Many thanks to the many LHC colleagues!

Elias Métral
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Measurements and interpretation of transverse beam instabilities in the CERN Large Hadron Collider (LHC) and extrapolations to HL-LHC

Elias Métral
BE/ABP-HSC (Collective/Coherent Effects)
15 BBLR / IP side => 120 in total
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CONTENTS

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- Observations, actions taken and lessons learned
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◆ Introduction

◆ Observations, actions taken and lessons learned
  ▪ Run 1 (2010-2012)
  ▪ 2015
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INTRODUCTION

- Transverse instabilities are a concern based on the experience of the LHC Run 1 (with 50 ns) and beginning of Run 2 (with 25 ns)
INTRODUCTION

- Transverse instabilities are a concern based on the experience of the LHC Run 1 (with 50 ns) and beginning of Run 2 (with 25 ns)

- Some instabilities observed & cured

- Some instabilities observed & Not cured

- 6.5 TeV in 2015 and 2016

- 4 TeV in 2012

- 3.5 TeV in 2010 and 2011

- 6.5 TeV in 2015 and 2016

- 4 TeV in 2012

- 3.5 TeV in 2010 and 2011

- Some instabilities observed & cured

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RUN 1 (2010-2012)
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- Measurements of transverse instabilities in the LHC started on Saturday 15/05/2010 during the 1st ramp with an ~ nominal bunch (with neither transverse damper nor Landau octupoles)
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- Measurements of transverse instabilities in the LHC started on Saturday 15/05/2010 during the 1st ramp with an ~ nominal bunch (with neither transverse damper nor Landau octupoles)
  - Instability at ~ 2 TeV for both beams
**RUN 1 (2010-2012)**

- Measurements of transverse instabilities in the LHC started on Saturday 15/05/2010 during the 1st ramp with an ~ nominal bunch (with neither transverse damper nor Landau octupoles)
  - Instability at ~ 2 TeV for both beams
  - “Christmas tree” in May!

![Tune Viewer - LHC - Continuous B1 (FFT1.B1)](image)

- All the lines are spaced by $Q_s \sim 3E-3$
RUN 1 (2010-2012)

- **Detailed study** 2 days after on flat-top ($Q' \sim 6$) with Landau octupoles which were reduced in steps
RUN 1 (2010-2012)

- Detailed study 2 days after on flat-top (Q’ ~ 6) with Landau octupoles which were reduced in steps

All the lines are spaced by Qs ~ 2E-3
RUN 1 (2010-2012)

- Detailed study 2 days after on flat-top ($Q' \sim 6$) with Landau octupoles which were reduced in steps

---

**Detailed Study**

- 2 days after on flat-top ($Q' \sim 6$) with Landau octupoles which were reduced in steps.

**Parameters**

- $Q_1 = 0.288107$, $Q_2 = 0.298082$, $|C|= 0.012477$, $E = 3500.3$ GeV.

**Lines Spacing**

- All the lines are spaced by $Q_s \sim 2 \times 10^{-3}$.

**Measured Instability**

- Rise-time: $9.8$ s

---

Elias Métral, HB2016 workshop, Malmö, Sweden, 05/07/2016
**RUN 1 (2010-2012)**

- **Detailed study** 2 days after on flat-top ($Q' \sim 6$) with Landau octupoles which were reduced in steps.

---

**Measured instability rise-time = 9.8 s**

- $Q_h$
- Amplitude $\uparrow \times [\text{a.u.}]$
- Time $\left[\text{s}\right]$
- $22:44:00$
- $120 \text{ s}$
- $22:46:00$

---

**All the lines are spaced by $Q_s \sim 2E^{-3}$**

---

Elias Métral, HB2016 workshop, Malmö, Sweden, 05/07/2016
RUN 1 (2010-2012)

- Detailed study 2 days after on flat-top \((Q' \sim 6)\) with Landau octupoles which were reduced in steps

Rise-time and Landau octupole current for stability (between -20 and -10 A) within factor \(\sim 2\) with predictions
RUN 1 (2010-2012)

- 1st TCBI rise-time studies (for mode 0) with 48 bunches (12 + 36)
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- Good agreement at 450 GeV
RUN 1 (2010-2012)

- 1\textsuperscript{st} 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)
RUN 1 (2010-2012)

- 1st 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 octupole current for stability at 3.5 TeV within factor ~ 2 with predictions (even less than predicted)
RUN 1 (2010-2012)

- Several other measurements of collective effects were also performed in good agreement with predictions.
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=> Everything started very well (~ as predicted)!
RUN 1 (2010-2012)

- Several other measurements of collective effects were also performed in good agreement with predictions

=> Everything started very well (~ as predicted)!

- Things started to become more involved when we tried to push the performance of the LHC in 2011, and in particular in 2012 (year of discovery of the “Higgs-like” boson)...
## RUN 1 (2010-2012)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E$</td>
<td>$7 \text{ TeV}$ (4 in 2012)</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>$N_b$</td>
<td>$1.15 \times 10^{11}$ (~ 1.6 in 2012)</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>$M$</td>
<td>2808 (1380 in 2012)</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>$\Delta t$</td>
<td>25 ns (50 in 2012)</td>
</tr>
<tr>
<td>Norm. rms. trans. emittance</td>
<td>$\varepsilon$</td>
<td>3.75 µm (~ 2.2 in 2012)</td>
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<tr>
<td>Revolution frequency</td>
<td>$f_0$</td>
<td>11245 Hz</td>
</tr>
<tr>
<td>Rms bunch length</td>
<td>$\sigma_z$</td>
<td>7.5 cm (~ 10 in 2012)</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>$Q$</td>
<td>18.4 nC (25.6 in 2012)</td>
</tr>
<tr>
<td>Total beam current</td>
<td>$I_b$</td>
<td>0.58 A (~ 0.4 in 2012)</td>
</tr>
</tbody>
</table>
### RUN 1 (2010-2012)

<p>| | | | | |</p>
<table>
<thead>
<tr>
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=> Bunch brightness reached: ~ \((1.6 / 1.15) \times (3.75 / 2.2)\) ~ 2.4 times larger than nominal (at 4 TeV)!
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=> Bunch brightness reached: \(\sim (1.6 / 1.15) \times (3.75 / 2.2) \sim 2.4\) times larger than nominal (at 4 TeV)!

=> Record peak luminosity: \(0.77 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\)
RUN 1 (2010-2012)

=> 3 types (in fact 2 after careful analysis) of instabilities were observed
RUN 1 (2010-2012)

- 1) In collision: “snowflakes”
RUN 1 (2010-2012)

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Courtesy of X. Buffat
1) In collision: “snowflakes”

Courtesy of X. Buffat
RUN 1 (2010-2012)

- **1) In collision: “snowflakes”**

- Always in H only (both beams)

*Courtesy of X. Buffat*
RUN 1 (2010-2012)

1) In collision: “snowflakes”

- Always in H only (both beams)
- Concerned initially only IP8 private bunches => Disappeared when filling scheme was changed
1) In collision: “snowflakes”

- Always in H only (both beams)
- Concerned initially only IP8 private bunches => Disappeared when filling scheme was changed
- Happens on selected bunches with insufficient tune spread (and thus Landau damping) due to no BBHO collisions (or offsets)
RUN 1 (2010-2012)

- 2) During the collapsing process (putting the beams into collision)
RUN 1 (2010-2012)

2) During the collapsing process (putting the beams into collision)

 Courtesy of G. Arduini
RUN 1 (2010-2012)

- 2) During the collapsing process (putting the beams into collision)

Example of instability at ~ 2.1 $\sigma$ in IP1 and ~ 1.2 $\sigma$ in IP5 (estimated from luminosities at the moment of the dump)
2) During the collapsing process (putting the beams into collision)

- Example of instability at ~ 2.1 $\sigma$ in IP1 and ~ 1.2 $\sigma$ in IP5 (estimated from luminosities at the moment of the dump)
- Also in H
2) During the collapsing process (putting the beams into collision)

- Example of instability at ~ 2.1 $\sigma$ in IP1 and ~ 1.2 $\sigma$ in IP5 (estimated from luminosities at the moment of the dump)
- Also in H
- Happened only once or twice during the intensity ramp-up => Was never observed later in operational conditions

**Courtesy of G. Arduini**
RUN 1 (2010-2012)

- 3) During or at the end of the squeeze process => End-Of-Squeeze Instability (EOSI)
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Courtesy of X. Buffat
RUN 1 (2010-2012)

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- Also in H

Courtesy of X. Buffat
RUN 1 (2010-2012)

- Actions taken
RUN 1 (2010-2012)

- Actions taken
  - Initial recommendations
RUN 1 (2010-2012)

- **Actions taken**
  - Initial recommendations
    - Chromaticities: as low as possible (1-2 units)
RUN 1 (2010-2012)

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    - Transverse damper gain: as low as possible
RUN 1 (2010-2012)

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  - Chromaticities: as low as possible (1-2 units)
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RUN 1 (2010-2012)

- **Actions taken**

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    - Chromaticities: as low as possible (1-2 units)
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  - With issues discussed before, several actions were taken to continue and push the performance
RUN 1 (2010-2012)

- **Actions taken**

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    - Chromaticities: as low as possible (1-2 units)
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    - Proposed to change the sign of the Landau octupoles such that the tune spreads from BBLR and octupoles do not fight against each other (S. Fartoukh)
RUN 1 (2010-2012)

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  - Proposed to change the sign of the Landau octupoles such that the tune spreads from BBLR and octupoles do not fight against each other (S. Fartoukh)
  - New values for the gain of the transverse damper, chromaticities and Landau octupole current suggested after a new analytical approach (NHTVS from A. Burov)
RUN 1 (2010-2012)

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    - New values for the gain of the transverse damper, chromaticities and Landau octupole current suggested after a new analytical approach (NHTVS from A. Burov)

=> Finally used high chromaticities (~ 15) + ~ maximum octupole current (max = + 550 A) + ~ maximum damper gain (50-turn damping)…
RUN 1 (2010-2012)

- Lessons learned
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- Lessons learned
  - Seems that main reason for which situation improved was the increase of chromaticity (which was not well corrected)
RUN 1 (2010-2012)

- **Lessons learned**
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    - Running at high chromaticity prevented to reach negative values
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- **Lessons learned**
  - Seems that main reason for which situation improved was the increase of chromaticity (which was not well corrected)
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    - Transverse damper was not fully bunch-by-bunch initially => More octupole current required for low chromaticities
RUN 1 (2010-2012)

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- Seems that main reason for which situation improved was the increase of chromaticity (which was not well corrected)
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  - Transverse damper was not fully bunch-by-bunch initially => More octupole current required for low chromaticities

Initial transverse damper

Fully bunch-by-bunch (flat gain)

 Courtesy of A. Burov
RUN 1 (2010-2012)

- Lessons learned
  - Change in octupole sign was finally found not to be helpful from both i) measurements
RUN 1 (2010-2012)

- **Lessons learned**
  - Change in octupole sign was finally found not to be helpful from both i) measurements

*Courtesy of T. Pieloni*
RUN 1 (2010-2012)

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==> EOSI could not be cured / understood yet

Courtesy of T. Pieloni
RUN 1 (2010-2012)

- **Lessons learned**
  - Change in octupole sign was finally found not to be helpful from both i) measurements

=> EOSI could not be cured / understood yet

=> Still potential worry for the future
RUN 1 (2010-2012)

- Lessons learned
  
  and ii) simulations (see stability diagram below)
RUN 1 (2010-2012)

- Lessons learned

and ii) simulations (see stability diagram below)  

Courtesy of X. Buffat

![Stability Diagram](image)
RUN 1 (2010-2012)

- Lessons learned

and ii) simulations (see stability diagram below)  

- However, a positive sign is predicted to be much better for the case of the Nominal configurations  
  ⇒ This is why the positive sign of the octupoles is used during Run 2

Courtesy of X. Buffat
RUN 1 (2010-2012)

◆ Lessons learned

- Main lesson learnt for the future was to better study the interplays between (all) the different mechanisms in a machine like the LHC
RUN 1 (2010-2012)

 Lessons learned

- Main lesson learnt for the future was to better study the interplays between (all) the different mechanisms in a machine like the LHC
- A lot of work has been done over the last few years with in particular
RUN 1 (2010-2012)

- **Lessons learned**
  - Main lesson learnt for the future was to better study the interplays between (all) the different mechanisms in a machine like the LHC
  - A lot of work has been done over the last few years with in particular
    - Proposed mechanism of the 3-beam instability (A. Burov)
RUN 1 (2010-2012)

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  - Detailed analysis of the transverse mode coupling instability of colliding bunches (S. White)
RUN 1 (2010-2012)

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  - Proposed mechanism of a modification of the stability diagram by some beam-induced noise (X. Buffat)

Courtesy of X. Buffat
RUN 1 (2010-2012)

- Lessons learned
  - Main lesson learnt for the future was to better study the interplays between (all) the different mechanisms in a machine like the LHC
  - A lot of work has been done over the last few years with in particular
    - Proposed mechanism of the 3-beam instability (A. Burov)
    - Detailed analysis of the transverse mode coupling instability of colliding bunches (S. White)
    - Proposed mechanism of a modification of the stability diagram by some beam-induced noise (X. Buffat) => To be able to learn more on stability diagrams from beam-based measurements, Beam Transfer Measurements (BTF) should be performed

Courtesy of X. Buffat
2015

- **Impedance-induced transverse beam instability**: Single bunch
Impedance-induced transverse beam instability: Single bunch

DELPHI with perfect damper

Courtesy of L.R. Carver

Elias Métral, HB2016 workshop, Malmö, Sweden, 05/07/2016
Impedance-induced transverse beam instability: Single bunch

Delphi with perfect damper

Courtesy of L.R. Carver
2015

- Destabilising effect of e-cloud at 6.5 TeV: 72 bunches
Destabilising effect of e-cloud at 6.5 TeV: 72 bunches

Courtesy of L.R. Carver
2015

- Destabilising effect of e-cloud at 6.5 TeV: 72 bunches

After some scrubbing

ΔΦ_s ~ 0.8 deg

1 node

τ ~ 0.5-1 s

Courtesy of L.R. Carver

Elias Métral, HB2016 workshop, Malmö, Sweden, 05/07/2016
Destabilising effect of e-cloud at 6.5 TeV: 72 bunches

\[ \tau \sim 0.5-1 \text{ s} \]
\[ \Delta \Phi_s \sim 0.8 \text{ deg} \]

1 node

\[ \tau \sim 15-20 \text{ s} \]
\[ \Delta \Phi_s \sim 0.3 \text{ deg} \]

2 nodes

Courtesy of L.R. Carver

DELPHI with perfect damper
Destabilising effect of linear coupling at injection
Destabilising effect of linear coupling at injection

When the injection working point was optimized (for e-cloud)
=> (0.275,0.295) instead of (0.28,0.31)
2015

- Destabilising effect of linear coupling at injection
  - When the injection working point was optimized (for e-cloud) => (0.275,0.295) instead of (0.28,0.31)
  - When Laslett tune shifts not corrected during injection
2015

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  - When the injection working point was optimized (for e-cloud) => (0.275,0.295) instead of (0.28,0.31)
  - When Laslett tune shifts not corrected during injection

![Graph showing intensity and energy with |Q_y-Q_x| values](image)

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<thead>
<tr>
<th>BBQ tunesH</th>
<th>BBQ tunes V</th>
<th>BSRT H</th>
<th>BSRT V</th>
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<tbody>
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<table>
<thead>
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<th>BSRT H</th>
<th>BSRT V</th>
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<td>0.02</td>
<td>0.009</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Courtesy of L.R. Carver
Destabilising effect of linear coupling at injection

- When the injection working point was optimized (for e-cloud) => (0.275,0.295) instead of (0.28,0.31)
- When Laslett tune shifts not corrected during injection

=> Believed to be due to linear coupling (see later)
2015

- 1\textsuperscript{st} BTF measurements in the LHC and 1\textsuperscript{st} stability diagram measured
2015

- 1st BTF measurements in the LHC and 1st stability diagram measured

**Courtesy of C. Tambasco**
2015

- 1ST BTF measurements in the LHC and 1st stability diagram measured

Calibration factor still needed

Courtesy of C. Tambasco
Closer look recently: why do we see a loop in the BTF and what are its characteristics?

ΔQ~3e-3

Courtesy of C. Tambasco
Closer look recently: why do we see a loop in the BTF and what are its characteristics?

Loop also revealed in simulation (COMBI)
Closer look recently: why do we see a loop in the BTF and what are its characteristics?

Mathematical description of the BTF of a loop

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Loop also revealed in simulation (COMBI)

Courtesy of C. Tambasco
Closer look recently: why do we see a loop in the BTF and what are its characteristics?

Mathematical description of the BTF of a loop

Next: what is the physics?
2015

- Actions taken
2015

- **Actions taken**
  - High chromaticities (~ 15) + ~ maximum octupole current (550 A)
2015

- **Actions taken**
  - High chromaticities (~ 15) + ~ maximum octupole current (550 A)
  - Detailed simulation campaign started to study effects of e⁻ from arc dipoles and quadrupoles but also from interaction regions
2015

- **Actions taken**
  - High chromaticities (≈ 15) + ≈ maximum octupole current (550 A)
  - Detailed simulation campaign started to study effects of e⁻ from arc dipoles and quadrupoles but also from interaction regions
  - With new injection working point, recommendation to correct both Laslett tune shifts and closest tune approach (|C⁻|), to avoid possible instabilities induced by linear coupling
2015

- **Actions taken**
  - High chromaticities (~15) + ~ maximum octupole current (550 A)
  - Detailed simulation campaign started to study effects of e\(^-\) from arc dipoles and quadrupoles but also from interaction regions
  - With new injection working point, recommendation to correct both Laslett tune shifts and closest tune approach (\(|C^-|\)), to avoid possible instabilities induced by linear coupling
  - Detailed analysis of effect of linear coupling on transverse beam instabilities also started with a single bunch at high energy
2015

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- High chromaticities (~ 15) + ~ maximum octupole current (550 A)
- Detailed simulation campaign started to study effects of $e^-$ from arc dipoles and quadrupoles but also from interaction regions
- With new injection working point, recommendation to correct both Laslett tune shifts and closest tune approach ($|C^-|$), to avoid possible instabilities induced by linear coupling
- Detailed analysis of effect of linear coupling on transverse beam instabilities also started with a single bunch at high energy
- BTF measurements started to be benchmarked
2015

- Lessons learned
Lessons learned

While it is still not completely clear why such high values were needed in 2012, it was clear in 2015 that an important e-cloud was still present at high energy and that it could drive the beam unstable.
2015

Lessons learned

- While it is still not completely clear why such high values were needed in 2012, it was clear in 2015 that an important e-cloud was still present at high energy and that it could drive the beam unstable

- Furthermore, linear coupling should be studied in more detail during all the LHC cycle
Destabilising effect of linear coupling at 6.5 TeV => Linear coupling can be beneficial or detrimental
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Why could linear coupling be a problem for beam stability?
Destabilising effect of linear coupling at 6.5 TeV => Linear coupling can be beneficial or detrimental

- Why could linear coupling be a problem for beam stability?

- => Because the coherent tunes are shifted by linear coupling differently compared to the incoherent tunes (providing the Landau damping) due to the nonlinear fields (from octupoles to create the tune spread). Therefore in some cases a too strong coupling can be detrimental, leading to instabilities due to a loss of transverse Landau damping.
DESTABILISING EFFECT OF LINEAR COUPLING IN THE HERA PROTON RING

E. Métral, CERN, Geneva, Switzerland
G. Hoffstaetter, F. Willeke, DESY, Hamburg, Germany

Abstract

Since the first start-up of HERA in 1992, a transverse coherent instability has appeared from time to time at the beginning of the acceleration ramp. In this process, the emittance is blown up and the beam is partially or completely lost. Although the instability was found to be of the head-tail type, and the chromaticity and linear coupling between the transverse planes was recognized as essential for the instability to occur, the driving mechanism was never clarified. An explanation of the phenomenon is presented in this paper using the coupled Landau damping theory. It is predicted that a too strong coupling can be detrimental since it may shift the coherent tune outside the incoherent spectrum and thus prevent Landau damping. Due to these features, the name "coupled head-tail instability" is suggested for this instability in the HERA proton ring.
DESTABILISING EFFECT OF LINEAR COUPLING IN THE HERA PROTON RING

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Abstract

Since the first start-up of HERA in 1992, a transverse coherent instability has appeared from time to time at the beginning of the acceleration ramp. In this process, the emittance is blown up and the beam is partially or completely lost. Although the instability was found to be of the head-tail type, and the chromaticity and linear coupling between the transverse planes was recognized as essential for the instability to occur, the driving mechanism was never clarified. An explanation of the phenomenon is presented in this paper using the coupled Landau damping theory. It is predicted that a too strong coupling can be detrimental since it may shift the coherent tune outside the incoherent spectrum and thus prevent Landau damping. Due to these features, the name "coupled head-tail instability" is suggested for this instability in the HERA proton ring.

Simple model used (externally given elliptical spectrum...) => Detailed simulation study currently being performed for the LHC by L.R. Carver (see after)
pyHEADTAIL simulations with an octupole as detuner
- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

\[ |C^-| = 0 \]

Courtesy of L.R. Carver
- pyHEADTAIL simulations with an octupole as detuner

- MADX with the real octupoles

\[ |C^-| = 0.002 \]

Courtesy of L.R. Carver
- pyHEADTAIL simulations with an octupole as detuner

LOF > 0

\[ |C^-| = 0.004 \]

Courtesy of L.R. Carver

- MADX with the real octupoles
- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

$$|C^-| = 0.006$$

Courtesy of L.R. Carver
pyHEADTAIL simulations with an octupole as detuner

MADX with the real octupoles

$$\text{LOF > 0}$$

$$|C^-| = 0.008$$

Courtesy of L.R. Carver
- pyHEADTAIL simulations with an octupole as detuner

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\[ |C^-| = 0.01 \]

Tune footprint for \( 3\sigma \) with \( i_{\text{det}} = 500 \, \text{A}, |C^-| = 0.01 \)
- pyHEADTAIL simulations with an octupole as detuner (LOF < 0)

- MADX with the real octupoles (LOF > 0, swapped tunes)

\[ |C^-| = 0 \]

Courtesy of L.R. Carver
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\[ |C^-| = 0.002 \]
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\[ |C^-| = 0.008 \]

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Courtesy of L.R. Carver

![Tune Footprint for 3σ with \( i_{\text{act}} = 500 \text{ A}, |C^-| = 0.008 \)]
- pyHEADTAIL simulations with an octupole as detuner (LOF < 0)

- MADX with the real octupoles (LOF > 0, swapped tunes)

\[ |C^-| = 0.01 \]

Courtesy of L.R. Carver
2016

- Physical mechanism => Simple model?
Physical mechanism => Simple model?

- $J_x = 0$ and $J_y = 1$
- $J_x = 1$ and $J_y = 0$
- $\text{LOF} < 0$
- $\text{LOF} > 0$

Focusing octupoles
\[ Q_u = Q_x - \frac{|C^-|}{2} \tan \alpha \]

\[ Q_v = Q_y + \frac{|C^-|}{2} \tan \alpha \]

\[ \Delta = Q_y + l - Q_x = q_y - q_x = Q_{sep} \]

\[ \tan(2\alpha) = \frac{|C^-|}{\Delta} \]
\( Q_v - Q_y = \frac{1}{2} \left( -\Delta + \sqrt{\Delta^2 + |C^-|^2} \right) \)

\( Q_u - Q_x = -\frac{1}{2} \left( -\Delta + \sqrt{\Delta^2 + |C^-|^2} \right) \)
Similar (but much smaller) behaviour seen
- Similar (but much smaller) behaviour seen

- Another ingredient is needed => Amplitude-dependent $C^-$
§ Similar (but much smaller) behaviour seen

§ Another ingredient is needed

$\Rightarrow$ Amplitude-dependent $C^-$

- Example found empirically:

$$|C^-| \times \left[ 1 + 0.15 \left( J_x - J_y \right) \right]$$
Similar (but much smaller) behaviour seen

Another ingredient is needed => Amplitude-dependent $C^-$

- Example found empirically:

$$|C^-| \times \left[ 1 + 0.15 \left( J_x - J_y \right) \right]$$
\[ |C^-| \times \left[ 1 - 0.15 \left( J_x - J_y \right) \right] \]
\[ |C^-| = 0.008 \]

\[ |C^-| \times \left[ 1 - 0.15 \left( J_x - J_y \right) \right] \]
2016

- **See also** R. Tomas et al., “Amplitude dependent closest tune approach” (submitted to PRAB) => However, the amplitude-dependent C discussed before is not the same as the one in the paper and has been deduced empirically => To be continued...
2016

- Dedicated instability measurements in the LHC on 16/04/2016
2016

- Dedicated instability measurements in the LHC on 16/04/2016
  - 1) During the betatron squeeze
2016

- Dedicated instability measurements in the LHC on 16/04/2016
  - 1) During the betatron squeeze
  - 2) At top energy (before the betatron squeeze)
2016

- 1) During the betatron squeeze: ADT on, Q’ ~ 9 and LOF = + 285 A

Transverse damper

Focusing octupoles
1) During the betatron squeeze: ADT on, $Q' \sim 9$ and $LOF = + 285 \, A$
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- Bump of $|C^-| \sim 0.008$
1) During the betatron squeeze: ADT on, Q’ ~ 9 and LOF = + 285 A

- Bump of |C⁻| ~ 0.008
- Q₁/Q₂ kept at 0.31/0.32 (tune feedback) => Qₓ ~ 0.312 and Qᵧ ~ 0.318 => Qᵧ – Qₓ ~ 0.006 (i.e. tune feedback is amplifying the coupling effect!)

Elias Métral, HB2016 workshop, Malmö, Sweden, 05/07/2016
1) During the betatron squeeze: ADT on, Q' ~ 9 and LOF = + 285 A

- Bump of |C| ~ 0.008
- Q1/Q2 kept at 0.31/0.32 (tune feedback) => Qx ~ 0.312 and Qy ~ 0.318 => Qy – Qx ~ 0.006 (i.e. tune feedback is amplifying the coupling effect!)
- Instability observed with LOF = + 285 A, i.e. ~ 4 times higher octupole current than uncoupled threshold
2016

- 2) At top energy (before the betatron squeeze)
2016

• 2) At top energy (before the betatron squeeze)

- $|C^-| \sim 0.001$ and $Q_{sep} = 0.03$:

$\Rightarrow$ Stability for LOF = + 71 A

*Courtesy of L.R. Carver*
2016

• 2) At top energy (before the betatron squeeze)

✧ $|C^-| \sim 0.001$ and $Q_{\text{sep}} = 0.03$: => Stability for LOF = + 71 A

✧ $|C^-| \sim 0.01$ and LOF = + 310 A => Instability for $Q_{\text{sep}} \sim 0.018$

Courtesy of L.R. Carver
This gives a factor $310 / 71 = 4.4$ increase in Landau octupole current compared to the uncoupled case.

Courtesy of L.R. Carver
2016

- Signs of e-cloud (?) instability in stable beam with batches of 72 bunches for $Q' \sim 15$
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“Pop corn” instability
Signs of e-cloud (?) instability in stable beam with batches of 72 bunches for Q’ ~ 15
- Only vertical (B1&B2)

“Pop corn” instability

Elias Métral, HB2016 workshop, Malmö, Sweden, 05/07/2016
2016

- Signs of e-cloud (?) instability in stable beam with batches of 72 bunches for $Q' \sim 15$
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  - At the end of trains of 72 bunches

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Elias Métal, HB2016 workshop, Malmö, Sweden, 05/07/2016
Signs of e-cloud (?) instability in stable beam with batches of 72 bunches for $Q' \sim 15$

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- Emittance BU by a factor $\sim 2$

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- Emittance BU by a factor $\sim 2$
- No beam loss

“Pop corn” instability

=> Was cured by increasing the vertical chromaticity (+7) in stable beam (to $\sim 22$)!
Elias Métal, HB2016 workshop, Malmö, Sweden, 05/07/2016

Fill 4979

\[ Q' \sim 15 \]


Courtesy of X. Buffat
Q' ~ 15

Courtesy of X. Buffat
2016

- Possible mechanism? (G. Iadarola and G. Rumolo)
Since few days we have been injecting batches of $2 \times 48$ bunches from the SPS instead of 1 batch of 72 bunches.
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![Graph]( Courtesy of X. Buffat)
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Courtesy of X. Buffat
2016

- Actions taken
Actions taken

- Linear coupling corrected all along the cycle and in particular during betatron squeeze
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- Laslett tune shifts now corrected automatically at injection
2016

- **Actions taken**
  - Linear coupling corrected all along the cycle and in particular during betatron squeeze
  - Laslett tune shifts now corrected automatically at injection
  - Vertical chromaticities increased by 7 units in stable beam (to reach values of ~ 20-25) => Almost completely suppressed vertical emittance blow-up
Actions taken

- Linear coupling corrected all along the cycle and in particular during betatron squeeze
- Laslett tune shifts now corrected automatically at injection
- Vertical chromaticities increased by 7 units in stable beam (to reach values of ~ 20-25) => Almost completely suppressed vertical emittance blow-up
- Next: try and measure vertical tune shift along a batch during stable beam to try and confirm the proposed mechanism for beam instabilities in stable beam => Expected tune shift of the order of $10^{-4}$...
2016

- Lessons learned
Lessons learned

- Linear coupling has to be well corrected all along the LHC cycle to avoid using too much octupole current
Lessons learned

- Linear coupling has to be well corrected all along the LHC cycle to avoid using too much octupole current
- Even in the presence of a large tune spread in stable beam (due to BBHO) the beam can become unstable
Lessons learned

- Linear coupling has to be well corrected all along the LHC cycle to avoid using too much octupole current.
- Even in the presence of a large tune spread in stable beam (due to BBHO) the beam can become unstable.
- Fortunately the beam could be stabilised by increasing considerably the vertical chromaticities (to values as high as ~ 20-25), which still leads however to sufficiently good lifetimes.

=> A high chromaticity does not seem to be an issue for the current LHC.
Lessons learned

- Linear coupling has to be well corrected all along the LHC cycle to avoid using too much octupole current.

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- Fortunately the beam could be stabilised by increasing considerably the vertical chromaticities (to values as high as ~20-25), which still leads however to sufficiently good lifetimes.

- => A high chromaticity does not seem to be an issue for the current LHC.

- Instabilities can also be observed during the collision (Adjust) process with the positive sign of the Landau octupoles (to be confirmed and studied in detail).
FUTURE
The LHC just reached the design peak luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at 6.5 TeV and with ~25% less bunches than nominal.
FUTURE

- The LHC just reached the design peak luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ at 6.5 TeV and with $\sim$25% less bunches than nominal.
- For HL-LHC the bunch brightness will increase by a factor $\sim 3$
FUTURE

- Impedance-induced transverse beam instability
FUTURE

- **Impedance-induced transverse beam instability**

Quasi-parabolic (~ 3.2 σ) transverse profile

SD-vs-Qp d=50 turns plane-x M2748 parabolic eps2.5um Nb2.2e11 sigmaz-0.081m oct-negative

**Courtesy of N. Biancacci**

Elias Métral, HB2016 workshop, Malmö, Sweden, 05/07/2016
Impedance-induced transverse beam instability

Quasi-parabolic \((\sim 3.2 \sigma)\) transverse profile

Baseline without Crab Cavities

SD-vs-Qp d=50 turns plane-x M2748 parabolic eps2.5um Nb2.2e11 sigmaz-0.081m oct-negative

Courtesy of N. Biancacci
FUTURE

- Impedance-induced transverse beam instability

SD-vs-Qp d=50 turns plane-x M2748 parabolic $\epsilon 2.5\mu m \text{Nb} 2.2e11 \sigma\text{m-0.081m oct-negative}$

**Quasi-parabolic (~ 3.2 $\sigma$) transverse profile**

FUTURE

◆ Beam-Beam
FUTURE

- Beam-Beam

Courtesy of C. Tambasco
FUTURE

- Beam-Beam

Recommendation: go from $2\sigma$ to $1\sigma$ in less than 1 s (i.e. faster than the predicted instabilities)

Courtesy of C. Tambasco
FUTURE

- E-cloud
FUTURE

- E-cloud => Huge campaign of simulations on-going
FUTURE

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  - Try and (fully) understand the recently observed vertical emittance blow-ups in stable beam after few hours in LHC
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  - How will the LHC conditioning evolve?
FUTURE

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  - Try and (fully) understand the recently observed vertical emittance blow-ups in stable beam after few hours in LHC
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E-cloud => Huge campaign of simulations on-going

- Try and (fully) understand the recently observed vertical emittance blow-ups in stable beam after few hours in LHC
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- Try and (fully) understand the recently observed vertical emittance blow-ups in stable beam after few hours in LHC
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- Effect(s) of the e\(^-\) in quadrupoles on beam stability?
FUTURE

- E-cloud => Huge campaign of simulations on-going
  - Try and (fully) understand the recently observed vertical emittance blow-ups in stable beam after few hours in LHC
  - How will the LHC conditioning evolve? Will we be able to remove the e\(^-\) from the dipoles? Effect(s) of these e\(^-\) on beam stability?
  - Effect(s) of the e\(^-\) in quadrupoles on beam stability?
  - Etc.

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CONCLUSION

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In a machine like the LHC, not only all the mechanisms have to be understood separately, but (ALL) the possible interplays between the different phenomena need to be analyzed in detail, including the:

- Beam-coupling impedance (with in particular all the necessary collimators to protect the machine but also new equipment such as crab cavities at large $\beta$-function)
- Linear and nonlinear chromaticity
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- Transverse damper
CONCLUSION

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  - Tune separation between the transverse planes (bunch by bunch)
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  - Tune separation between the transverse planes (bunch by bunch)
  - Tune split between the two beams (bunch by bunch)
  - Transverse beam separation between the two beams
  - Noise
CONCLUSION

In a machine like the LHC, not only all the mechanisms have to be understood separately, but (ALL) the possible interplays between the different phenomena need to be analyzed in detail, including the

- Beam-coupling impedance (with in particular all the necessary collimators to protect the machine but also new equipment such as crab cavities at large $\beta$-function)
- Linear and nonlinear chromaticity
- Landau octupoles (and other intrinsic nonlinearities)
- Transverse damper
- Space charge
- Beam-beam: BBLR and BBHO
- Electron cloud
- Linear coupling strength
- Tune separation between the transverse planes (bunch by bunch)
- Tune split between the two beams (bunch by bunch)
- Transverse beam separation between the two beams
- Noise
- Etc.
CONCLUSION

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  - E-cloud => *Already measured in MD/physics but simulations still to come*