverse FB
- Transverse instabilities → Transverse FB
PS brightness limitations overview

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
$N_b = 2 \times 10^{11} \text{ ppb} \rightarrow 3 \times 10^{11} \text{ ppb with new feedback}$

Injection flat bottom:
Space charge $\rightarrow$ Injection @2GeV
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Longitudinal CBI $\rightarrow$ New damper
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Transverse instabilities $\rightarrow$ Transverse FB

26 GeV/c

Acceleration/Bunch splittings
Longitudinal CBI $\rightarrow$ New damper
Transient beam loading
Transition crossing $\rightarrow$ New damper

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Injection flat bottom:
Space charge $\rightarrow$ Injection @2GeV
Headtail instability $\rightarrow$ Transverse FB
Space-charge: current limitations

The beam tune-spread is trapped between the 4Qy=25 and the integer.

- If one increases the vertical tune to avoid emittance growth due to the integer, the beam loss increases because of the 4\textsuperscript{th} order resonance

- Choice of working point is a compromise between beam loss and emittance blow-up
4Qy resonance mitigation

- The preferred hypothesis is that the 4\(^{th}\) order resonance is a **structure resonance driven by space charge**.

- The resonance is driven by the space charge force modulation which has a harmonic (8x6.25=50) of the symmetry of the machine (50x "FD DF")

\[\Rightarrow\] If one **changes the vertical integer tune**, then the space charge harmonic should be different from the lattice one, and shouldn’t be excited anymore. (ex: 8\(^{*}\)7.25=58).

- A proposed mitigation is under-study, where the integer tunes are changed from (6,6) to (5,7). A measurement campaign started in 2014 and the first results seem to be very promising.

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8\(\geq\)Q\(v\)\(\geq\) 7 closed orbit

6\(\geq\)Q\(x\)\(\geq\) 5 closed orbit

Measured closed orbit with the split tunes optics
PS Limitations for high-intensity beams: what we learned from the CNGS run

Injection
- losses due to optics
- losses due to oscillations
- 1.4 GeV

Acceleration
- RF voltage limited at transition
- TMCl instabilities at transition
- 14 GeV/c

Extraction
- losses due to extraction mechanism
- CT/MTE

Magnetic field [G]

Time [ms]
Injection oscillations at PS injection

- Fast buildup of intra-bunch oscillations (few turns after injection)
- Oscillations primarily observed in vertical plane
  - PSB recombination is in the vertical plane
- Oscillations contribute to beam loss at injection
- Visible each time the beam is injected
- Effect due to image charges/currents (indirect space charge) associated to an injection error

\[ I_p = 375 \cdot 10^{10} \text{ ppb (Meas.)} \]

\[ I_p = 700 \cdot 10^{10} \text{ ppb (Meas.)} \]

Simulations
Injection oscillations: comparison

measurement

simulation
Injection oscillations: comparison

**Measurement**

**Simulation**

![Graphs showing measurement and simulation results for injection oscillations.](image)
Last week results

Injection oscillations observed also on LHC-beams. Damper can effectively cope with that.
Continuous Extraction (CT, 70’s): the principle

- Horizontal tune set to 6.25 phase advance per turn of 90°.
- The beam is de-bunched (PS main RF - 10 MHz, SPS main RF 200 MHz)
  - Capture losses at SPS injection
- A part of the proton beam is pushed by a slow and a fast bumps beyond the blade of an electrostatic septum.
  - Instantaneous losses around the ring due to scattering with septum blade
- The sliced beam that receives the kick of the electrostatic septum is extracted during the current machine turn. The rest is extracted with the same mechanism within the next 4 turns.
- The five beam slices feature the same intensity but different optical parameters.
  - Mismatch at SPS injection
PS Multi-Turn Extraction experiment, 20-11-2006
Depleting the beam core via unstable resonance excitation

MTE: Multi-Turn extraction

Time: 900 ms
Qx = 6.2470
Qy = 6.2898

Straight Section 54
I = 2.6E12 ppb

Core

BWS 54
1.6 \times 10^{13} 16/12/09
SPS limitations overview – LHC beams
SPS limitations overview – LHC beams

Injection flat bottom:
Capture losses, incoherent losses
Space charge
TMCI
SPS limitations overview – LHC beams

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

Along the whole cycle:
Electron cloud for 25 ns
SPS limitations overview – LHC beams

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 – LHC beams

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

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

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
\[ N_b = 1.3 \times 10^{11} \text{ ppb} \rightarrow 2 \times 10^{11} \text{ ppb} \text{ with RF upgrade and a-C} \]
Space charge tune shift – SPS

- 50 ns BCMS beam on LHC filling cycle
  - Single batch with $N \sim 2 \times 10^{11}$ p/b @inj. and $\varepsilon_n \sim 1.1 \mu$m
  - Measurements for different tunes
  - Average of 5 measurements at the end of flat bottom
  - No (vertical) blow-up for $Q_y \geq 0.21 \rightarrow$ consistent with expected tune shift

Expect (Q20)
$\Delta Q_x \sim 0.11$
$\Delta Q_y \sim 0.20$
Space charge tune shift – SPS

- 50 ns BCMS beam on **LHC filling cycle**
  - Single batch with \( N \sim 2 \times 10^{11} \) p/b @inj. and \( \varepsilon_n \sim 1.1 \mu m \)
  - Measurements for different tunes
  - Average of 5 measurements at the end of flat bottom
  - No (vertical) blow-up for \( Q_y \geq 0.21 \rightarrow \) consistent with expected tune shift

- **Measurement at end of flat bottom with 3 BCMS batches**
  - Similar emittances for all batches (different storing times)! **Transmission around 95% (without scraping)**
  - During LHC filling with BCMS beam had even \( \Delta Q_y = 0.21 \rightarrow \) considered as present maximum

\[
\Delta Q_x \sim 0.11 \\
\Delta Q_y \sim 0.20
\]

---

**Bunch-by-bunch Wire Scanner measurements not calibrated**
Capture loss due to PS bunch shape (after rotation in longitudinal phase space)

Shape can be improved by higher PS voltage: => tails are less populated but losses are there!

H. Timko et al., ESME simulations of realistic bunch distribution from PS tomography (no intensity effects included)

Capture losses: un-captured beam after injection

Uncaptured beam is always moving to the left. Energy loss ($dp/p < 0$) due to resistive impedance?

Injection at 26 GeV/c

A few seconds later
SPS 200 MHz travelling wave RF cavities

- **Present situation:**
  - 2 cavities of 5 sections
  - 2 cavities of 4 section

- **Power/cavity limit**
  - Presently 0.7 MW (continuous mode)
  - Around 1.05 MW for ½ ring in pulsed mode with new LLRF

- **Beam loading: less voltage available for higher intensity!**
  - 5-section cavities are less efficient for high intensity due to beam loading

- **Upgrade:**
  - rearrange the 4 existing cavities into 6
    - 2x4+4x3 = 20 sections, with 2 spare sections
    - gives also 20% less impedance
  - 2 additional new power plants with 1.6 MW each
Estimation of maximum intensity from SPS

- Present situation: 4 cavities, 0.7 MW & 7.5 MV available → $1.3 \times 10^{11}$ p/b

- Higher voltage required for higher intensity
  - larger $\epsilon_i$ to avoid loss of Landau damping (LD): $V \sim N$
  - to compensate potential well distortion (PWD): $V \sim N$

Otherwise longer bunches at extraction and losses in LHC
Estimation of maximum intensity from SPS

• Present situation: 4 cavities, 0.7 MW & 7.5 MV available → 1.3x10^{11} p/b

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• After LLRF upgrade: 4 cavities, 1.05 MW pulsing → 1.45x10^{11} p/b

• After full RF upgrade: 4 cavities with 1.05 MW & 2 cavities with 1.6 MW → 2.0x10^{11} p/b

Scaling to preserve bunch length at extraction based on presently achieved performance and understanding of stability scaling ...

[further details in the presentation of H. Damerau]
Estimation of maximum intensity from SPS

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Scaling to preserve bunch length at extraction based on presently achieved performance and understanding of stability scaling ...

Ongoing efforts within LIU SPS to identify impedance sources in view of possible impedance reduction campaign, but not easy!

\[ V \text{ for } \tau = \text{ const} \quad (LD \& PWD) \]

"further details in the presentation of H. Damerau"
e-cloud: 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
Bunch length along the batch during cycle for high intensity beam

5.6x10^{13} injected, 15% losses

(AB-Note-2005-034 RF, T. Bohl et al.)
Nominal CNGS Cycle

- Injected beam is practically debunched
- Bunches not well defined after injection

Beam structure after injection

Bunch Length

Average and min-max for each frame

- transition
- instability at the end of the cycle

C. Lazaridis
Reducing beam losses

- Losses due to instabilities around 2.8 s in the cycle
  - Maximum 200 MHz RF voltage
- Tried reducing voltage to improve stability
  - Constant bucket area
  - Increasing synchrotron frequency spread inside the bunch

For intensities ~$3.7 \times 10^{13}$ losses are 3.5%
⇒ 0.2% reduction in high-energy losses
Summary injectors losses

- LHC beam losses produced by:
  - Space charge at injection (PSB – PS – SPS)
  - Transverse instabilities (PSB – PS)
  - Longitudinal instabilities (PS – PSB)
  - Insufficient RF power (SPS)
  - Not optimized bunch shape at transfer (PS → SPS)

- High intensity beam losses produced by:
  - Mechanical aperture (PSB – PS – SPS) and optics mismatch at injection (PS → SPS)
  - Beam instabilities (or oscillations PSB → PS)
  - Extraction mechanism (PS → SPS)
  - Absence of bunch-to-bucket transfer (PS → SPS)