COLLECTIVE EFFECTS IN THE LHC AND ITS INJECTOR COMPLEX

Elias Métral (Invited talk, THYB03, 25 + 5 min, 26 slides)

Dedicated to Dieter Möhl (my PHD thesis director) who passed away last night. Many thanks for all!

- Introduction and main challenges
- Best results so far and main limitations from collective effects
  - LHC INJECTORS: LINAC2 (4), PSB, PS, SPS
  - TUXA02 (R. Garoby)
  - LHC MOXBP01 (S. Myers), THPPP020
- Some (nice) pictures
- Conclusion and outlook
- APPENDIX: Some (more) pictures and results
LHC injector chain

- **Duoplasmatron**: Source @ 90 keV (kinetic energy)
- **LINAC2**: Linear accelerator @ 50 MeV
- **PSBooster**: Proton Synchrotron Booster @ 1.4 GeV
- **PS**: Proton Synchrotron @ 25 GeV
- **SPS**: Super Proton Synchrotron @ 450 GeV
- **LHC**: Large Hadron Collider @ 7 TeV

3. De Man 16/05/2003 - proportions not to scale
15 BBLR / IP side => 120 in total

High-luminosity

LHC

CMS

ATLAS

ALICE

LHC-B

+ TOTEM + ALFA

=> PACMAN bunches (# integrated beam-beam effect)
INTRODUCTION AND MAIN CHALLENGES (1/4)

◆ 2 MAIN CHALLENGES FOR LHC => Very high $B$ (2-in-1 SC magnets + superfluid helium at 1.9 K) and very high $Lumi$

◆ PEAK LUMINOSITY

$$L_{peak} = \left( \frac{e c^2}{8 \pi^2 E_0} \right) \left( B \frac{\rho}{R} \right) \left( \frac{N_b}{\varepsilon_n} \right) \left( N_b M \right) \frac{F\left( \theta_c, \sigma_z, \beta^*, \varepsilon_n / \gamma \right)}{\beta^*}$$

- 1st term: constant
- 2nd term: Magnetic field (8.33 T $\leftrightarrow$ 7 TeV proton energy)
- 3rd term: Bunch brightness $\Rightarrow$ SC, BBHO, IBS, TCBI of higher head-tail modes (-1) to be stabilized by Landau octupoles
- 4th term: Total beam current $\Rightarrow$ RF heating, TCBI of mode 0 to be stabilized by transverse damper, TMCI, e-cloud, BBLR, cryogenic load, collimation system (large impedance)...
- 5th term: Lattice (high gradient quadrupole lenses and interaction region geometry), BBLR, RF voltage (bunch length)...
Maximum possible $= 1 / \beta^*$

Neglecting the hour glass effect

$\Delta Q_{\text{BBLR}} \propto \frac{K_{\text{LR}} N_b \varepsilon_n}{\theta_c^2 \beta^* \gamma}$

$\sigma^\text{nom}_z = 7.5 \text{ cm}$

$\beta^*_\text{2012} (4 \text{ TeV}) = 60 \text{ cm}$

$\beta^*_\text{nom} (7 \text{ TeV}) = 55 \text{ cm}$

$\Rightarrow$ Future upgrades with smaller $\beta^*$: crab cavities, smaller bunch length (additional RF system), flat beams, BBLR compensation…

Elias Métral, IPAC2012, New Orleans, Louisiana, USA

MOPPC027, TUPPR027, WEPPC027, TUPPR077
2 MAIN CHALLENGES FOR THE LHC INJECTORS

- Preservation of transverse emittance => High brightness
- Generation of longitudinal structure (25 ns bunch spacing)
  - Very long bunches (~ 180 ns at 4σ) at PSB-PS transfer
  - Very short bunches (~ 1-1.5 ns at 4σ) at SPS extraction

=> Multiple bunch splittings in PS: 12 for 25 ns (and 6 for 50 ns)

=> As PSB could not deliver beams with sufficient brightness, a double-batch scheme was proposed

=> Due to large SC at PS injection, PSB extraction kinetic energy was raised from 1 to 1.4 GeV
INTRODUCTION AND MAIN CHALLENGES (4/4)

Bunch Disposition in the LHC, SPS and PS

- **LHC (1-Ring) = 88.924 μs**

<table>
<thead>
<tr>
<th>Batch</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-batch</td>
<td>from PSB</td>
</tr>
<tr>
<td>4-batch</td>
<td>from PS</td>
</tr>
<tr>
<td>72 b (= 6 × 12) from PS</td>
<td></td>
</tr>
<tr>
<td>288 b (= 4 × 72) from SPS</td>
<td></td>
</tr>
<tr>
<td>2808 b (= 39 × 72 / ring) in LHC</td>
<td></td>
</tr>
<tr>
<td>73 bunches 25ns spacing</td>
<td></td>
</tr>
</tbody>
</table>

Two-batch filling for LHC

- **PSB** h=1
- **PS** h=7

6 b (= 4 + 2) from PSB
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton energy [TeV]</td>
<td>4.0</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>50</td>
<td>25</td>
<td>25 50</td>
</tr>
<tr>
<td>Bunch population [$10^{11}$ p/b]</td>
<td>1.35</td>
<td>1.15</td>
<td>2.2 3.5</td>
</tr>
<tr>
<td>Norm. rms.trans. emittance [$\mu$m]</td>
<td>~ 2.1</td>
<td>3.75</td>
<td>2.5 3.0</td>
</tr>
<tr>
<td>Peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>~ 0.56</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Injectors</th>
<th>50 ns</th>
<th>25 ns</th>
<th>Single bunch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TUXA02</strong></td>
<td># p/b [$10^{11}$]</td>
<td>($\varepsilon_{nx}+\varepsilon_{ny}$) / 2 [$\mu$m]</td>
<td># p/b [$10^{11}$]</td>
</tr>
<tr>
<td>PSB</td>
<td>See plot PSB emittance vs. bunch intensity</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>PS</td>
<td>1.9</td>
<td>1.9</td>
<td>1.4</td>
</tr>
<tr>
<td>SPS nom.</td>
<td>1.6</td>
<td>1.9</td>
<td>1.15</td>
</tr>
<tr>
<td>SPS new optics</td>
<td>1.7</td>
<td>?</td>
<td>1.2</td>
</tr>
<tr>
<td>LHC</td>
<td>1.45</td>
<td>~ 2.3</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>1.35</td>
<td>~ 2.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>
MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (1/6)

◆ LINAC2-PSB
  ▪ Space charge:
    • “Space charge limit” under investigation (~ - 0.5 already achieved, losses) => Dynamic working point + resonances compensation
    • LINAC4 (160 MeV) will replace LINAC2 (50 MeV) => Factor 2
    • To profit from this in PS => Increase PSB extraction kinetic energy from 1.4 to 2 GeV => Factor 1.6

◆ PS
  ▪ “Space charge limit” under investigation (~ - 0.26 already reached)
  ▪ Horizontal head-tail instability on the long 1.2 s injection flat bottom => No pb with linear coupling. Studies ongoing for 2 GeV
MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (2/6)

- e-cloud build-up (and sometimes instabilities if bunch too small for too long a time) => No pb for the moment but under investigation for future requests  

- Longitudinal plane
  - Coupled-bunch instabilities during the ramp after transition and on flat-top. Limit at ~ $1.9 \times 10^{11}$ p/b (for both 25 ns and 50 ns) => Wideband kicker
  - Transient beam loading during bunch splitting => New one-turn delay feedbacks

- SPS
  - Fast vertical single-bunch instability at injection (with very low positive chromaticity). Limit at ~ $1.6 \times 10^{11}$ p/b in good agreement with impedance model (without space charge) but the “clear” mode-coupling could not be observed (maybe indirect measurement of mode-coupling / decoupling)
=> New optics with a lower gamma transition (to increase distance from transition). Expected new limit $\geq 3.5 \times 10^{11}$ p/b.

- “Space charge limit” under investigation (~ 0.19 already achieved)

- e-cloud
  - Major problem for many years for nominal LHC beam
  - Beam quality seems to be acceptable since 2011 (which still needs to be fully understood)
  - For higher intensities => Plan to coat large parts of the inside of the SPS vacuum chambers with amorphous carbon
  - New optics should also be better for the e-cloud instability. Detailed studies ongoing
  - High-bandwidth feedback (CERN – US LARP)
LONGITUDINAL PLANE

- Instability during the ramp. Limit at \( \sim 2 \times 10^{10} \) p/b at the end of the ramp => 4\(^{th}\) harmonic RF system (800 MHz) and controlled longitudinal emittance blow-up. Beneficial effect of new optics under investigation

- Beam loading => RF power upgrade (for future requests)

LHC

- e-cloud => Scrubbing (4-fold strategy + some solenoids added) with high chromaticity

- Loss of longitudinal Landau damping => Controlled blow-up

TRANSVERSE COHERENT INSTABILITIES

- Mode 0 => Transverse damper. Rise-times measured close to predictions at 450 GeV and maybe factor 2-3 faster at 3.5 TeV

- Mode – 1 => Landau octupoles (single- and coupled-bunch). 2 dedicated measurements close to predictions

**MOPPC001, WEPPR068, WEPPR076**

**WEPPR073**
MAIN LIMITATIONS FROM COLLECTIVE EFFECTS (5/6)

- **Transverse impedance**
  - Large transverse (imaginary) impedance from collimators can lead to a loss of transverse Landau damping => Increase Landau octupoles’ current. Ongoing studies to fully understand the larger than predicted current in operation.
  - Larger than predicted transverse (imaginary) impedance could lead to TMCI. Current thresholds: \( \sim 9 \, 10^{11} \, \text{p/b} \) (450 GeV) and \( \sim 4 \, 10^{11} \, \text{p/b} \) (4 TeV, 2012 with tight collimators setting) => In case of problem, increase chromaticity, high-bandwidth FB, reduce imp. …

- **Beam-beam**
  - HO: \( \xi \sim 0.034 \) achieved for 2 collision points (IP1 and IP5), i.e. \( \sim 0.017 / \text{IP} \) (nominal value was \( \sim 0.0035 \)) => Small emittance!
  - PACMAN => Alternating crossing scheme to compensate for the tunes (orbits can only be minimized)
• Coherent beam-beam modes => With few bunches only. Tune split if needed (but should not with many bunches)
• Leveling (by transverse offsets) => For IP2 and IP8 (in operation since 2011)
• Coherent instabilities observed when crossing angle too small or transverse offsets between ~ 1 and 2 \( \sigma \) in IP1 and IP5 or ? => Under investigation

- RF heating (real part of the longitudinal impedance)
  • Injection kickers  WEPPR071
  • Injection protection collimator  WEPPR068
  • RF fingers => Task force in 2012

=> Longer bunch usually better (10 cm rms used in 2012 vs. 7.5 cm nominal)

- UFOs (Unidentified Falling Objects)  THPPP086
SOME (NICE) PICTURES (1/11)

- SPS TMCI

1st: Broad-Band impedance model

WITHOUT SC

SC ONLY

(square-well air-bag, Blaskiewicz1998)

Benoit Salvant
Resistive-wall WITHOUT SC

\[ \frac{Q - Q_x}{Q_S} \]

\( i \times 10^{11} \)

\( N_{th} \approx 1.3 \)

\[ \Delta Q_{SC} / Q_S \approx 50 \]

Resistive-wall WITH SC

\[ \frac{Q - Q_x}{Q_S} \]

\( i \times 10^{11} \)

\( N_{th} \approx 1.4 \)

\[ \Delta Q_{SC} / Q_S \approx 14 \]
**SOME (NICE) PICTURES (3/11)**

- Loss of longitudinal Landau damping during LHC acceleration when the longitudinal emittance is too small

Ongoing studies with Van Kampen modes (A. Burov) => Intensity threshold could be 1 order of magnitude lower

Predicted $Z/n \sim 0.09 \Omega$ (with all collimators)

Elena Shaposhnikova et al.
Single-bunch head-tail instability \( m = -1 \) without Landau octupoles (for \( Q' \sim 6 \)) on LHC flat-top.

- **Rise-time and Landau octupoles’ current for stability** (between 10 and 20 A) within factor \( \sim 2 \) with predictions.
TCBI rise-time studies (for mode 0) with 48 bunches (12 + 36)

- Good agreement at 450 GeV
- ~ 2-3 faster rise-times observed at 3.5 TeV (but uncertainty on chromaticities)
- Landau octupoles’ current for stability at 3.5 TeV within factor ~ 2 with predictions (less than predicted => Studies with Q” ongoing)
ECLOUD studies in the LHC with 25 ns beam

2011 scrubbing history of LHC arcs

$\delta_{\text{max}}$ has decreased from the initial 2.1 to 1.52 in the arcs!

Giovanni Iadarola, Giovanni Rumolo et al.
Simulations $\rightarrow \delta_{\text{max}}$ fixed to 1.5 (added $2e9p^+/m$ uncapt. beam)

Measurements $\rightarrow$ the energy loss per bunch is obtained from the stable phase shift

Obtained from an energy balance for the e-cloud

G. Iadarola, G. Rumolo, J.E. Muller, E. Shaposhnikova et al.
Beam-beam
- PACMAN effects clearly visible

G. Papotti, W. Herr et al.
Bunch-by-bunch orbit measurements variation of the vertex centroid in IP1

W. Herr, R. Bartoldus et al.
SOME (NICE) PICTURES (11/11)

- Coherent beam-beam modes have been observed colliding 2 bunches (demonstrated by analysis of sum and difference of the measured positions of the 2 beams)
- Symmetry breaking suppresses modes as expected

- Without BB collisions

- With BB collisions

X. Buffat, T. Pieloni et al.
CONCLUSION AND OUTLOOK

- Relatively good understanding of the many collective effects and possible cures
- Detailed upgrade plan for the injectors has been clearly defined
- In the LHC, the possible limitations should come from
  - Loss of Landau damping for the TCBI of head-tail mode - 1
  - e-cloud effects for the 25 ns beam
  - RF heating
  - Beam-beam (with its variety of effects and in particular its interplay with the transverse impedance, Landau damping through octupoles and transverse damper)
  
  => Some coherent instabilities observed with too small crossing angle or transverse offsets (~ 1-2 σ) in IP1 and IP5 or ?, with rise-times similar to the predicted ones from the impedance…

  … with some perturbations expected from the UFOs

Still to be fully understood!
CO-AUTHORS


ACKNOWLEDGEMENTS

M. Giovannozzi, many (other) people from CERN (OP team…) and other labs
APPENDIX:

SOME (MORE) PICTURES AND RESULTS
Transverse emittances < ~ 1 µm can be done by transverse shaving.
Horizontal head-tail instability

\[ I_{\text{skew}} = 0.33 \, \text{A} \]

\[ I_{\text{skew}} = -0.07 \, \text{A} \]

\[ I_{\text{skew}} = 0.73 \, \text{A} \]

\[ |K_0| \left( \times 10^{-5} \right) \left[ \text{m}^{-2} \right] \]

\[ I_{\text{skew}} \approx 0.33 \, \text{A} \pm 0.1 \, \text{A} \]
2 (stabilizing) effects predicted with linear coupling
- Transfer of instability growth rates
- Transfer of Landau damping

Measurements in 2011 on a 2 GeV plateau by E. Benedetto seem to be in qualitative agreement (no stability above the diagonal). Ongoing analyses
- HEADTAIL simulations confirmed the transfer of instability growth rates (chromaticity sharing).

- Effect of space charge remains to be studied in detail but a lot of progress has been made over the last few years (Burov2009-2011, Balbekov2011, Kornilov-Frankenheim2010) which can explain why space charge has almost no effect => $\Delta Q_{SC} / Q_s >> 1$ (~150)
Longitudinal coupled-bunch instability
- **e-cloud**: Appears only in the last stages of the RF gymnastics before extraction. Dedicated experiment (shielded pickup) available.
A fast vertical single-bunch instability can be observed at injection with very low positive chromaticity (believed to be TMCI).

H. Burkhardt et al.

Synchrotron period ≈ 7 ms

\[ \xi_y \approx 0 \]

\[ p = 26 \text{ GeV/c} \quad N_b \approx 1.2 \times 10^{11} \text{ p/b} \]

\[ \varepsilon_I \approx 0.2 \text{ eVs} < \varepsilon_I^{LHC} = 0.35 \text{ eVs} \]

Instability suppressed by increasing the chromaticity

\[ \xi_y = 0.8 \]
SPS (2/5)

⇒ Travelling-wave pattern along the bunch

$\xi_y = 0.14$

$\langle y \rangle$ [a.u.]

Time [$\times 0.125\,\text{ns}$]

$1^{\text{st}}$ trace (in red) = turn 2

Head

Tail
Assuming the coasting-beam formalism with peak values (and a Broad-Band impedance), the intensity threshold scaling (without space charge) is given by

\[ N_{b}^{th,y} \propto \frac{f_{r}^{BB}}{Z_{y}^{BB}} \left| \frac{\eta}{\beta_{y}} \right| \varepsilon_{L} \left( 1 + \frac{f_{\xi_{y}}}{f_{r}^{BB}} \right) \]

- Increase the chromatic frequency
- Chromaticity jump in case transition has to be crossed

Increase the beam longitudinal emittance (when possible)

Try to decrease the impedance and/or increase the resonance frequency => Impedance reduction campaign

Try to decrease the impedance and/or increase the resonance frequency => Impedance reduction campaign

Change the optics to decrease the betatron function and/or go further away from transition => New optics studied
- Longitudinal instabilities

- Depends on single-bunch and total beam intensity
- More critical if smaller long. emitt.
Space charge studies

Hannes Bartosik et al. (new optics)
LHC (1/9)

- 22:44:00 => Black
- 22:44:55 => Blue
- m = -1

- 22:44:00 => Black
- 22:45:19 => Green
- m = -1

- 22:44:00 => Black
- 22:45:59 => Red
- m = -1
- m = -2
- m = +1
- m = +2
- m = -3

◆ Single-bunch head-tail instability m = -1 at 3.5 TeV without Landau octupoles
Benchmark between HEADTAIL and theoretical stability diagram (Berg-Ruggiero1996)
TCBI rise-time studies (for mode 0) with 48 bunches (12 + 36)

- Landau octupoles used at 3.5 TeV to stabilize the beam

<table>
<thead>
<tr>
<th>Landau octupole current [A]</th>
<th>Beam 1</th>
<th>Beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEADTAIL predictions</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>(Gaussian bunch)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurements</td>
<td>60</td>
<td>70</td>
</tr>
</tbody>
</table>

- Simulations are more critical (but uncertainty on chromaticities)
- Remaining difference could maybe be explained by the Q'' effect introduced by the octupoles (ongoing analyses)
Transverse (real) coherent tune shift measurements

LHC (4/9)

- Transverse (real) coherent tune shift measurements

Nicolas Mounet

Total tune shift

IR7 collimators

TDI

$\Delta Q_y (\text{exp}) / \Delta Q_y (\text{simu.})$ vs energy
LHC (5/9)

- TMCI at injection

WITHOUT SC

SC ONLY

(square-well air-bag, Blaskiewicz1998)

Nicolas Mounet

\[ \text{Without SC} \]

\[ \text{SC ONLY} \]

\[ \Delta Q_{SC} / Q_s \]

\[ \Delta Q / Q_s \]

\[ \text{LHC inj. nominal} \sim 0.26 \]

\[ \text{LHC inj. 2012} \sim 0.77 \]
LHC (6/9)

- TMCI at 4 TeV

![Graph showing Re[(Q-Qx)/Qs] vs. Nb (10 p/b)]

Nicolas Mounet
It is in fact the Power Spectrum $P_{\text{dB}}(f)$.

Coupled-bunch lines spaced by $M f_0 \sim 20 \text{ MHz}$ (for 50 ns bunch spacing) => It would be $\sim 40 \text{ MHz}$ for 25 ns.

Themis Mastoridis and Philippe Baudrenghien
LHC (8/9)

- **e-cloud**
  - Pressure rise, heat load in the arcs, beam instability, emittance growth and synchronous phase shift
  - Successful dedicated scrubbing run for physics operation in 2011
### LHC (9/9)

- **e-cloud summary (at the end of 2011)**

<table>
<thead>
<tr>
<th></th>
<th>Uncoated straight section</th>
<th>Arc dipoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated $\delta_{\text{max}}$</td>
<td>1.35</td>
<td>1.52</td>
</tr>
<tr>
<td>Threshold $\delta_{\text{max}}$ (25ns, 450 GeV)</td>
<td>1.25</td>
<td>1.45</td>
</tr>
<tr>
<td>Threshold $\delta_{\text{max}}$ (25ns, 3.5 TeV)</td>
<td>1.22</td>
<td>1.37</td>
</tr>
<tr>
<td>Threshold $\delta_{\text{max}}$ (50ns, 450 GeV)</td>
<td>1.63</td>
<td>2.2</td>
</tr>
<tr>
<td>Threshold $\delta_{\text{max}}$ (50ns, 3.5 TeV)</td>
<td>1.58</td>
<td>2.1</td>
</tr>
</tbody>
</table>

- **Prediction for the scrubbing time needed for 25 ns physics operation:** ~ 20 h of beam time (i.e. ~ 2 weeks)