SINGLE-BUNCH INSTABILITY STUDIES
IN THE LHC AT 3.5 TeV/c

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(and thanks to all the impedance and LHC teams)

- 3 measurements performed with ~ 1E11 p/b bunches
  - SA 15/05/10 => Unstable bunch during the ramp
  - SU 16/05/10 => Stabilization with Landau octupoles
  - MO 17/05/10 => Longer bunch + Stabilization with Landau octupoles
- Reminder on the nominal beam parameters
- Reminder on the Transverse Single-Bunch Instability (TSBI) mechanisms
- Reminder on the theoretical predictions with nominal parameters (beam and collimators) at 7 TeV/c
- Simulation predictions at 3.5 TeV/c: Nominal case vs. MD on 17/05/10
- Measurements done during the Dedicated MD on MO 17/05/10
- Conclusion and future work
- Appendices
THE 3 MEASUREMENTS

- A 1\textsuperscript{st} ramp was tried with a single-bunch of \(\sim 1E11\) p/b (on both B1 and B2) on SA 15/05/2010 => The bunch was unstable at \(\sim 1.8\) TeV/c for B1 and \(\sim 2.1\) TeV/c for B2. This led to beam losses of few 10ens of %

- A 2\textsuperscript{nd} ramp was tried on SU 16/05/2010 with a function in the Landau octupoles put by Mike Lamont (from Stephane Fartoukh few years ago, reaching 200 A at 3.5 TeV/c) => Only B2 was available (due to PS problem) and more than 1.2E11 p/b reached 3.5 TeV/c. The beam was unstable at 3.5 TeV/c when the octupoles were removed. Note that the long. emittance was \(\sim 0.3\) eVs and the full bunch length \(\sim 0.6\) ns

- A 3\textsuperscript{rd} ramp was tried on MO 17/05/2010, with the same octupoles function, but then reducing the current in the octupoles at 3.5 TeV/c to find the threshold value. Note in this case the longitudinal emittance was \(\sim 2\) times bigger (by removing the phase loop at injection => Filamentation after phase error)
REMINDER ON THE NOMINAL BEAM PARAMETERS

Table 6.1: The Main Beam and RF Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Injection 450 GeV</th>
<th>Collision 7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch area (2σ)*</td>
<td>eVs</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Bunch length (4σ)*</td>
<td>ns</td>
<td>1.71</td>
<td>1.06</td>
</tr>
<tr>
<td>Energy spread (2σ)*</td>
<td>10⁻³</td>
<td>0.88</td>
<td>0.22</td>
</tr>
<tr>
<td>Intensity per bunch</td>
<td>10¹¹ p</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>Transverse emittance V/H</td>
<td>μm</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>Intensity per beam</td>
<td>A</td>
<td>0.582</td>
<td>0.582</td>
</tr>
<tr>
<td>Synchrotron radiation loss/turn</td>
<td>keV</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>h</td>
<td>-</td>
<td>13</td>
</tr>
<tr>
<td>Intrabeam scattering growth time - H</td>
<td>h</td>
<td>38</td>
<td>80</td>
</tr>
<tr>
<td>- L</td>
<td>h</td>
<td>30</td>
<td>61</td>
</tr>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>400.789</td>
<td>400.790</td>
</tr>
<tr>
<td>Harmonic number</td>
<td></td>
<td>35640</td>
<td>35640</td>
</tr>
<tr>
<td>RF voltage/beam</td>
<td>MV</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Energy gain/turn (20 min. ramp)</td>
<td>keV</td>
<td>485</td>
<td></td>
</tr>
<tr>
<td>RF power supplied during acceleration/ beam</td>
<td>kW</td>
<td>~275</td>
<td></td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>Hz</td>
<td>63.7</td>
<td>23.0</td>
</tr>
<tr>
<td>Bucket area</td>
<td>eVs</td>
<td>1.43</td>
<td>7.91</td>
</tr>
<tr>
<td>RF (400 MHz) component of beam current</td>
<td>A</td>
<td>0.87</td>
<td>1.05</td>
</tr>
</tbody>
</table>

* The bunch values at 450 GeV are an upper value for the situation after filamentation, ~ 100 ms after each batch injection. The bunch parameters at injection are described in the text.
Head-Tail instability if $Q' \neq 0$

- $Q' \geq 0$ above transition, to damp the most critical mode (0)
- But $Q'$ should be as small as possible not to excite the high-order head-tail modes (and it is also better for beam lifetime)
- It will develop if there is no intrinsic or external (e.g. from octupoles) nonlinearities $\Rightarrow$ Landau damping (Trade-off)
- Linear coupling can help or not

When $\Delta Q$ (mode 0, i.e. usual tune) $\sim - Q_s$

- Increasing $Q'$ can help (as predicted and seen in the SPS for instance during MDs)
- But high $Q'$ can decrease the beam lifetime $\Rightarrow$ Trade-off
- Can be stabilized by octupoles but the tune spread required is usually huge ($\sim Q_s$)
- Increasing the long. emittance / bunch length helps
- Linear coupling and Space Charge can also help (or not)

TMC instability (even if $Q' = 0$)

- $N_b$ [p/b]
Which means that we are below the TMCI intensity threshold (if our impedance model is good)
The solution is to reduce the chromaticity as much as possible (but still > 0, if not using a transverse feedback) and use Landau octupoles (if the “unknown” intrinsic nonlinearities are not sufficient).

An instability rise-time of ~ 0.8 s was predicted (with the nominal beam parameters at 7 TeV/c and $Q_x' \sim 6$), with neither intrinsic nonlinearities nor Landau octupoles.
COMPARISON BETWEEN THEORY AND HEADTAIL SIMULATIONS FOR THE NOMINAL CASE AT 7 TeV/c

Theory (2006)

HEADTAIL simulations (2010)
## SIMULATION SETTINGS AT 3.5 TeV/c: NOMINAL VS. MD 17/05/10

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>MD 17/05/2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb [p/b]</td>
<td>1.15E11</td>
<td>1.05E11</td>
</tr>
<tr>
<td>Qx</td>
<td>64.31</td>
<td>64.28</td>
</tr>
<tr>
<td>Qy</td>
<td>59.32</td>
<td>59.31</td>
</tr>
<tr>
<td>Sigma bunch length</td>
<td>0.056 cm</td>
<td>0.06 cm</td>
</tr>
<tr>
<td>Momentum spread</td>
<td>1.2 10^{-4}</td>
<td>0.9 10^{-4}</td>
</tr>
<tr>
<td>Qs</td>
<td>2.9 10^{-3}</td>
<td>2.0 10^{-3}</td>
</tr>
<tr>
<td>Non linear bucket</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>RF voltage (used for matching only)</td>
<td>16 MV</td>
<td>8 MV</td>
</tr>
<tr>
<td>Longitudinal emittance (used for matching only)</td>
<td>1 eVs</td>
<td>0.8 eVs</td>
</tr>
<tr>
<td>Collimator settings</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The simulations were performed over 100,000 turns => As the rise-time are small, the error can be important => To be re-checked over a larger number of turns

Meaning that it does not develop yet over 100,000 turns
An horizontal rise-time of $\sim 4.3$ s is predicted for $Q_x' \sim 6$, with neither intrinsic nonlinearities nor Landau octupoles.
COMPARISON OF THE SIMULATED INSTABILITY RISE-TIMES
AT 3.5 TeV/c: NOMINAL SETTINGS VS. MD of 17/05/10

- Rise-time (Nominal) ~ 6.6 s
- Rise-time (MD) ~ 4.3 s

$Q_x' = 6$
With the same function for the octupoles as on SU 16/05/10 (i.e. 200 A at 3.5 TeV/c)
Steps observed after transverse instabilities and subsequent beam losses
MEASUREMENTS DONE
DURING THE DEDICATED MD ON MO 17/05/10 (3/7)

[Graphs showing data analysis and measurements.]

Elias Métral, LHC
B2 was unstable when \( \text{loct} = -10 \, \text{A} \)
MEASUREMENTS DONE DURING THE DEDICATED MD ON MO 17/05/10 (5/7)
The mode $m = -1$ (at - $Q_s$ from the tune) clearly grows up ($Q_s \sim 2E-3$)

The other Head-Tail modes follow, as predicted

- $m = +1$
- $m = +2$
- $m = -2$
- $m = -3$
Measured instability rise-time = 9.8 s
CONCLUSION AND FUTURE WORK

- It seems that the observed single-bunch instability with ~ 1E11 p/b at high energy is a Head-Tail instability of mode m = -1 (as predicted for $Q_x' \sim 6$, as it was the case during the MD on MO 17/05/2010)
  - Measured instability rise-time ~ 9.8 s (with 10 A in the octupoles): the simulation prediction with the correspondent beam and collimators settings at 3.5 TeV/c is ~ 4.3 s, with neither intrinsic nonlinearities nor Landau octupoles
  - The bunch can be stabilized by Landau damping with a current in the octupoles of ~ 20 A (with 10 A, B2 was unstable): We have some theoretical predictions for this as well but not yet for the MD case => HEADTAIL simulations are running and the results should come soon…
  - For the nominal beam at 7 TeV/c, a rise-time of less than 1 s is predicted for $Q_x' \sim 6$
- Only the observed single-bunch instability was discussed here, but good agreements were also obtained for the dedicated MDs on transverse coherent tune shifts vs. intensity
APPENDICES
Which means that we are below the TMCI intensity threshold (if our impedance model is good)
REMINDER ON THE THEORETICAL PREDICTIONS WITH NOMINAL PARAMETERS AT 7 TeV/c (2/2)

Single-bunch

Y-plane

Coupled-bunch

Elias Métral, LHC Beam Commissioning Working Group meeting, 08/06/2010
The colored dots there are for the coupled-bunch instability, but the stability diagrams are the same (it corresponds here to the maximum current $I_{oct} = 550$ A)
The tune shift for the single-bunch is (see page 5)

\[
\text{Re}[\Delta Q_x] \approx -1.5 \times 10^{-4} \\
\text{Im}[\Delta Q_x] \approx -0.2 \times 10^{-4}
\]

- To have stability this point should be inside the stability diagram, which is the case if one uses Landau octupoles at full current
- In fact we see that with a single bunch the octupole current could even be reduced by a factor $\sim 2 \Rightarrow I_{\text{oct}} \sim 275$ A should be enough
Elias Métral, LHC Beam Commissioning Working Group meeting, 08/06/2010

SA 15/05/2010 (3/5)

LHC - B1 - Fill#0.0
2010-05-15 10:19:32
RAW&FFT: 8192 turns@2.5Hz
no excitation
Q1 = .283084  Qx = .284771
Q2 = .310223  Qy = 308536
|C-| = .013106  E = 1902.4 GeV
Q'x = ???
Q'y = ???

All the lines are spaced by Qs ~ 3E-3
Beam losses observed in IR7
Corresponds to $\text{I_{oct}} = 200 \text{ A}$ (and the max is 550 A)
SU 16/05/2010 (3/9)

BEAM SETUP: RAMP

Energy: 3500 GeV  I(B1): 0.00e+00  I(B2): 1.22e+11

Comments 16-05-2010 23:56:53:

10% above nominal bunch at flat top

LHC Operation in CCC: 77600, 70480

PM Status B1 ENABLED  PM Status B2 ENABLED
=> Qs ~ 4.5E-3 at 450 GeV/c

=> Qs ~ 2E-3 at 3.5 TeV/c
All the lines are spaced by $Q_s \sim 2 \times 10^{-3}$.
Ramp down of the octupoles at 3.5 TeV/c
The instability seems to develop only when loct=0A (but depends on the rise-time) => A finer scan was made on MO 17/05/2010
Injections with phase loops OFF

=> The beams will be longer and the longitudinal emittance larger. Note that nice longitudinal dipolar instabilities were observed on both beams (see movie from Stefano)